

# SYNOPTIC WEATHER LAB NOTES

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CLASS REPORT # 1

# SYNOPTIC WEATHER LAB NOTES

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## Preface

This set of class notes was compiled beginning in the Fall of 1977 as part of the reading material for courses and lectures in synoptic meteorology at the University of Virginia and at Colorado State University. While the material does not represent an exhaustive review of the field, it is intended to introduce the beginning atmospheric science student to the topic. The linkage of synoptic meteorology to the dynamics and thermodynamics of atmospheric processes is emphasized. At this time, while additional refinements and details in the text are desired, it is felt that it would be useful to complete and distribute the material in a somewhat more formal manner. The author would appreciate comments from readers on significant oversights left out of the introductory notes, along with errors of commission. The author specifically thanks Chris Landsea for his very valuable suggestions and corrections to the text.

The word processing preparation, and final editorial completion of the work was very competently completed by Dallas Staley. This support for the preparation of the published version of the notes was provided by NSF Grant #ATM 86-16662, #ATM 89-15265, and #ATM-9910857.

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# 1. Introduction

This book is designed to give students an overview of the rationale and techniques used in synoptic weather forecasting. It assumes a basic knowledge of atmospheric dynamics and thermodynamics, but repeats certain fundamental concepts which are of particular importance in understanding the material.

The text is segmented into material which focuses on the depiction of the vertical structure of the atmosphere (Section 2), depiction of the horizontal structure of the atmosphere (Section 3), thermodynamic analyses (Section 4), and climatology (Section 5).

For information on mesoscale forecasting the reader is referred to Ray (1986), while nowcasting is discussed by Browning (1982). This author defines synoptic forecasting as hydrostatic weather features which are near gradient balance above the planetary boundary (i.e., earth's friction layer). Mesoscale systems are also hydrostatic but the divergent component of the horizontal wind is a significant part of their structure. Nowcasting includes both synoptic and mesoscale effects and is defined by this author as being able to interpret weather signs; i.e., 1) completely on your own without any external aid – based on personal experience and discussion with local residents in the specific geographic locale of interest; or 2) support or disregard of National Weather Service predictions on the basis of your observations.

## 2. Depiction of the Vertical Structure of the Atmosphere

### 2.1 Quantitative Measures of the Vertical Profile

The first law of thermodynamics can be written as:

$$ds = C_p \left( \frac{dT_v}{T_v} \right) - \left( \frac{R_d}{p} \right) dp \quad (\text{page 11 from Pielke 1984}) \quad (2.1)$$

where  $s$  is entropy,  $C_p$  is the specific heat at constant pressure (1005 J K<sup>-1</sup> kg<sup>-1</sup> for dry air),  $T_v$  is virtual temperature<sup>1</sup>,  $R_d$  is the gas constant for dry air (287 J K<sup>-1</sup> kg<sup>-1</sup>), and  $p$  is pressure.

When no heat is gained or lost,  $ds = 0$ , so that:

$$d(\ln T_v) = (R_d/C_p) d \ln p \quad (2.2)$$

Integrating Eq. (2.2) between two points with a temperature and pressure combination of  $T_{v1}$ ,  $P_1$ , and  $T_{v2}$ ,  $P_2$ , and taking antilogs yields:

$$T_{v2}/T_{v1} = (P_2/P_1)^{R_d/C_p} \quad (2.3)$$

Let  $P_2 = 1000$  mb and  $T_{v2} = \theta$ , then Eq. (2.3) becomes:

$$\theta = T_v [1000/p \text{ (in mb)}]^{R_d/C_p} \quad (2.4)$$

or

$$T_v = \theta (1000 \text{ mb})^{C_p/R_d} p^{R_d/C_p} = (\text{constant}) \theta p^{0.286} \quad (2.5)$$

A graphical solution of Eq. (2.5) is illustrated in Fig. 2.1. In atmospheric applications, the  $p$  scale is inverted since pressure decreases with height. Normally the up direction on a page is related to a positive upward vertical direction.

As an example, for  $T_v = 300$  K,  $p = 1000$  mb; and for  $T_v = 270.5$  K,  $p = 700$  mb, and  $\theta = 300$  K in both cases. For  $T_v = 248$  K,  $p = 700$  mb;  $\theta = 275$  K [ $0^\circ\text{C} = 273.16$  K].

Other quantities can be plotted on such a thermodynamic diagram<sup>2</sup>. The *mixing ratio* is defined as the ratio of the mass of water vapor,  $m_v$ , to the mass of dry air,  $m_d$ ,

$$w = \frac{m_v}{m_d} = \frac{\rho_v}{\rho_d} \quad (2.6)$$

---

<sup>1</sup> $T_v = T(1 + 0.61w)$  where  $w$  is defined by Eq. (2.6).  $T_v$  is always greater than or equal to  $T$  and is used in order to account for the observation that water vapor has a smaller atomic weight than the dry air which it replaces in a volume.

<sup>2</sup>Henceforth, in these notes,  $T$  will be used to represent virtual temperature.

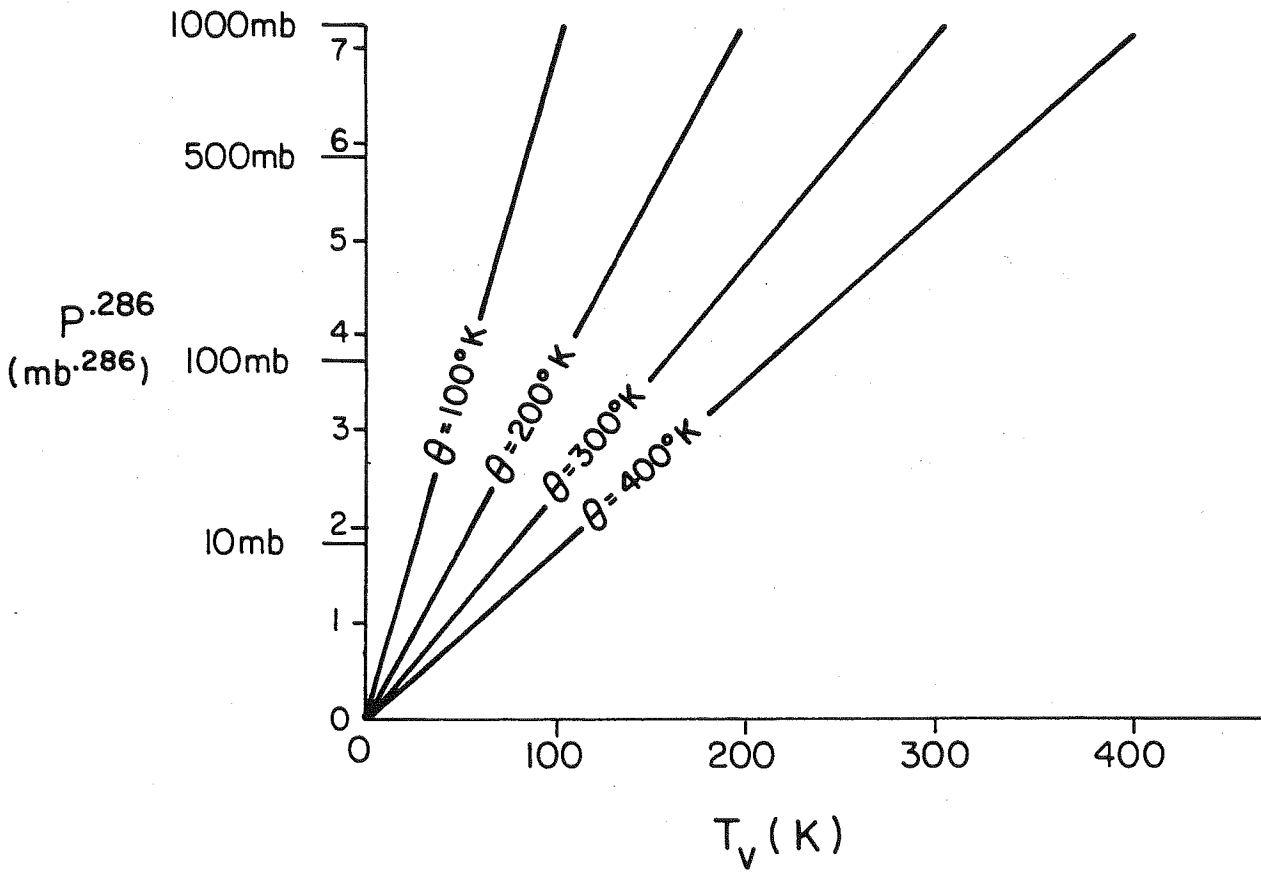


Figure 2.1: Relation between  $T_v$ ,  $p$ , and  $\theta$  in dry air.

Since the volume of the air in which the water vapor and dry air is contained is the same, the corresponding densities,  $\rho$ , can be inserted in place of the mass.

From the ideal gas law:

$$\rho_v = \frac{p_v}{R_v T} = \frac{e}{R_v T}; \quad \rho_d = \frac{p_d}{R_d T} \quad (2.7)$$

where  $R_v = 461 \text{ J K}^{-1} \text{ kg}^{-1}$  and by convention  $e = p_v$  is used. The temperature of the dry air and water vapor are assumed the same. The pressure of the dry air can be rewritten as  $p - e$ , where  $p$  is the total pressure using Dalton's law of partial pressures.

Equation (2.6) can then be written as:

$$w = \frac{e}{R_v T} \bigg/ \left( \frac{p - e}{R_d T} \right) = 0.622e / (p - e) \quad (2.8)$$

since  $R_d/R_v = 0.622$ .

The *maximum* amount of water vapor that a parcel of air can hold at a given temperature is written as:

$$w_s = 0.622e_s / (p - e_s) \quad (2.9)$$

where  $e_s$  is the saturation vapor pressure.

Experimental work has permitted the specification of  $e_s$  as a function of temperature, so that:

$$w_s \cong \frac{3.8}{p} \exp \left[ \frac{21.9(T - 273.2)}{(T - 7.7)} \right]; \quad T \text{ in Kelvin} \quad (2.10)$$

for typical tropospheric values with  $p \gg e_s$ .

An important distinction in Eq. (2.10) is that  $w_s$  is saturated with respect to liquid water. A different formulation (maximum difference of about  $0.2 \text{ g kg}^{-1}$ ) is applicable for saturation with respect to ice. Since  $w_s$  is a function of  $p$  and  $T_v$ , values of  $w_s$  could also be drafted on Fig. 2.1 and on whatever other type of thermodynamic representation is chosen.

Relative humidity is defined from  $w$  and  $w_s$  as:

$$RH = 100w/w_s \quad (2.11)$$

The value of  $w$  can be determined by measuring the *dewpoint temperature*,  $T_D$ . This is the temperature at which *condensation will occur if the atmosphere is cooled at constant pressure* (i.e., isobarically). Thus, when  $T = T_D$ ,  $w = w_s$  (i.e., a value of  $w$  at temperature  $T$  corresponds to  $w_s$  at temperature  $T_D$ ).

When the atmospheric water content and pressure are constant,  $w$  and  $T_D$  remain constant. Since  $w_s$  is a function of temperature, however, the relative humidity will vary as a function of temperature. An example of this situation is illustrated in Fig. 2.2 (e.g., see Eq. 2.10).

A *frost point temperature*,  $T_F$ , can similarly be defined as the temperature at which deposition (e.g., frost formation) occurs when air is cooled isobarically at constant pressure until the air becomes saturated with respect to ice.

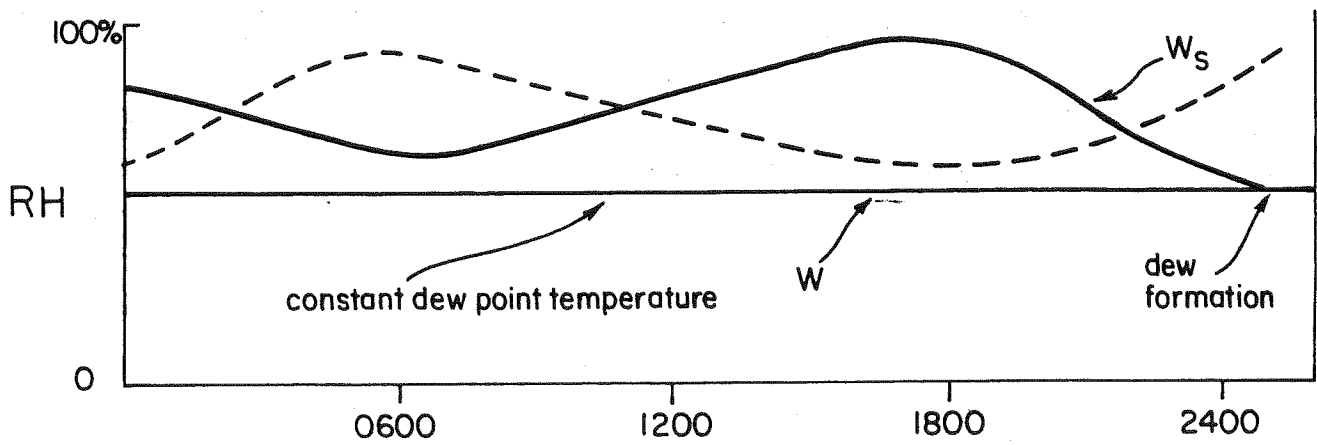


Figure 2.2: Schematic illustration of the relation of relative humidity to dewpoint temperature. This pattern is characteristic of a summer day in which diurnal heating causes a variation of air temperature, but the absolute water content of the air does not vary during the day.

Since the saturation vapor pressure of liquid water is always greater than or equal to the saturation vapor pressure of ice:

$$T_D \geq T_F.$$

When phase changes of water occur, heat is added or deleted from a parcel of air so that potential temperature,  $\theta$ , is no longer conserved. For the situation of liquid phase changes, the first law of thermodynamics can be written as:

$$C_p \frac{dT}{T} - \frac{R_d}{p} dp = \frac{-L}{T} dw_s \quad (2.12)$$

where  $L$  is the latent heat of condensation.

The term on the right of Eq. (2.12) can be written as:

$$\frac{1}{T} dw_s \cong d \left( \frac{w_s}{T} \right)$$

as long as  $dw_s/T \gg w_s dT/T^2$  which it is for reasonable tropospheric conditions (e.g., see Pielke 1984, pg. 268).

Equation (2.12) can then be written as:

$$C_p \frac{dT}{T} - \frac{R_d}{P} dp \cong -L d \left( \frac{w_s}{T} \right) \quad (2.13)$$

From Eqs. (2.1) and (2.4), Eq. (2.13) can be rewritten as:

$$\frac{C_p}{\theta} d\theta \cong -L d \left( \frac{w_s}{T} \right) \quad (2.13a)$$

If it is required (as seems intuitive) that  $w_s/T \rightarrow 0$  as  $T \rightarrow 0$  K (e.g., see Fig. 2.7 of Wallace and Hobbs 1977; saturation moisture content goes to zero faster than temperature goes to zero) then an *equivalent potential temperature* is defined from:

$$C_p \int_{\theta}^{\theta_E} d \ln \theta \cong -L \int_{w_s/T}^0 d \left( \frac{w_s}{T} \right),$$

which after integrating and taking antilogs yields:

$$\theta_E \cong \theta \exp \left( \frac{L}{C_p} \frac{w_s}{T} \right). \quad (2.14)$$

The quantity  $\theta_E$  corresponds to the temperature of a parcel if it were moved to 1000 mb with all of its water vapor condensed and heat released. Obviously, from Eq. (2.14),  $\theta_E \geq \theta$ , with  $\theta_E \cong \theta$  at low water vapor contents (e.g., in cold atmospheres).

Contours of constant  $\theta_E$  are placed on thermodynamic diagrams since  $\theta_E$  is *conserved* to saturation – it is a measure of the potential heat increase due to complete saturation of the water vapor present and is independent of the actual amount that has condensed.



There are a wide range of presentations of thermodynamic properties on thermodynamic charts. Four examples, reproduced from AWS (1979), are presented in Figs. 2.3a-d. Byers (1959, pp. 177-180) also discuss different forms of presentation of thermodynamic properties, such as the Stüve diagram which has  $T$  by  $\ln p$  axes and the tephigram which has  $T$  by  $\theta$  axes.

Vertical sounding data is transmitted in the United States via either the Service C (synoptic code) teletype network or the Federal Aviation Administration FAA 604 teletype circuit. These data are distributed two times daily at 00 GMT and 12 GMT (i.e., 1700 MST and 0500 MST). The procedure to decode this information and an example are presented as Appendices A and B.

## 2.2 Qualitative Measures of the Vertical Profile

The appearance and type of clouds overhead provide considerable information regarding atmospheric conditions. Cloud types can be summarized as follows.

There are ten genera of clouds.

cirrus	nimbostratus
cirrocumulus	stratocumulus
cirrostratus	stratus
altocumulus	cumulus
altostratus	cumulonimbus

Each can be divided into species and varieties. The atmosphere, for use in cloud specification, is divided into three levels: high, middle, and low.

- High
  - cirrus
  - cirrocumulus
  - cirrostratus
- Middle
  - altocumulus
  - altostratus
- Low
  - stratus
  - stratocumulus
- Lower – extending up to high levels, for some cases
  - nimbostratus

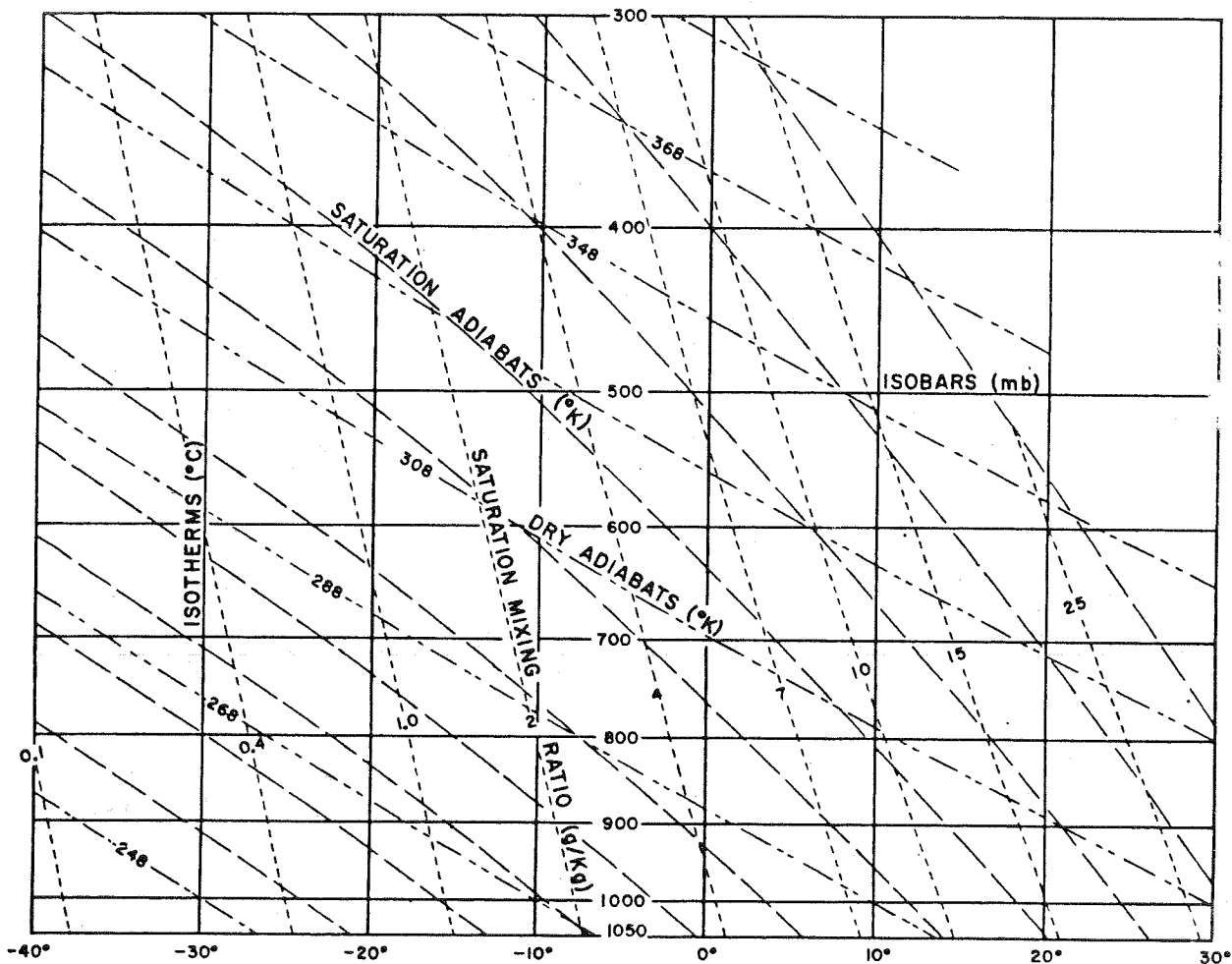


Figure 2.3: (a). Coordinate system of the emagram (from AWS 1979).

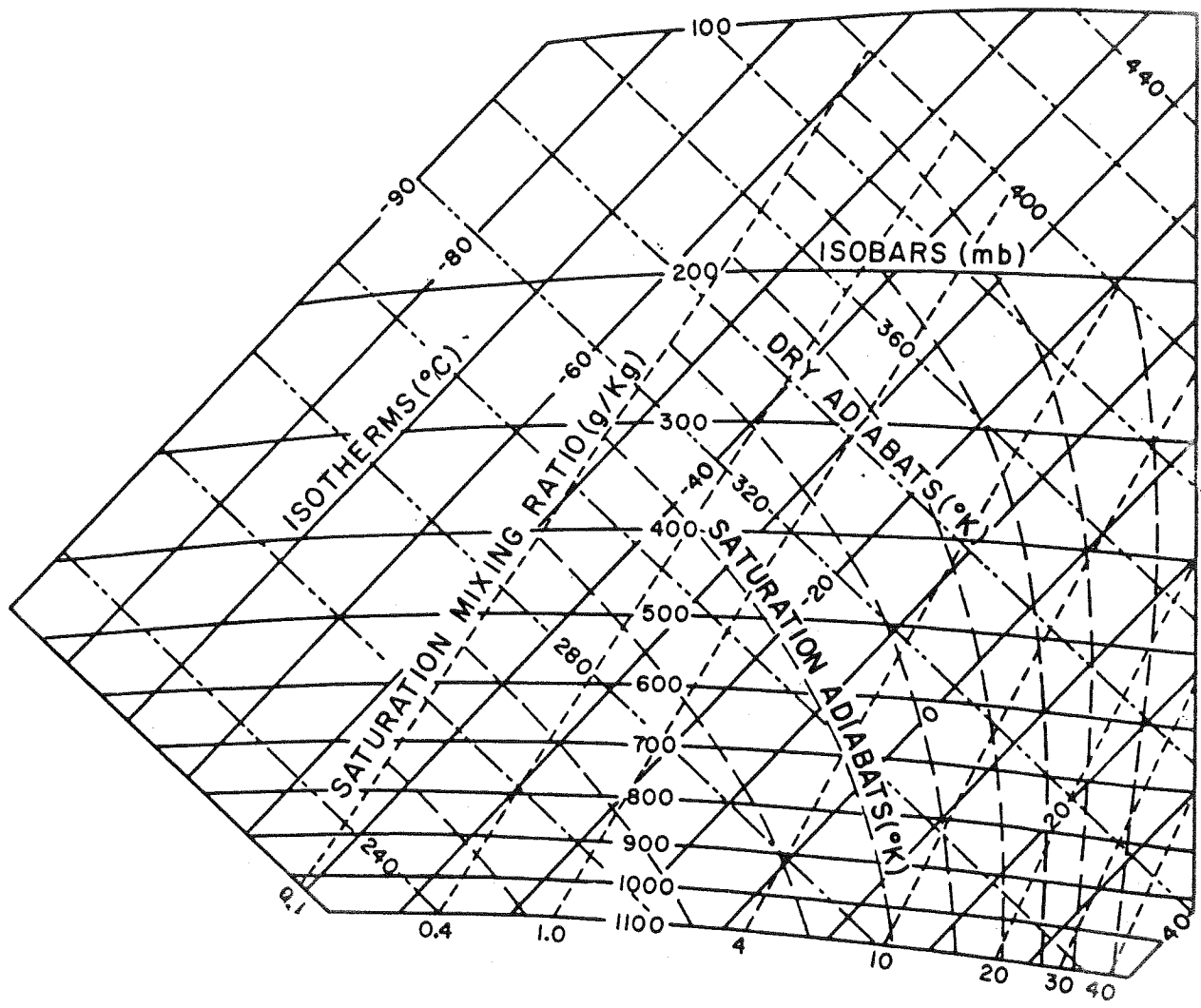


Figure 2.3: (b). Coordinate system of the tephigram (from AWS 1979).

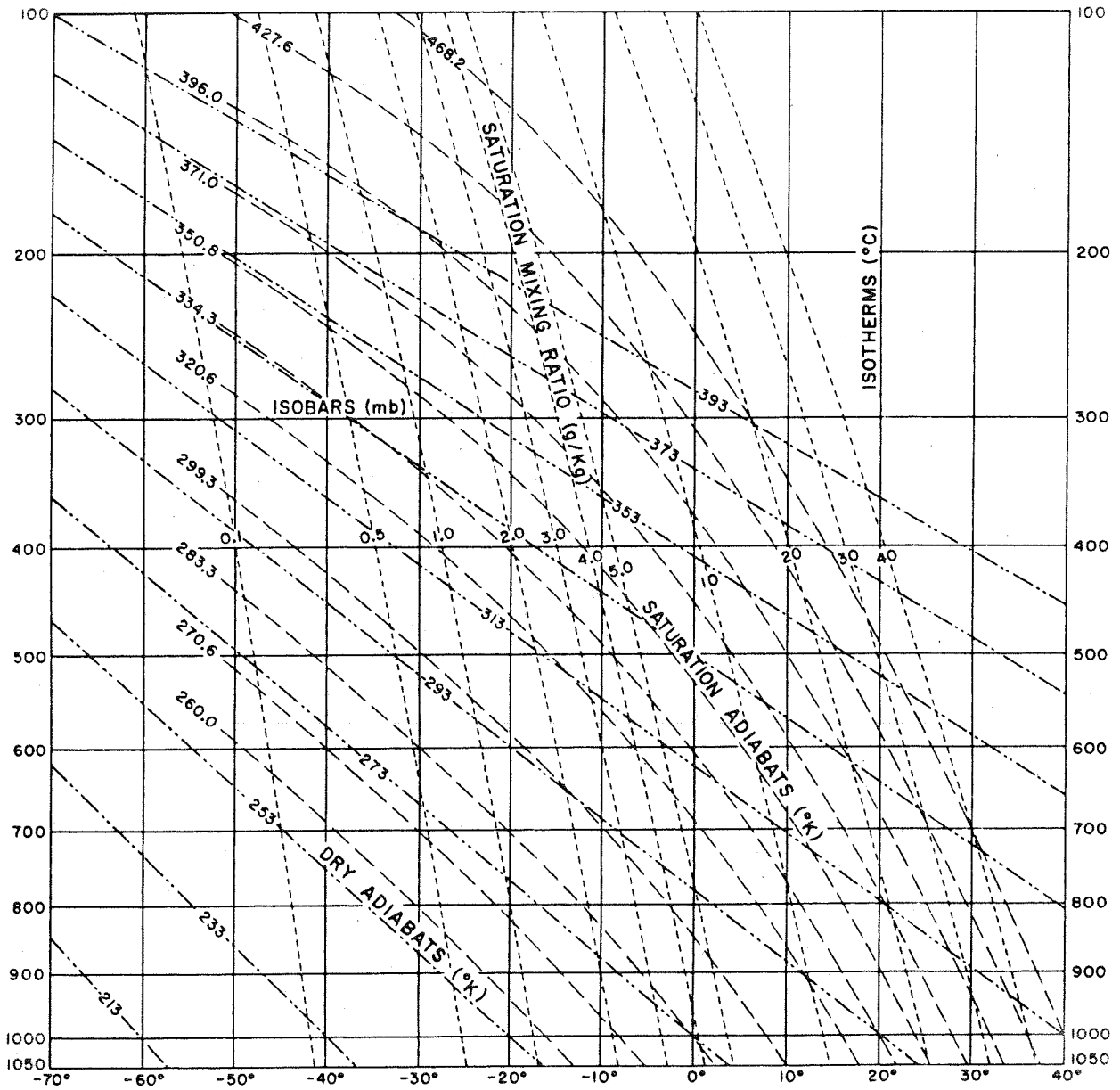


Figure 2.3: (c). Coordinate system of the Stüve ("pseudo-adiabatic") diagram (from AWS 1979).

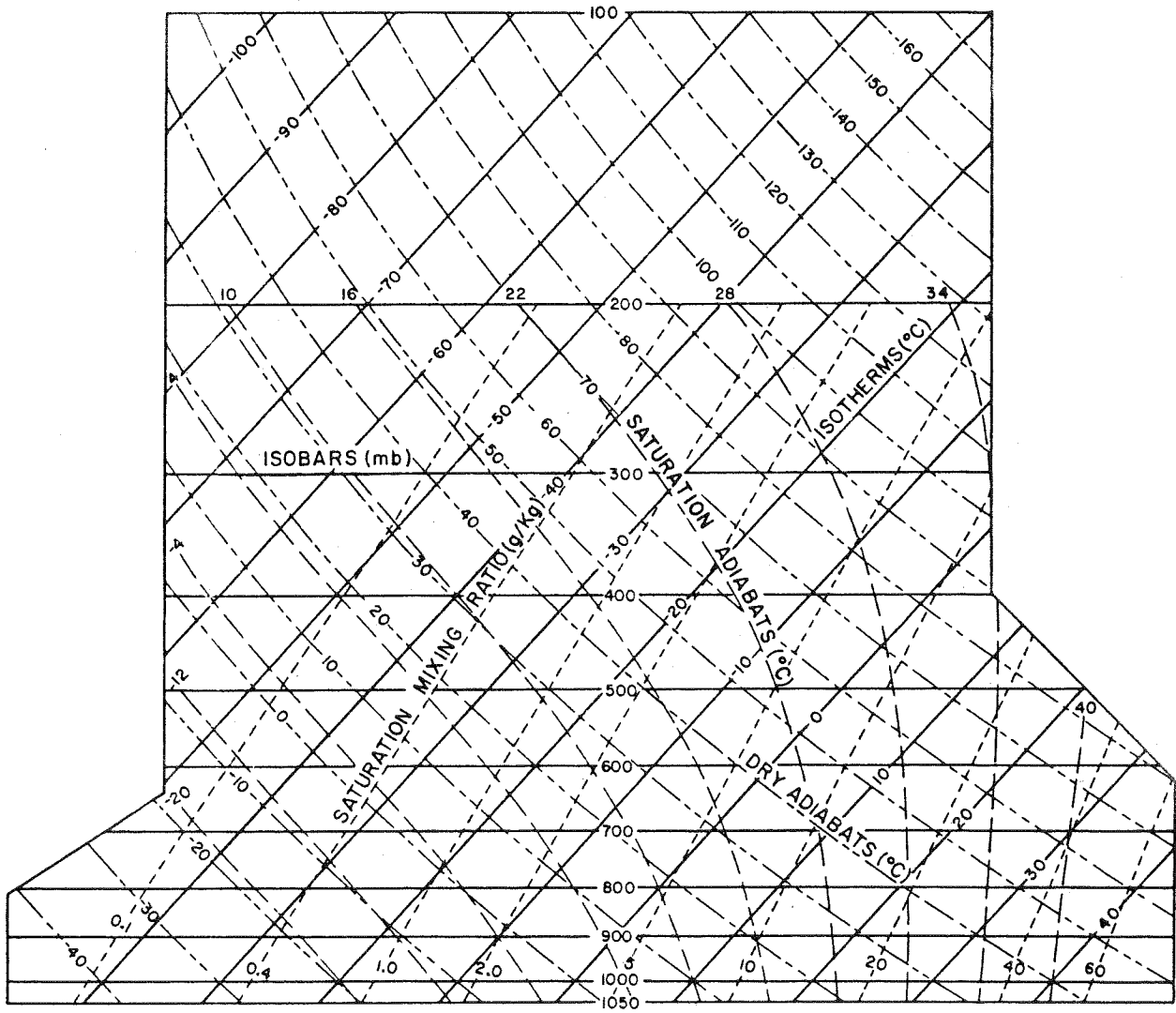


Figure 2.3: (d). Coordinate system of the skew T, log P diagram (from AWS 1979).

- cumulus
- cumulonimbus

Pictures of these clouds are presented in Byers (1959, pp. 107-119). From WMO (1957) they are described as follows:

1. Cirrus – Detached clouds in the form of white, delicate filaments or white or mostly white patches or narrow bands. These clouds have a fibrous (hairlike) appearance.
  - (a) Ice clouds, sun or moon shining through ice crystals – clouds produces a halo if the cloud is uniformly thick.
  - (b) Often brilliantly colored well after sunset or sunrise – bright yellow or red.
2. Cirrocumulus – Thin, white patch, sheet, or layer of cloud without shading, composed of very small elements in the form of grains, ripples, etc., merged or separate, and more or less regularly arranged. Most of the elements have an apparent width of less than one degree.
  - (a) Ice clouds.
  - (b) Often look like small flakes or very small globular masses.
  - (c) When well marked in a uniform arrangement, sailors call it a mackerel sky.
  - (d) Least frequently observed of cirrus types.
3. Cirrostratus – Transparent, whitish cloud veil of fibrous (hairlike) or smooth appearance, totally or partially covering the sky, and generally producing halo phenomena.
  - (a) Appearance ranges from white sheet to a very thin layer that only slightly whitens the blue sky.
  - (b) Indefinite edges, generally.
  - (c) Ice.
4. Alto cumulus – White or grey, or both white and grey, patchy, sheet, or layer of cloud, generally with shading, composed of laminae, rounded masses, rolls, etc., which are sometimes partly fibrous or diffuse and which may or may not be merged. Most of the regularly arranged small elements usually have an apparent width of between one and five degrees.
  - (a) Shapes similar to cirrocumulus, however, usually have dark shading underneath (probably higher water content), and elements appear larger.
  - (b) Do not produce halo.
  - (c) Edges often thin and translucent and exhibit irisations (bright plays of color) which supposedly are found only in this type of cloud.

- (d) Low-level altocumulus have smaller elements than stratocumulus.
  - (e) May occur at more than one level.
  - (f) Composed of liquid water droplets, frequently supercooled.
5. Altostratus – Greyish or bluish cloud sheet or layer of striated, fibrous, or uniform appearance, totally or partially covering the sky and having parts thin enough to reveal the sun at least vaguely, as through ground glass. Altostratus does not show halo phenomena.
- (a) Never shows definite shape configurations, although light and dark patches may alternate.
  - (b) Shadows of objects on the ground are never visible.
  - (c) Frequently referred to as “snow-sky” in winter.
  - (d) Low altostratus may be distinguished from stratus or nimbostratus because of darker, more uniform grey of the stratus and nimbostratus (again, probably higher water content in the latter) and the fibrous structure and whitish gleam often visible in the altostratus.
  - (e) If light spots do not shine where sun or moon is, then clouds are probably not altostratus, but stratus or nimbostratus.
  - (f) Altostratus may be generated from altocumulus (by large-scale upward motion) or altocumulus may be generated from altostratus by subsidence.
6. Nimbostratus – Grey cloud layer, often dark, the appearance of which is rendered diffuse by more or less continuously falling rain or snow which in most cases reaches the ground. It is thick enough throughout to blot out the sun. Low ragged clouds frequently occur below the layer with which they may or may not merge.
- (a) Most often a low cloud form. Distinguishable from stratocumulus in that it has no discrete, or at least regular cloud elements. Darker than stratus, virga or precipitation at the ground and higher variable bases.
  - (b) In midlatitude storms, often develops from thickening and lowering altostratus.
  - (c) “Bad weather clouds.”
7. Stratocumulus – Grey or whitish, or both grey and whitish, patch, sheet, or layer of cloud which almost always has dark parts, composed of tassellations, rounded masses, rolls, etc., which are nonfibrous (except for virga), and which may or may not be merged. Most of the regularly arranged small elements have an apparent width of more than five degrees.
- (a) Cloud elements aligned in one or two directions.

- (b) Often have appreciable vertical development, but are softer, more irregular shaped than cumulus. If seen from above they are capped at a very uniform level (usually by an inversion).
  - (c) Thick stratocumulus can change into nimbostratus if precipitation starts and eliminates irregular bases.
  - (d) Clouds seen over mountainous regions of Pennsylvania, Virginia, and West Virginia during cold outbreaks.
8. Stratus – Generally grey cloud layer with a fairly uniform base which may give drizzle, ice prisms, or snow grains. When the sun is visible through the cloud, its outline is clearly discernible. Stratus does not produce halo phenomena except possibly at very low temperatures. Sometimes stratus appears in the form of ragged patches.
- (a) Uniform top.
  - (b) Same characteristics as fog (i.e., little vertical motion).
9. Cumulus – Detached clouds, generally dense and with sharp outlines developing vertically in the form of rising mounds, domes or towers, of which the bulging upper part often resembles a cauliflower. The sunlit parts of these clouds are mostly brilliant white; their base is relatively dark and nearly horizontal. Sometimes cumulus is ragged.
- (a) Over land, most often found during the day.
  - (b) Indicative of strong vertical development.
  - (c) Four species are recognized.
    - i. *Cumulus humulus* – fair weather (i.e., little vertical development)
    - ii. *Cumulus mediocris*
    - iii. *Cumulus congestus* – significant, vigorous development
    - iv. *Fractocumulus*
10. Cumulonimbus – Heavy and dense cloud, with a considerable vertical extent, in the form of a mountain or huge tower. At least part of its upper portion is usually smooth or fibrous, or striated, and nearly always flattened; this part often spreads out in the shape of an anvil or vast plume. Under the base of this cloud which is often very dark, there are frequently, low ragged clouds either merged with it or not, precipitation sometimes in the form of virga.
- (a) Extends through all levels, often bursting through the tropopause into the stratosphere.
  - (b) From underneath, appears like nimbostratus but turbulent motion of clouds is more pronounced.



(c) Mamma clouds frequently extend down from the cloud.

The following characteristics of cumulus clouds can be used to aid in the interpretation of local weather:

- Uniform, flattened tops are indicative of a temperature inversion which the clouds cannot penetrate.
- Dark cumulus clouds are associated with high liquid water content.
- Cumulus clouds which tilt with height indicate vertical shear of the horizontal wind.
- Spacing between cumulus and their size gives an idea as to the preferred horizontal scale of the turbulent subcloud eddies which generate the clouds. Moreover, the cumulus clouds tend to form in horizontal lines in the direction of the mean wind in the cloud layer, indicative of helical turbulent rolls, once the wind speed exceeds a certain value.
- Cumulus towers which are hard-looking indicate that the clouds are growing rapidly and have not had time to entrain much ambient air.
- Cumulus towers which are diffuse-looking indicate clouds are growing relatively slowly with drier and colder air entraining significantly into the cloud.
- Low cloud bases of cumulus clouds indicate that the subcloud layer is relatively moist; high cloud bases of cumulus clouds indicate that the subcloud layer is relatively dry.
- Lightning from cumulus clouds indicate they have deepened to colder than 0°C and have ice particles present. Turbulence causing repeated collisions of ice particles is a common mechanism to build electric charge in cumulus clouds.
- Mammatus clouds indicate turbulence at higher levels is causing sinking and rising air on relatively small scales. The mamma clouds (which are called such because they look like breasts) are the downward moving air.

The following characteristics of stratiform clouds can be used to aid in the interpretation of local weather:

- The absence of a well-defined, visible base indicates that precipitation is falling below the base. Rain is generally whitish-grey, while snow is more whitish. This characteristic of the sky gives rise to the expressions “grey-laden skies” for rain and “snow-sky” for snow.
- The thicker the cloud and/or the greater the liquid water content, the darker the base. With very thick clouds, lights will be required indoors and occasionally even outdoor lights will come on.

- A diffuse *corona* around the moon or sun is indicative of a water cloud. If a well-defined ring (a *halo*) surrounds the moon or sun with the most common angular distance of  $22^\circ$ , then the cloud is composed of ice crystals.
- If the cloud base elevates with time, the lower atmosphere is drying. If it lowers with time, the lower atmosphere is becoming more moist.
- Multi-leveled stratiform cloud systems generally indicate an organized synoptic system, particularly if a thickening with time and/or to the horizon is noted.

In terms of the quantitative vertical profile of thermodynamic properties, clouds which are stratiform (i.e., stratus, altostratus, cirrostratus, cirrus, and nimbostratus) occur when the atmosphere is stable to saturated vertical motion as discussed in Section 4. Clouds which are cumuliform (i.e., cumulus, cumulonimbus, stratocumulus, altocumulus, and cirrocumulus) occur when some region within the atmosphere is unstable to saturated motion; or when the region below the cloud is unstable to dry motion and the turbulent eddies reach up to the saturation level. Stratocumulus clouds are the best example of the latter cloud type.

Additional discussion regarding clouds is presented in later sections.

## 3. Depiction of the Horizontal Structure of the Atmosphere

### 3.1 Introduction

The evaluation of the north-south; east-west (i.e.,  $x-y$ ) variation of meteorological quantities is performed for:

- the surface, and
- the upper levels.

As discussed shortly, there are several frames of references which can be used to plot and analyze the measured and evaluated meteorological variables.

### 3.2 Surface Analysis

The procedure by which the United States Weather Service plots and analyzes surface observations is described in Appendix C and on pages 6-1 to 6-9 of Rieck (1979).

A number of important attributes of the North American surface analyses are summarized below:

- Map base is on a 1:10 million scale
- Maps are prepared at 00Z and every three hours thereafter
- The station model which is plotted on the map can display the following information:
  - Total cloud cover
  - Direction and speed of the near-surface wind (using wind barbs and pointing into the direction of the wind)
  - Present weather
  - Sea-level pressure (only the tens and unit value of pressure in mb. The leading digits are assumed known)
  - Temperature (in °F)
  - Low, middle, and high cloud types
  - Dewpoint temperature (°F)
  - Amount and character of pressure change
  - 6 hour precipitation total (inches)
  - Special weather phenomena, if any
  - Water temperature, if ship data

Additional details concerning the station model are presented in Appendix C.

The sources of surface data are from what are referred to as Service A teletype (the airways circuit) and Service C teletype (the synoptic reports). The Federal Aviation Administration has combined these two sources of information into what is referred to as the FAA604 circuit.

The only field which is contoured on the standard three-hourly surface map is sea-level pressure. These contours are analyzed as follows:

- Solid lines at 4 mb intervals
- Dashed lines at the 2 mb interval between the solid lines in areas of a weak pressure gradient
- The central pressure of highs and lows is indicated by underlined 2-digit numbers in the tens and units value of the pressure in mb

The analysis of pressure is smoothed so as to provide a field of *synoptic*-scale variations of pressure without the contamination by smaller-scale features which are insufficiently resolved.

In preparing the analysis, the following aids are used.

- Previous surface analyses
- Radar information valid shortly before map time
- All United States and Canadian hourly airway reports
- Most recent 1000-500 mb thickness, 500 and 850 mb height contours and temperatures (discussed later in this section)
- Geostationary satellite pictures and movie loops

Fronts are placed on the analysis using the Abridged U.S. Weather Analysis Code as revised 1 June 1968. An example of a surface map is given in Fig. 3.1.

### 3.3 Upper-Air Analysis

There are a number of options that could have been chosen as the  $x - y$  representation. The meteorological variables could have been evaluated at:

- Constant height,  $z$
- Constant pressure,  $p$
- Constant height above terrain,  $z - z_G$
- Constant pressure below the surface pressure,  $p_G - p$

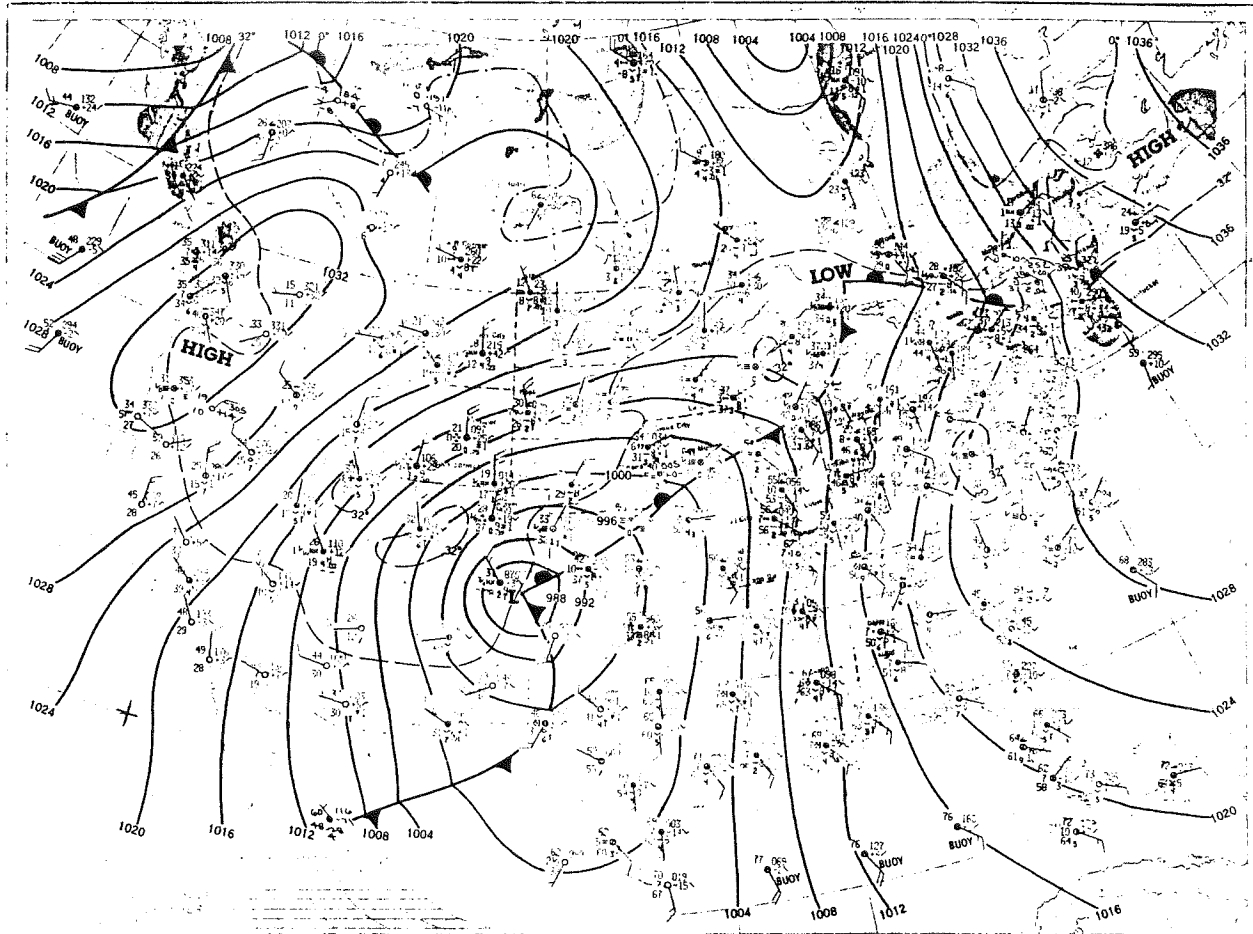
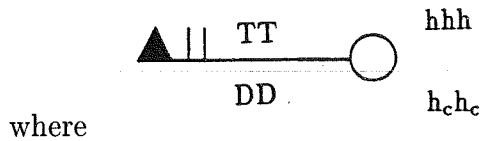


Figure 3.1: An example of a surface weather map.

- Constant potential temperature,  $\theta$
- Constant potential temperature above the surface value of potential temperature,  $\theta - \theta_G$

Currently, the weather service evaluates upper-air conditions using *constant pressure* analyses. In weather service numerical models,  $x - y$  levels are written in “so-called” *sigma* representations which are a form of constant pressure less than the surface pressure.

### 1. Upper-air plotting model from radiosonde and rawinsonde



TT: temperature in whole degrees Celsius (a Fahrenheit to Celsius conversion table is given in Appendix D)




DD: depression of the dewpoint temperature in whole degrees Celsius: if  $DD < 5^\circ\text{C}$  the station circle is darkened

$h_c h_c$ : 12 hour height change (printed in italics)

hhh: i) in meters on the 850 mb and 700 mb charts with the thousands of meters value omitted

ii) tens of meters on the 500 mb, 300 mb, and 200 mb analyses with the meter, and if applicable, the 10,000 meter value omitted

wind direction: plotted to 36 compass points

wind speed: flag  50 knots  $\cong 25 \text{ m s}^{-1}$   
 barb  10 knots  $\cong 5 \text{ m s}^{-1}$   
 half-barb  5 knots  $\cong 2.5 \text{ m s}^{-1}$

The wind barb points into the direction *from* which the wind is blowing.

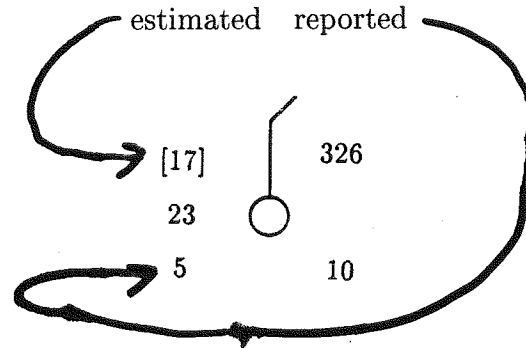
The following modifications can occur in the station model.

- If TT, hhh, or DD is missing, nothing is plotted.
- If  $TT < -41^\circ\text{C}$ , DD is left off.
- If  $DD > 29^\circ\text{C}$ , X is plotted for DD.
- When the wind direction or speed is missing, an M is plotted.
- If the wind speed is less than  $1.5 \text{ m s}^{-1}$ , LV is plotted (i.e., light and variable).

- over elevated terrain which is higher than the pressure surface, temperature values are estimated by an analysis program and values are marked with a bracket to the right (e.g., for all stations above 1200 meters):

$$T_{850 \text{ mb}} = 0.352 (z_{700 \text{ mb}} - z_{850 \text{ mb}}) - T_{700 \text{ mb}} - 546.3 \text{ (with } z \text{ in meters) ; } T \text{ in } ^\circ\text{C}$$

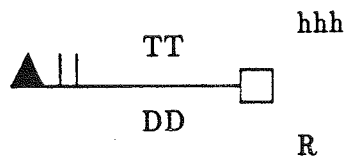
If 850 mb is near the ground, two temperatures may be given, one bracketed, e.g.,



The bracketed one (i.e., estimated from the analysis routine) is used in the contouring of the data.

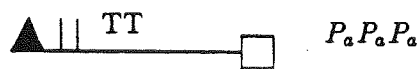
- Apparent erroneous data are marked with brackets by an analyst.

## 2. Upper-air data from reconnaissance aircraft (RECCO)



Reconnaissance data within 6 hours of the synoptic time are plotted. The new information plotted is *R* which provides the type of reconnaissance.

## 3. Aircraft report (AiREP)



where  $P_a P_a P_a$  is the pressure altitude of the aircraft in hundreds of feet (e.g., 290 = 29,000 feet).

AiREPS are plotted which occur within  $\pm 3$  hours of the synoptic time at the upper-air level which is closest to the altitude of the aircraft.

#### 4. Satellite wind estimates



The pressure altitude of the estimated wind is reported from those values obtained within  $\pm 6$  hours of the synoptic chart time.

#### 5. Satellite sounding



This data is plotted if within  $\pm 6$  hours of the synoptic chart time.

The contouring of the upper-air charts is as follows:

- Solid lines are labeled in decameters
- Contour intervals are:
  - 30 m on the 850 mb chart
  - 30 m on the 700 mb chart
  - 60 m on the 500 mb chart
  - 120 m on the 300 mb chart and 200 mb chart
- Standard contours for these pressure surfaces are:
  - 850 mb – 1500 m
  - 700 mb – 3000 m
  - 500 mb – 5520 m
  - 200 mb – 11700 m
- The locations of centers of high and low heights are indicated with an "x" together with either an "H" or an "L". The value at "x" is given in decameters.
- Temperatures are at 5°C intervals.
- Isotachs (lines of constant wind speed) are contoured on the 200 mb and 300 mb charts with short dashed lines at 20 kt ( $\sim 10 \text{ m s}^{-1}$ ) intervals beginning at a speed of 30 kts ( $\sim 15 \text{ m s}^{-1}$ ). Shading and no shading boundary at 70 kt ( $\sim 35 \text{ m s}^{-1}$ ) intervals are used to enhance jet positions.

Examples of upper-air analyses are given in Fig. 3.2.



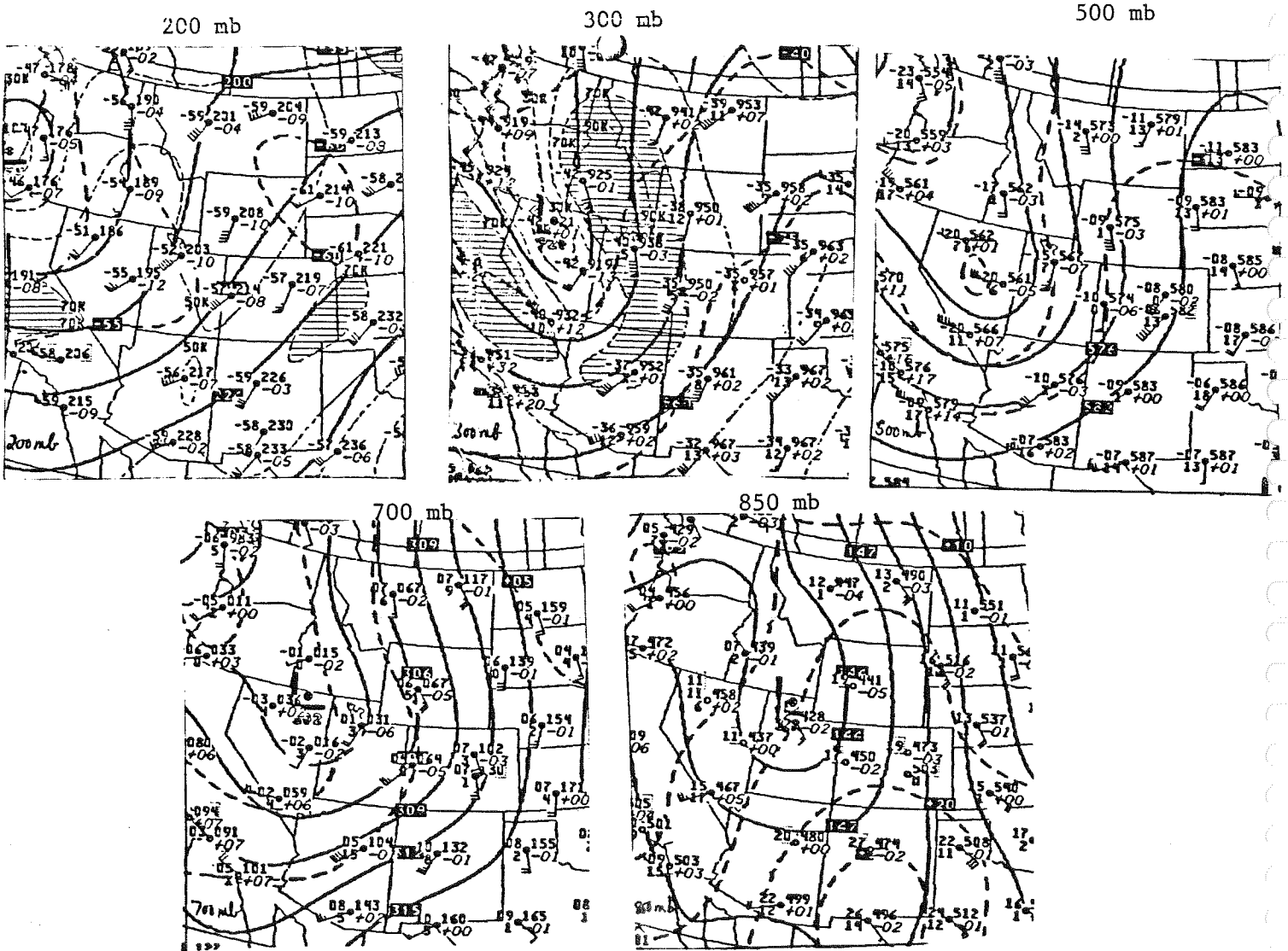


Figure 3.2: Examples of National Weather Service upper-air synoptic analyses at the standard levels. (Note: For this draft, all maps are at the same time except 200 mb.)

### 3.4 Balance Winds

The equation of motion can be written as:

$$\frac{d\vec{V}}{dt} = -\frac{1}{\rho}\nabla p - 2\vec{\Omega} \times \vec{V} - \vec{F} + \vec{G} \quad (3.1)$$

where  $\vec{\Omega}$  is the angular velocity of the earth (positive pointing upward from the north pole);  $|\Omega| = 2\pi/\text{day}$  corresponding to the rotation rate of the earth ( $2\vec{\Omega} \times \vec{V}$  is called the *Coriolis term* and arises only because we are referring to acceleration in a rotating coordinate system, e.g., the earth; see Pielke 1984, pp. 13-14).  $\vec{F}$  represents the effect of friction and  $\vec{G}$  is the gravitational vector.

If we adopt the Cartesian,  $\vec{i}$ ,  $\vec{j}$ , and  $\vec{k}$  representation of the unit vectors, then the horizontal components of Eq. (3.1) can be written as:

$$\begin{aligned} \frac{du}{dt} &= -\frac{1}{\rho}\frac{\partial p}{\partial x} + fv - \hat{f}w - Fu \\ \frac{dv}{dt} &= -\frac{1}{\rho}\frac{\partial p}{\partial y} - fu - Fv \end{aligned} \quad (3.2)$$

where  $f = 2|\Omega| \sin \phi$ ,  $\hat{f} = 2|\Omega| \cos \phi$  with  $\phi$  the latitude.

For the case of

- no friction (i.e.,  $F_u = F_v \equiv 0$ )
- no acceleration (i.e.,  $du/dt = dv/dt \equiv 0$ )
- $|u|; |v| \gg |w|$  as is typical on the synoptic scale (e.g., see Pielke 1984, pg. 27) so that  $\hat{f}w$  is ignored):

then

$$u = -\frac{1}{\rho f}\frac{\partial p}{\partial y} \equiv u_g; v = \frac{1}{\rho f}\frac{\partial p}{\partial x} \equiv v_g \quad (3.3)$$

where  $u_g$  and  $v_g$ , the geostrophic wind components are *defined* by these relations.

In vector notation, the geostrophic wind relation can be written as:

$$\vec{V}_g = \vec{k} \times \frac{1}{\rho f}\nabla_z p \quad (3.4)$$

where  $\nabla_z$  is the horizontal gradient operator (i.e.,  $\vec{i}\frac{\partial}{\partial x} + \vec{j}\frac{\partial}{\partial y}$ ). The correspondence of Eqs. (3.4) to (3.3) can be checked by expanding Eq. (3.4) using the definition of the vector cross product, i.e.,

$$\vec{V}_g = u_g\vec{i} + v_g\vec{j} = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ 0 & 0 & 1 \\ \frac{1}{\rho f}\frac{\partial p}{\partial x} & \frac{1}{\rho f}\frac{\partial p}{\partial y} & 0 \end{vmatrix}$$

From Eq. (3.4) it is evident that:

- $\vec{V}_g$  must be horizontal and perpendicular to  $\nabla_{HP}$  (i.e., the wind direction is parallel to the isobars).
- $\vec{V}_g$  has a direction such that high pressure is to the right in the northern hemisphere and to the left in the southern hemisphere.
- since  $\rho$ , the density, is nearly constant at a given height,  $\vec{V}_g$  is almost linearly proportional to the pressure gradient (i.e., the larger  $\nabla_z p$ , the larger  $\vec{V}_g$ ).
- a given value of  $\nabla_z p$  will result in a stronger  $\vec{V}_g$  at lower latitudes because  $f$  is smaller (this is illustrated in Fig. 3.3).

The relation of geostrophic wind direction to the pressure gradient is illustrated in Fig. 3.4.

Of course, as we have already discussed in this section, the National Weather Service plots and analyzes meteorological variables on constant pressure surfaces. Therefore, the equivalent specification of  $\vec{V}_g$  in Eq. (3.4), on a constant pressure surface, needs to be obtained.

The relation between a pressure surface and a constant height level for a small angle between the two and small distances can be drawn as shown in Fig. 3.5. For simplicity, but without loss of generality, any variation in  $y$  is neglected.

If we choose a surface (or in this case a line) where  $dp = 0$  then:

$$\frac{\delta z}{\delta x} = -\frac{\partial p}{\partial x} \bigg/ \frac{\partial p}{\partial z} \quad (3.5)$$

The denominator in Eq. (3.5) can be obtained if vertical accelerations and Coriolis effects are ignored in Eq. (3.1), so that the evaluation of Eq. (3.1) in the  $\vec{k}$  direction becomes:

$$\frac{\partial p}{\partial z} = -\rho g \quad (3.6)$$

where  $\vec{G} = g\vec{k}$  has been used. Equation (3.6) is the *hydrostatic equation* which merely states, for the earth's atmosphere, that pressure at a level is proportional to the mass of air above that level.

Using Eq. (3.6) in Eq. (3.5) results in:

$$\frac{\delta z}{\delta x} = \frac{1}{\rho g} \frac{\partial p}{\partial x}$$

or in the limit as  $\delta z$  and  $\delta x$  go to zero,

$$\lim_{\substack{\delta z \rightarrow 0 \\ \delta x \rightarrow 0}} \frac{\delta z}{\delta x} = \frac{\partial z}{\partial x} = \frac{1}{\rho g} \frac{\partial p}{\partial x}; \quad g \frac{\partial z}{\partial x} = \frac{1}{\rho} \frac{\partial p}{\partial x}$$

Therefore,  $\frac{1}{\rho} \frac{\partial p}{\partial x}$  in Eq. (3.2) can be replaced by  $g \partial z / \partial x$ . A similar result, of course, results from performing this derivation in the  $y$ -direction (i.e.,  $(1/\rho) \partial p / \partial y = g \partial z / \partial y$ ).

**GESTROPHIC WIND SCALE  
CONSTANT PRESSURE SURFACES**

Contour Interval 200 gph  
( 1.280533 gph = 1 gpm = 0.88 gdm )

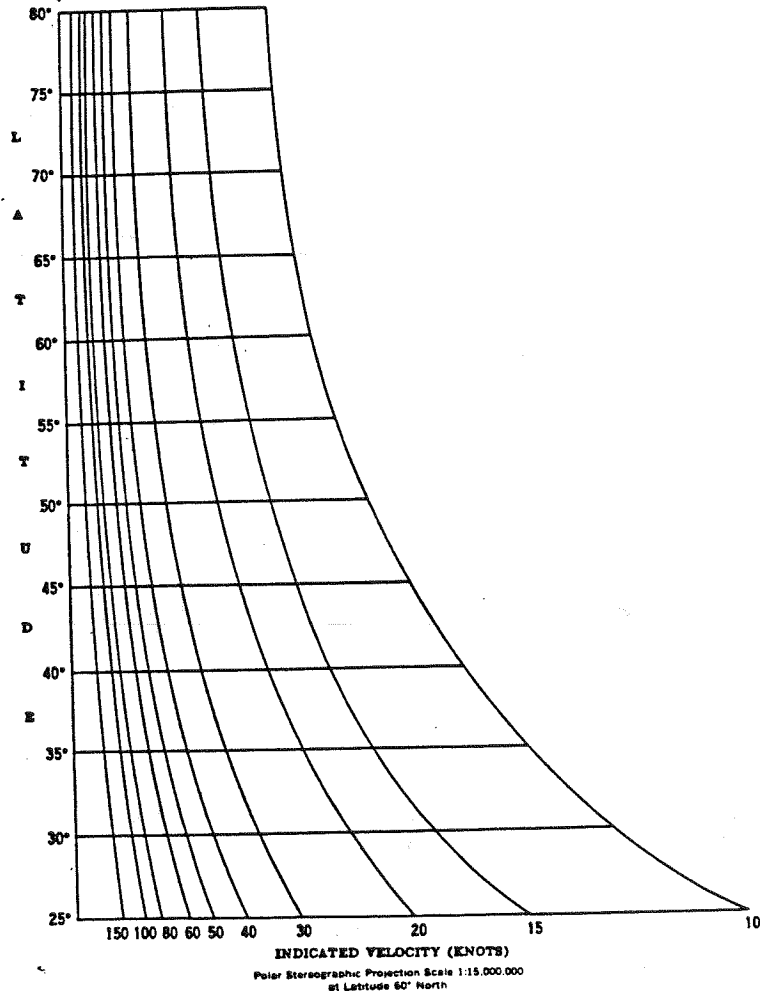


Figure 3.3: Relation between geostrophic wind speed and latitude.

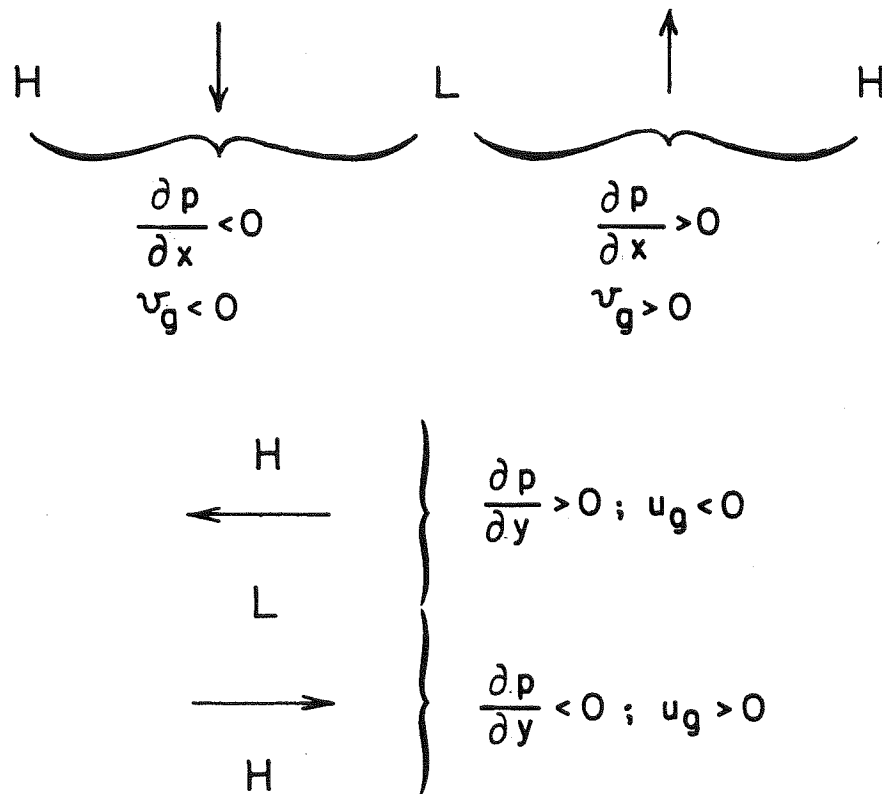


Figure 3.4: Schematic of the relation between pressure gradient and the geostrophic wind direction on a constant height surface.

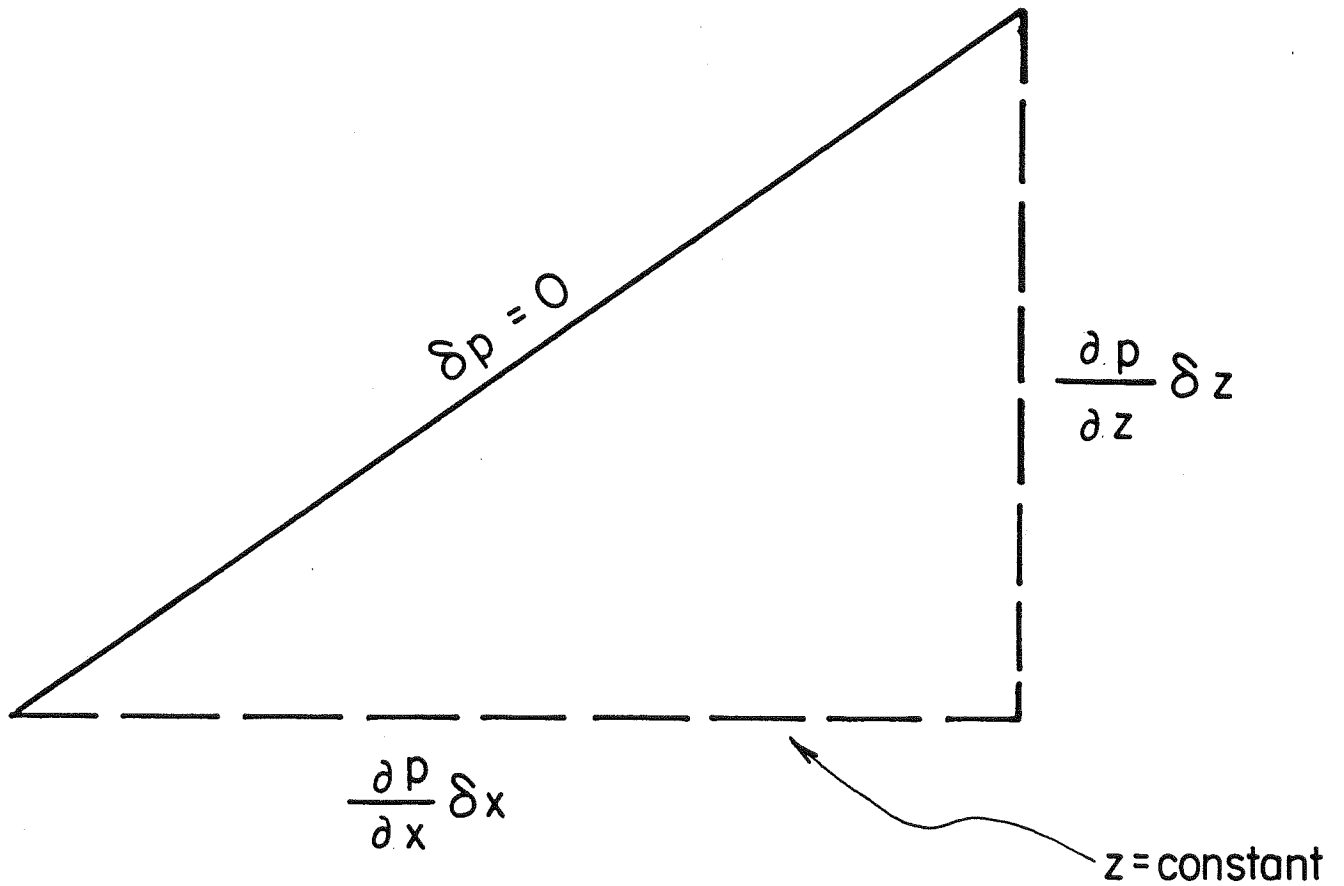


Figure 3.5: The relation between a constant pressure and constant height surface. The angle between the two is exaggerated here as found on the synoptic scale in order to better illustrate the relation.

Thus, Eq. (3.2) can be rewritten as:

$$\begin{aligned}\frac{du}{dt} &= -g\frac{\partial z}{\partial x} + fv - \hat{f}w - \vec{F}_u \\ \frac{dv}{dt} &= -g\frac{\partial z}{\partial y} - fu - \vec{F}_v\end{aligned}\tag{3.7}$$

which is the form for acceleration when the height gradient is evaluated on a constant pressure surface. An important distinction between Eq. (3.7) and Eq. (3.2) is that the pressure gradient force is no longer dependent on density,  $\rho$ , which varies significantly with height.

The geostrophic wind obtained from Eq. (3.7), in the same manner as used to derive Eq. (3.3), is:

$$u_g = -\frac{g}{f}\frac{\partial z}{\partial y}; \quad v_g = \frac{g}{f}\frac{\partial z}{\partial x}$$

or in vector notation:

$$\vec{V}_g = \vec{k} \times \frac{g}{f}\vec{\nabla}_p z\tag{3.8}$$

where the gradient operation,  $\nabla_p$ , is on a constant pressure surface.

An alternative (but equivalent) procedure to obtain  $g\nabla_p z$  from  $(1/p)\nabla_z p$  is possible using the chain rule. Let pressure be written as  $p(x, y, \sigma, t) = p[x, y, z(x, y, \sigma, t), t]$  where  $\sigma$  is a generalized vertical coordinate<sup>3</sup>. Then, by the chain rule:

$$\left(\frac{\partial p}{\partial x}\right)_{y,\sigma,t} = \left(\frac{\partial p}{\partial x}\right)_{y,z,t} + \left(\frac{\partial p}{\partial z}\right)_{x,y,t} \left(\frac{\partial z}{\partial x}\right)_{y,\sigma,t}\tag{3.9a}$$

$$\left(\frac{\partial p}{\partial y}\right)_{x,\sigma,t} = \left(\frac{\partial p}{\partial y}\right)_{x,z,t} + \left(\frac{\partial p}{\partial z}\right)_{x,y,t} \left(\frac{\partial z}{\partial y}\right)_{x,\sigma,t}\tag{3.9b}$$

$$\left(\frac{\partial p}{\partial \sigma}\right)_{x,y,t} = \left(\frac{\partial p}{\partial z}\right)_{x,y,t} \left(\frac{\partial z}{\partial \sigma}\right)_{x,y,t}\tag{3.9c}$$

where the subscript to the left facing brace indicates which independent variables are held constant.

Equations (3.9a) and (3.9b) can also be written as:

$$\nabla_\sigma p = \nabla_z p + \frac{\partial p}{\partial z}\nabla_\sigma z$$

so that,

---

<sup>3</sup>Generalized vertical coordinates are discussed in more detail in Pielke (1984, Chapter 6).

$$\frac{1}{\rho} \nabla_z p = \frac{1}{\rho} \nabla_\sigma p - \frac{1}{\rho} \frac{\partial p}{\partial z} \nabla_\sigma z \quad (3.10)$$

If  $\sigma = p$  as performed earlier in this section,

$$\frac{1}{\rho} \nabla_z p = g \nabla_p z$$

as in Eq. (3.8) since  $\nabla_p p \equiv 0$ .

The relation given by Eq. (3.10) can also be used to obtain other representations of the pressure gradient force. For instance, let  $\sigma = \theta$ , so that Eq. (3.10) becomes:

$$\frac{1}{\rho} \nabla_z p = \frac{1}{\rho} \nabla_\theta p + g \nabla_\theta z \quad (3.11)$$

where the hydrostatic equation, Eq. (3.6), has been used. Differentiating Eq. (2.4) logarithmically, using the operation  $\nabla_\theta$ , yields:

$$\frac{1}{\theta} \nabla_\theta \theta = 0 = \frac{1}{T} \nabla_\theta T - \frac{R_d}{C_p p} \nabla_\theta p$$

which by rearranging gives:

$$\frac{R_d T}{p} \nabla_\theta p = \frac{1}{\rho} \nabla_\theta p = C_p \nabla_\theta T$$

Therefore, Eq. (3.11) becomes:

$$\frac{1}{\rho} \nabla_z p = \nabla_\theta [C_p T + g z] \quad (3.12)$$

where the neglect of the small variation of  $C_p$  due to water vapor gradients along  $\theta$  permits its introduction inside of the gradient operator.<sup>4</sup> The quantity inside of the brackets is called the *Montgomery stream function*.

A more general form of a balanced wind can be derived if accelerations due to curvature in the height or pressure fields is considered. The geostrophic wind, given by Eqs. (3.4) and (3.8), assumes that the flow is straight. This acceleration can be derived as follows.

Figure 3.6 illustrates an example of curved flow around a circle<sup>5</sup>. The change in the gradient wind over a small time period is given by  $\delta \vec{V}_{gr}$  where  $\delta \theta$  is the angular displacement. The vector  $\vec{r}$ , with magnitude,  $R_T$ , is the position vector.

<sup>4</sup>The small variation of  $C_p$  as a function of water vapor content is discussed in Haltiner and Martin (1957).

<sup>5</sup>The following discussion is based on material in Holton (1972) and in Richards et al. (1962).



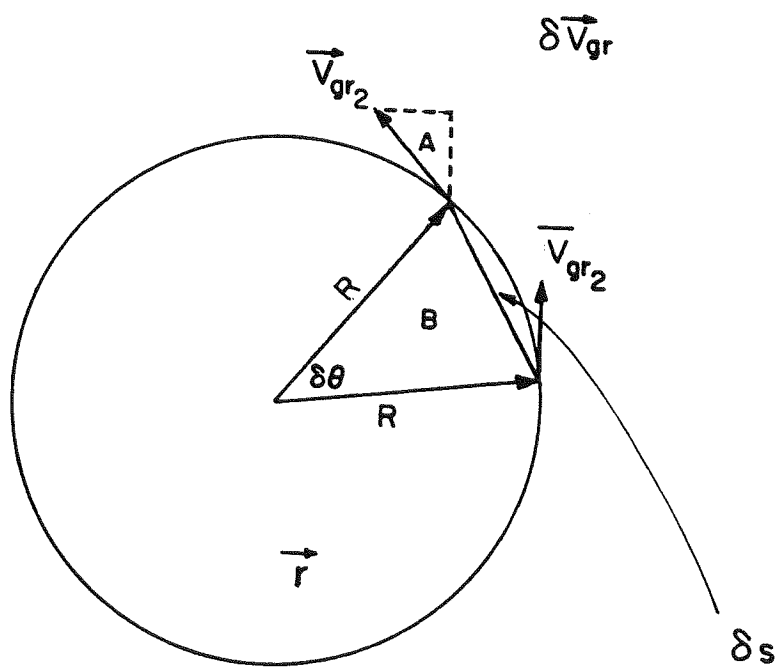


Figure 3.6: Illustration of curved flow (based on Holton 1972 and Richards et al. 1962).

Triangles A and B, defined in Fig. 3.6, are similar triangles because A has the two sides with magnitude  $|\vec{V}_{gr}|$  and B has the two sides  $R_T$ . Therefore, the angle opposite the side with  $\delta\vec{V}_{gr}$  is also  $\delta\theta$ , i.e.,

$$\frac{|\delta\vec{V}_{gr}|}{|\vec{V}_{gr}|} = \frac{\delta s}{R_T} = \sin \delta\theta \cong \delta\theta \text{ for small } |\delta\theta|$$

Thus,  $|\delta\vec{V}_{gr}| = |\vec{V}_{gr}|\delta\theta$ . Dividing by  $\delta t$ , taking the limit as  $\delta t \rightarrow 0$  and noting that  $\delta\vec{V}_{gr}$  becomes directed towards the origin, yields:

$$\lim_{\delta t \rightarrow 0} \frac{\delta\vec{V}_{gr}}{\delta t} \rightarrow \frac{d\vec{V}_{gr}}{dt} = |\vec{V}_{gr}| \frac{d\theta}{dt} \left( \frac{-\vec{r}}{R_T} \right) \quad (3.13)$$

where the unit vector  $\vec{r}/R_t$  provides the direction to  $d\vec{V}_{gr}/dt$ . Since,

$$|\vec{V}_{gr}| = \frac{d\theta}{dt} R_T$$

(e.g.,  $2\pi R_T \equiv$  circumference of the circle, so that  $2\pi R_T/\text{time}$  is speed), then Eq. (3.13) can be rewritten as:

$$\frac{d\vec{V}}{dt} = \frac{|\vec{V}_{gr}|^2}{R_T^2} (-\vec{r}) \quad (3.14a)$$

In order to interpret Eq. (3.14a), this relation will be evaluated at the four points illustrated in Fig. 3.7.

In component form, Eq. (3.14a) at the four points noted in Fig. 3.7 are:

$$\left. \begin{array}{l} \frac{du}{dt} = 0 \\ \frac{dv}{dt} = \frac{-U_{gr}^2}{R_T} \end{array} \right\} \text{at } B \quad \left. \begin{array}{l} \frac{du}{dt} = 0 \\ \frac{dv}{dt} = \frac{U_{gr}^2}{R_T} \end{array} \right\} \text{at } D$$

$$\left. \begin{array}{l} \frac{dv}{dt} = 0 \\ \frac{du}{dt} = \frac{-V_{gr}^2}{R_T} \end{array} \right\} \text{at } A \quad \left. \begin{array}{l} \frac{dv}{dt} = 0 \\ \frac{du}{dt} = \frac{V_{gr}^2}{R_T} \end{array} \right\} \text{at } C$$

In interpreting these relations it is important to note that it is the radius of the *trajectory*,  $R_T$ , not the streamline (which could be denoted as  $R_s$ ) which determines the curvature of the flow. A streamline and a trajectory will be the same only if the flow field is spatially and temporally fixed. Also, the trajectory motion does not have to be circular as used for convenience to derive these relations. Since  $\delta t \rightarrow 0$  in the derivation of Eqs. (3.13) and (3.14a), only the instantaneous radius of the curved path of the trajectory need be used.

In order to illustrate the balanced wind which develops when the acceleration due to curvature is included in Eq. (3.2) along with the pressure gradient force and Coriolis terms,

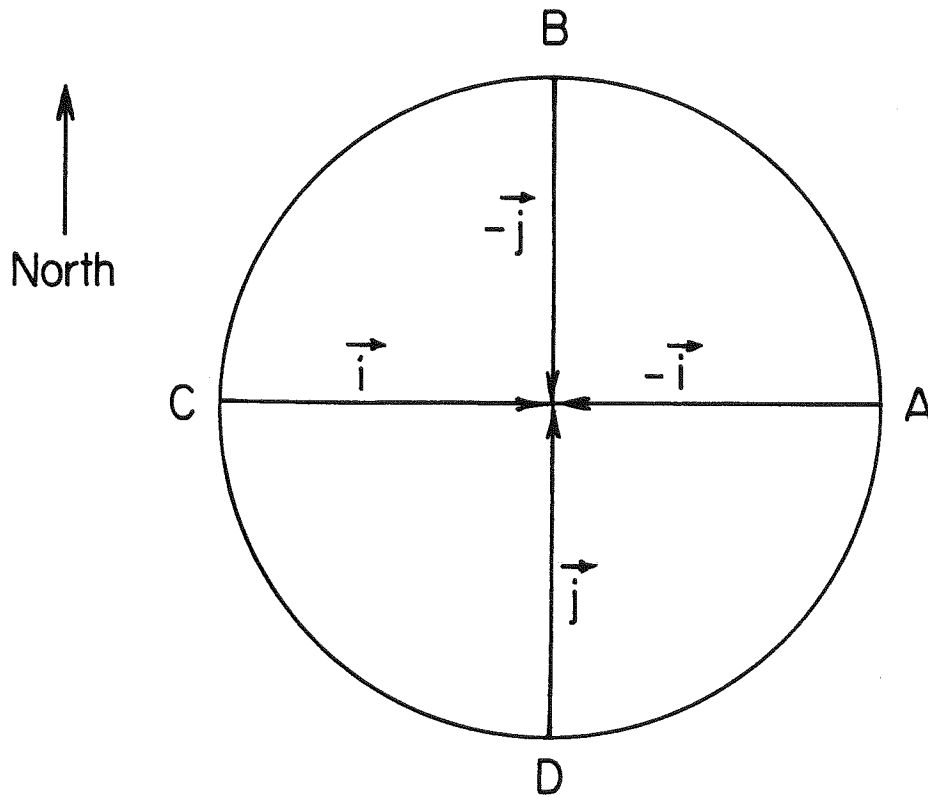


Figure 3.7: Circular curved flow used to evaluate Eq. (3.14). The direction of the unit vector  $-\vec{r}$  at points  $A$ ,  $B$ ,  $C$ , and  $D$  are denoted by the appropriate Cartesian unit vector. North is towards the top of the page.

the specification of Eq. (3.14a) at point  $A$  will be used. There is no loss of generality since a coordinate system could always be rotated so that a point of interest corresponds to location  $A$ .

At  $A$ ,  $u_g = 0$ , while  $v_g > 0$  for a low and  $v_g < 0$  for a high in the northern hemisphere. For this case, using Eq. (3.14a) in Eq. (3.2) with the frictional effect and the  $\hat{f}w$  Coriolis term ignored, yields:

$$\frac{-v_{gr}^2}{R_T} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + f v_{gr},$$

and since  $(-1/\rho)(\partial p/\partial x) = -f v_g$ ,

$$\frac{-v_{gr}^2}{R_T} = -f v_g + f v_{gr} = f (v_{gr} - v_g) \quad (3.14b)$$

The velocity,  $v_{gr}$ , which solves this relation is referred to as the *gradient wind*. Rearranging of this expression results in:

$$v_{gr}^2 + f R_T v_{gr} - R_T f v_g = 0 \quad (3.15)$$

Using the quadratic equation formula,  $v_{gr}$  in Eq. (3.15) is given as:

$$v_{gr} = \left( -f R_T \pm \sqrt{f^2 R_T^2 + 4 R_T f v_g} \right) / 2 \quad (3.16)$$

For a cyclone in the northern hemisphere<sup>6</sup>,  $v_g > 0$  at  $A$  so that the radical in Eq. (3.16) is always real for this case and there is no limit in this relation to the magnitude of the gradient wind.

In contrast, however, for an anticyclone,  $v_g < 0$  at  $A$  in the northern hemisphere so that  $f^2 R_T^2 > 4 R_T f v_g$ , i.e.,

$$v_g < f R_T / 4 \quad (3.17)$$

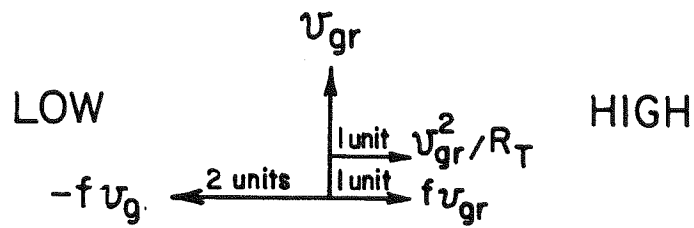
is required for the radical to be real. Therefore, Eq. (3.16) suggests that there is a constraint on the magnitude of the pressure gradient force in anticyclones that does not exist for synoptic lows. This is the reason that lows on the synoptic weather map often have tight gradients while highs do not.

Equation (3.15) can also be rewritten as:

$$\frac{v_{gr}^2}{R_T f} + v_{gr} = v_g \quad (3.18)$$

Thus,  $v_{gr} < v_g$  for a cyclone since  $v_g > 0$  at  $A$  but  $|v_{gr}| > |v_g|$  for an anticyclone since  $v_g < 0$  at  $A$ . These inequalities indicate that for the same pressure gradient (as represented by the geostrophic wind), the gradient balanced wind is stronger around a high than a low. This stronger wind around a high (and the associated greater curved centripetal acceleration) is the reason that a limit to the strength of the pressure gradient force, as represented by Eq. (3.17), occurs.

cyclone (a)



anticyclone (b)

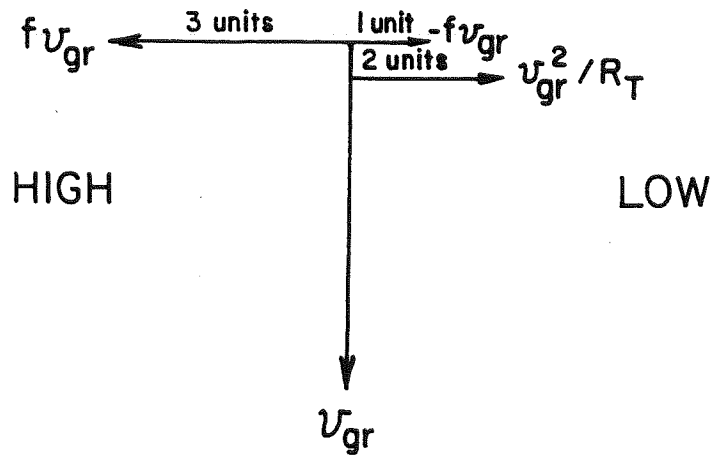


Figure 3.8: Schematic of the balance of acceleration in Eq. (3.14a) for (a) a cyclone, and (b) an anticyclone.

The balance of forces that are contained in Eq. (3.14b) are illustrated in Fig. 3.8. The gradient winds associated with the low are *subgeostrophic* because the centripetal acceleration term helps balance the acceleration due to the pressure gradient force. Therefore, the Coriolis terms,  $f v_{gr}$  and  $v_{gr}$ , need not be large.

In contrast, the winds associated with the anticyclone are *supergeostrophic* because a large Coriolis acceleration (and hence a large value of  $v_{gr}$ ) is needed to balance the sum of the acceleration due to the pressure gradient force and the centripetal acceleration.

When the Coriolis force is neglected in Eq. (3.14b), the equation represents a balance between the centripetal acceleration and the pressure gradient force. This balance, referred to as *cyclostrophic wind balance*, is used to estimate wind speeds in small-scale vortices such as tornadoes and dust devils. From Eq. (3.14b) the balance can be written as:

$$\frac{-v_d^2}{R_T} = -f v_g = -\frac{1}{\rho} \frac{\partial p}{\partial x} \quad (3.18a)$$

where  $v_g$  can be used to define the pressure gradient. The cyclostrophic wind is thus obtained from:

$$v_d = \pm \sqrt{\frac{R \partial p}{\rho \partial x}} \quad (3.18b)$$

As an example, a tornado with a radius of 0.5 km, a pressure gradient of 100 mb km<sup>-1</sup>, and an air density of 1.25 kg m<sup>-3</sup> would have a cyclostrophic wind balance of 63 m s<sup>-1</sup>.

While both plus and minus solutions of Eq. (3.18b) are possible, the circulation is usually cyclonic since the parent thunderstorm is generally rotating cyclonically due to Coriolis turning as a result of wind flow, on a fairly large scale, into the cumulonimbus system. It is thought that intense updrafts in the thunderstorm vertically stretch some of its circulation, thereby creating the strong vortex of the tornado. Intense horizontal shears between the vortex and surrounding ambient air create even smaller-scale vortices called *suction vortices*, which may be the source of the greatest tornado damage. The most severe tornadoes often occur in families when the atmosphere is favorable for their development over a large area. Over 300 people were killed in the midwest and southeast U.S. in one day in April, 1974 during a tornado family outbreak.

An evaluation of the influence of friction on the resultant balance can also be achieved by retaining the friction terms in Eq. (3.2),  $F_u$  and  $F_v$ , in the derivation of Eq. (3.14b). By defining, for example,

$$F_u = C_D u^2 ; \quad F_v = C_D v^2,$$

the more general form of Eq. (3.14b) (i.e., with friction) can be written as:

$$\frac{V_F^2}{R_T} + f V_F = f V_g + C_D V_F^2 \quad (3.19)$$

---

<sup>6</sup>The same result, of course, applies in the southern hemisphere because with a cyclone there  $v_g < 0$  but  $f < 0$ , also.

where  $V_F$  is, in general, at some angle to the gradient wind and  $F_V = C_D V_F^2 = C_D (u_F^2 + v_F^2)$ . The subscript,  $F$ , indicates that frictional effects are included. The variable  $C_D$  is a drag coefficient which is a function of height above the ground and the thermodynamic stability. The geostrophic wind speed is  $V_g = |\vec{V}_g|$ , and is defined by  $V_g = \frac{g \partial z}{f \partial n}$  where  $n$  is perpendicular to the height contours. A schematic illustration of a balance wind that can result from this balance of forces is illustrated in Fig. 3.9. Of particular importance is the deceleration of the flow and the turning of the wind towards low pressure. This results in low-level divergence out of anticyclones and low-level convergence into cyclones. Note that:

- the frictional acceleration acts directly opposite to the direction of the wind;
- the Coriolis acceleration is perpendicular to the wind direction; and
- the centripetal acceleration is also perpendicular to the instantaneous wind direction.

### 3.5 Thickness

As will be shown in this section, on the synoptic scale the vertical distance between two pressure surfaces is proportional to the mean temperature in the intervening layer. The hydrostatic relation, Eq. (3.6), is used to obtain the relation, i.e.,

$$\frac{\partial p}{\partial z} = -\rho g = \frac{-p g}{R_d T}$$

using the ideal gas law ( $p = \rho R T$ ). This equation can also be written as:

$$\frac{\partial \ln p}{\partial z} = -\frac{g}{R_d T} \quad (3.20)$$

Integrating Eq. (3.20) between two heights ( $z_1, z_2; z_2 > z_1$ ) corresponding to two pressure surfaces ( $P_1, P_2; P_2 < P_1$ ) yields:

$$\int_{z_1}^{z_2} \frac{\partial \ln p}{\partial z} dz = \ln \frac{P_2}{P_1} = -\frac{g}{R_d} \int_{z_1}^{z_2} \frac{dz}{T} = -\frac{g}{R_d} (z_2 - z_1) \left( \overline{\frac{1}{T}} \right) \quad (3.21)$$

where the mean value theorem of calculus has been used to remove  $1/T$  from the integrand. If it is assumed that  $\left( \overline{1/T} \right) \cong 1/\overline{T}$ , then Eq. (3.21) can be written, after rearranging, as:

$$(z_2 - z_1) = \Delta z = \frac{R_d \overline{T}_v}{g} \ln (P_1/P_2). \quad (3.22)$$

Therefore, as stated earlier in this section, the *thickness* between two pressure surfaces is proportional to the mean temperature,  $\overline{T}$ , in that layer.

Characteristic thickness distributions for four types of synoptic weather features are schematically illustrated in Fig. 3.10. Note that the subtropical anticyclone (a *warm core*

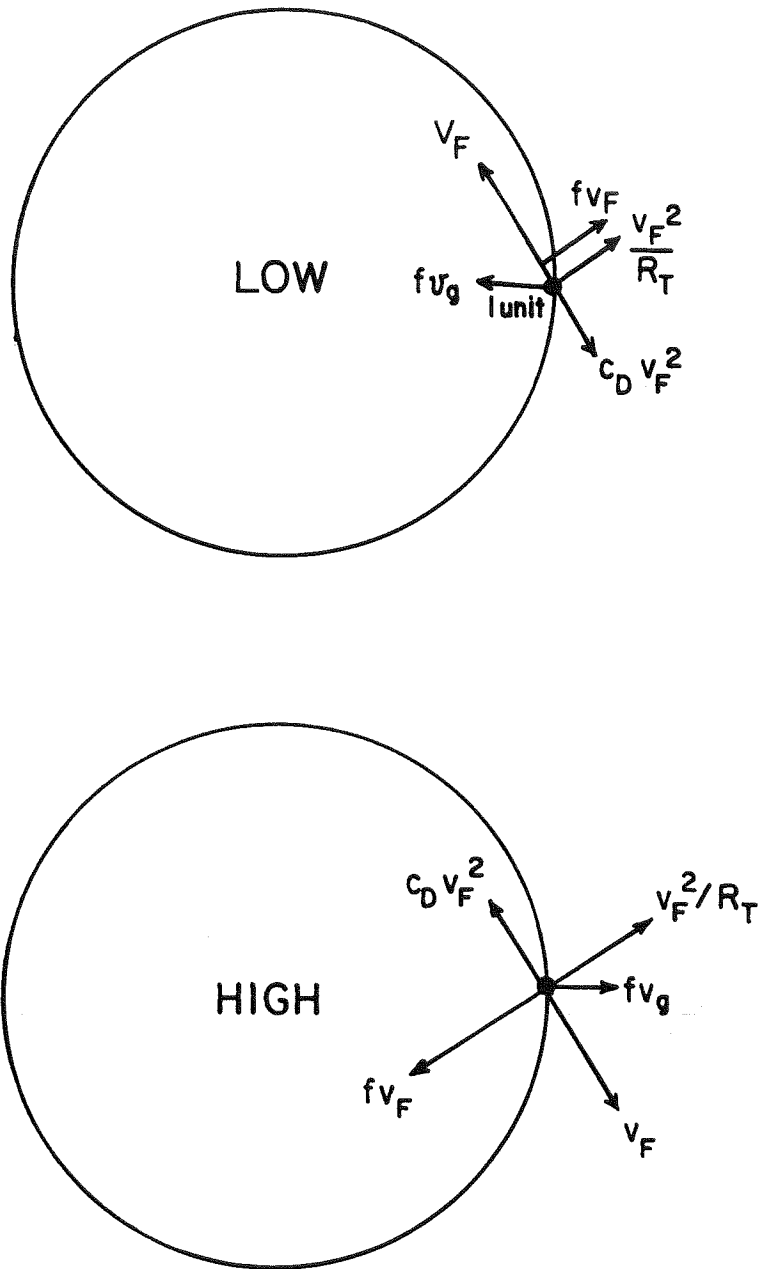


Figure 3.9: A schematic of the resultant balance wind when accelerations due to a pressure gradient, centripetal, Coriolis, and frictional accelerations are present for (a) a cyclone, and (b) an anticyclone.



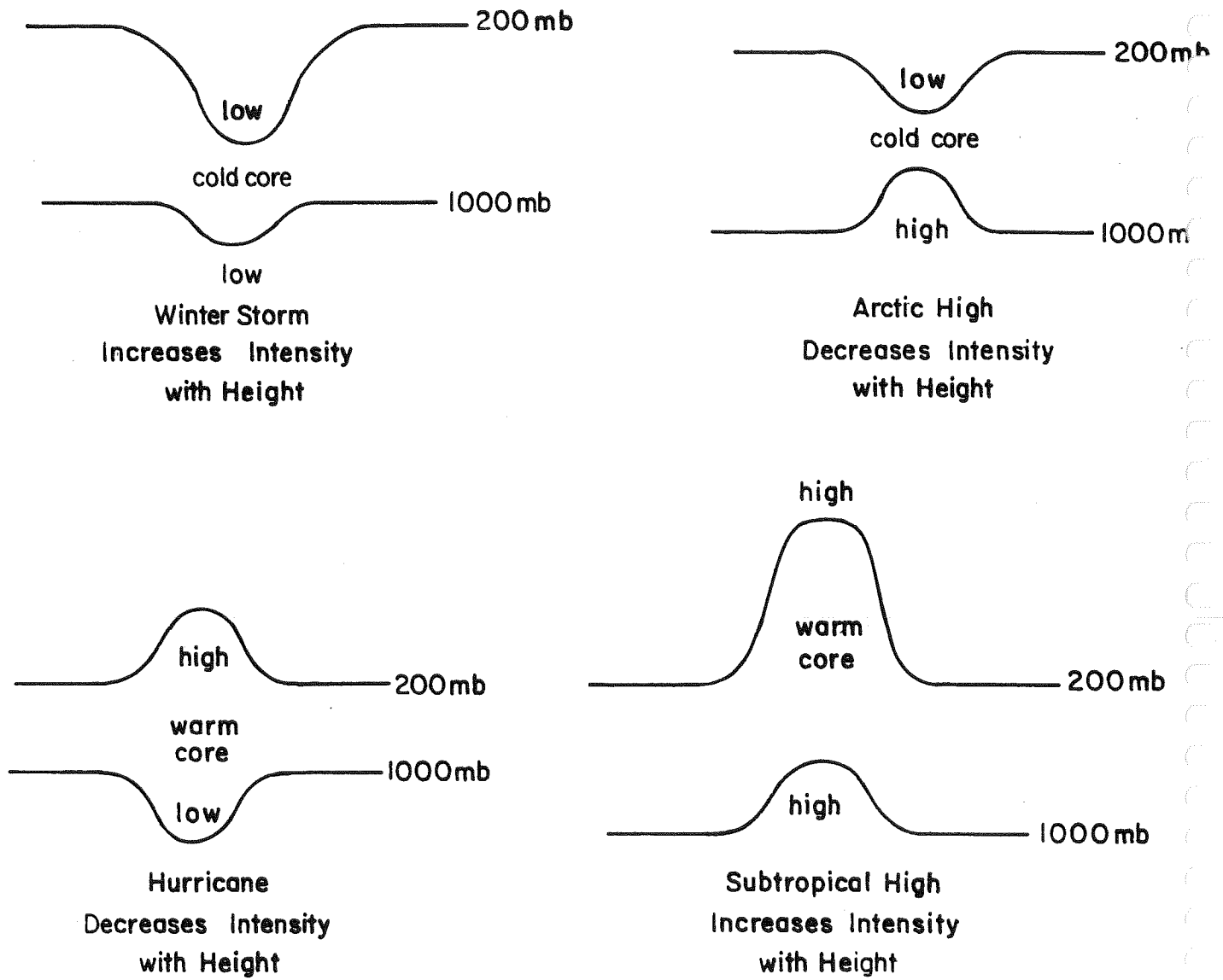


Figure 3.10: Schematic illustration of the thickness distribution associated with four types of synoptic weather features.

Table 3.1: Thickness values associated with a 50% chance of snow given that precipitation is occurring (from TPBS 1974).

	$\Delta z _{\text{rain/snow}}$
Bismark, North Dakota	5413
Bristal, Tennessee	5387
Baltimore, Maryland	5362
Beckley, West Virginia	5426
Chicago, Illinois	5391
Columbia, Missouri	5400
El Paso, Texas	5467
Goodland, Kansas	5461
Denver, Colorado	5501
Cheyenne, Wyoming	5509
Grand Junction, Colorado	5454
Havre, Montana	5410
Lander, Wyoming	5501
Medford, Oregon	5262
Minneapolis, Minnesota	5408
Missoula, Montana	5396
Norfolk, Virginia	5371
Philadelphia, Pennsylvania	5361
Pueblo, Colorado	5489
Reno, Nevada	5427
Seattle-Tacoma, Washington	5205

system) and the extratropical cyclone (a *cold core* system) increase in intensity with height. Therefore, these systems would be expected to be even better defined at upper tropospheric levels than at the surface. In contrast, the tropical cyclone (a *warm core* system) and the polar anticyclone (a *cold core* system) become less intense with height.

The magnitude of the thickness is often used to characterize local weather. In the eastern United States near sea level for instance,  $\Delta z = 5400$  m for the 1000 to 500 mb layer (i.e.,  $\bar{T} = -1.6^\circ\text{C}$ ) closely corresponds to the 50% probability between rain and snow if precipitation is occurring, while  $\Delta z \geq 5700$  m (i.e.,  $\bar{T} = 13.5^\circ\text{C}$ ) usually is associated with sultry weather. Specific examples for selected U.S. cities of the thickness values associated with a 50% probability of rain or snow are listed in Table 3.1. Note the substantially higher values of  $\Delta z|_{\text{rain/snow}}$  for sites such as Denver and Cheyenne which are located at relatively high altitudes so that only a portion of the 1000-500 mb thickness actually exists. Generally, the warmest part of the layer does not occur. The lowest thicknesses are along the west coast where the distribution of temperature with height tends to be less stable during the precipitation events than in the eastern United States. This is because most precipitation in the

winter occurs poleward of warm fronts in the eastern United States where the atmosphere tends to be more stably stratified. In the coastal regions of the western United States the precipitation is frequently post-cold frontal where a much less stable sounding occurs. Thus, a lower value of  $\bar{T}$  is required along the west coast than the east coast for snow to reach the surface. Despite relatively cold temperatures aloft along the west coast, the relatively warm temperatures near the surface melt the snow before it reaches sea level. (In the mountains along the west coast, however, the more rapid decrease of temperature with height results in a lower snow level than would generally occur in the eastern United States with the same sea-level temperature.)

Thickness analyses are also used to locate synoptic fronts and to estimate their intensity. By definition, a synoptic front must be associated with a horizontal gradient of thickness. The surface intersections of fronts are located on the warm side of the thickness gradient and they usually tilt poleward with height. The method to determine the specific location of surface fronts is discussed in Section 3.8.1.

The procedure to graphically analyze thickness from two constant pressure analyses is illustrated in Fig. 3.11. An alternative is to directly calculate  $\Delta z$  from the sounding data, plot it on a base map, and analyze the plotted fields.

### 3.6 Thermal Wind

From Eq. (3.8) the geostrophic wind can be written as:

$$\vec{V}_g = \vec{k} \times \frac{g}{f} \vec{\nabla}_p z$$

Differentiating this expression with respect to pressure yields:

$$\frac{\partial \vec{V}_g}{\partial p} = \frac{g}{f} \vec{k} \times \vec{\nabla}_p \frac{\partial z}{\partial p}$$

which, since  $\partial z / \partial p = -1 / \rho g = -R_d T / gp$  by the hydrostatic relation and the gas law, results after rearranging in:

$$\frac{\partial \vec{V}_g}{\partial \ln p} = -\frac{R_d}{f} \vec{k} \times \vec{\nabla}_p T \quad (3.23)$$

Therefore, the change of geostrophic wind with pressure is proportional to the gradient of temperature on a constant pressure surface.

Integrating Eq. (3.23) between two pressure surfaces and rearranging gives:

$$\int_{\ln p_1}^{\ln p_2} \frac{\partial \vec{V}_g}{\partial \ln p} d \ln p = \vec{V}_{g_{p_2}} - \vec{V}_{g_{p_1}} = \Delta \vec{V}_g = \frac{R_d}{f} \vec{k} \times \vec{\nabla}_p \bar{T} \left[ \ln \frac{P_1}{P_2} \right] \quad (3.24)$$

where the mean value theorem of calculus has been used to extract  $\vec{\nabla}_p \bar{T}$  from the integral. The quantity  $\Delta \vec{V}_g$  is referred to as the *thermal wind*.

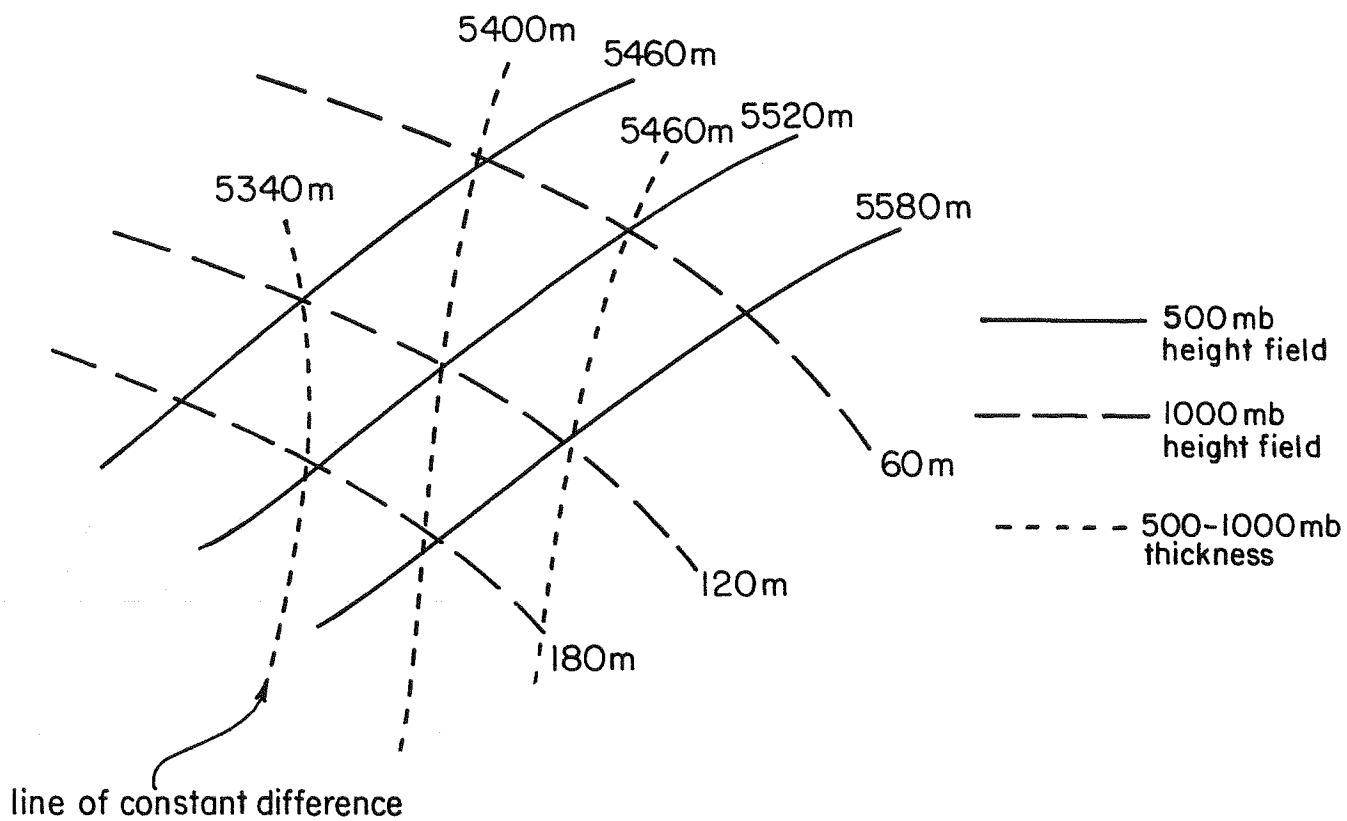


Figure 3.11: A schematic illustrating the procedure to graphically determine thickness. Two rules are to *include all intersections* of the two constant pressure height fields and *not to cross contours*.

Equation (3.24) can also be written in terms of the thickness gradient. Performing the gradient operation on Eq. (3.22) yields:

$$\nabla_p(\Delta z) = \frac{R_d}{g} \ln(P_1/P_2) \vec{\nabla}_p \bar{T},$$

so that Eq. (3.24) can be rewritten as:

$$\Delta \vec{V}_g = \frac{g \vec{k}}{f} \times \vec{\nabla}_p(\Delta z) \quad (3.25)$$

Since the magnitude of  $\Delta \vec{V}_g$  is related to the value of the average horizontal temperature gradient through the thickness equation,  $|\Delta \vec{V}_g|$  is used to classify the strength of synoptic fronts. Using the pressure surfaces 1000 mb and 500 mb, the following criteria have been established for use by the U.S. Weather Service;

	$ \Delta \vec{V}_g  < 12.5 \text{ m s}^{-1}$	$\rightarrow$ no front
$12.5 \text{ m s}^{-1}$	$<  \Delta \vec{V}_g  \leq 25.0 \text{ m s}^{-1}$	$\rightarrow$ weak front
$25.0 \text{ m s}^{-1}$	$<  \Delta \vec{V}_g  \leq 37.5 \text{ m s}^{-1}$	$\rightarrow$ moderate front
$37.5 \text{ m s}^{-1}$	$<  \Delta \vec{V}_g $	$\rightarrow$ strong front

Subjectively, the category of frontal strength is raised one level by the Weather Service if the weather along the front is unusually active, or lowered one level if there is very little activity.

Since  $\vec{V}_g$  at 1000 mb is usually small, to the extent that the geostrophic wind approximates the actual wind, strong winds at 500 mb are indicative of a strong front. In addition, since the same sign of the synoptic temperature gradient generally exists up to the tropopause, the geostrophic wind continues to increase with height. Above the tropopause, the temperature gradient reverses sign<sup>7</sup> so that the geostrophic wind decreases with height. The region of strongest geostrophic wind near the tropopause height is referred to as the *jet stream*.

The magnitude and direction of the thermal wind can be used to estimate temperature advection. As illustrated in Fig. 3.12, geostrophic winds which rotate counterclockwise (i.e., *back*) with height are associated with *cold advection* in the northern hemisphere. Geostrophic winds that turn clockwise (i.e., *veer*) with height are due to *warm advection*. In the southern hemisphere the reverse is true (i.e., backing winds with height are associated with warm advection). Cold advection in a layer of the atmosphere simply means that,

$$\frac{\partial \bar{T}}{\partial t} < 0 \text{ because } -\vec{V} \cdot \nabla_p \bar{T} < 0$$

while warm advection is:

$$\frac{\partial \bar{T}}{\partial t} > 0 \text{ because } -\vec{V} \cdot \nabla_p \bar{T} > 0,$$

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<sup>7</sup>This characteristic of the heights above the tropopause is discussed in Section 5.

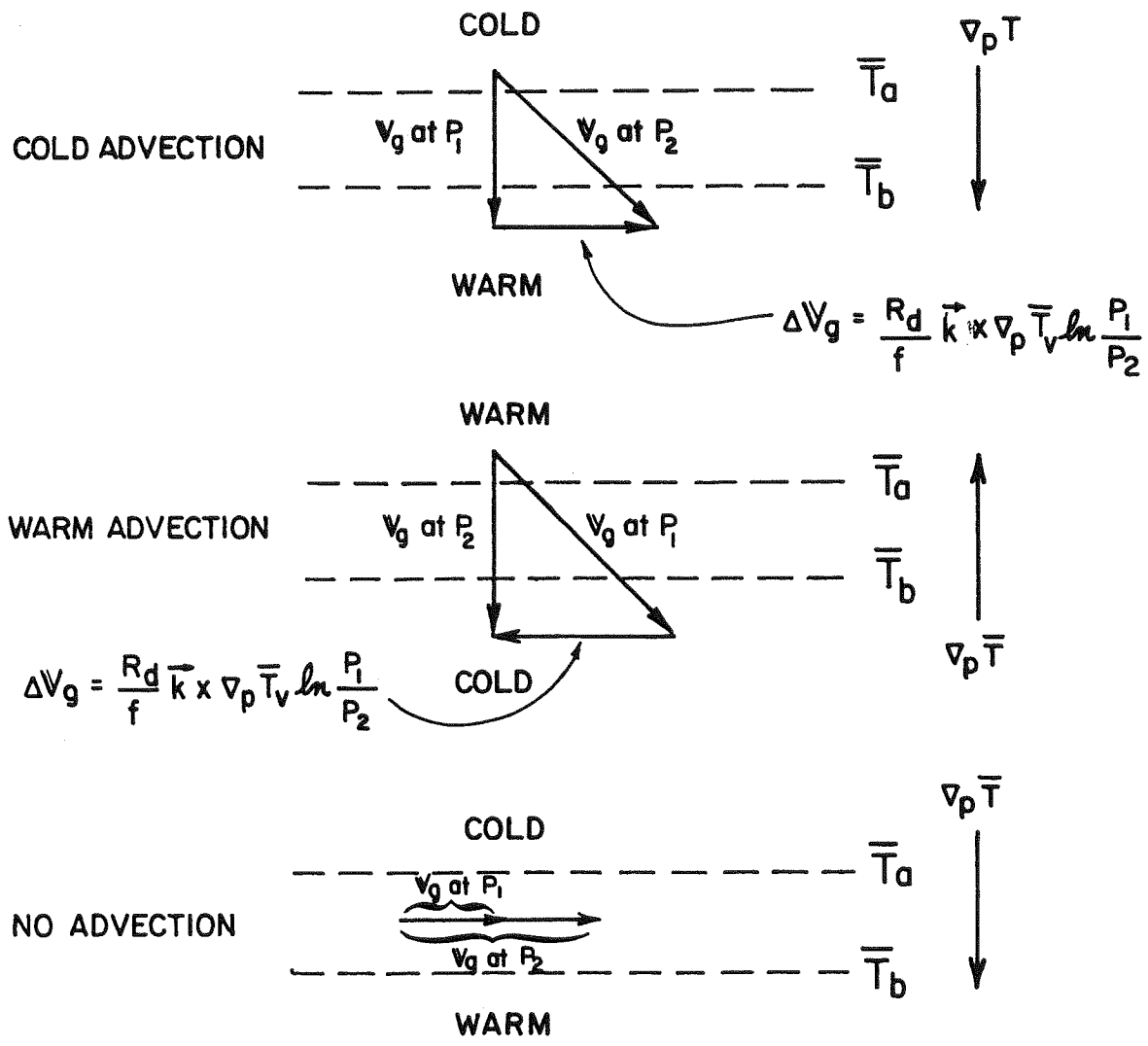


Figure 3.12: A schematic illustration of the relation between the thermal wind and temperature advection. In this figure,  $\bar{T}_a < \bar{T}_b$  and  $P_1 > P_2$ .

where  $\vec{V}$  is the average wind vector in the layer.

In the case of no temperature advection, as illustrated in Fig. 3.12, only the speed of the geostrophic wind, not the direction, changes with height. With cold air towards the pole, this requires that the westerlies increase in speed with height with a low-level westerly geostrophic wind. With warm air towards the north the westerlies would decrease with height for this situation.

An illustration as to why geostrophic winds back with height in the northern hemisphere under cold advection, while geostrophic winds veer with height during warm advection, is illustrated in Fig. 3.13. As sketched in that figure, troughs (often written as “trofs”) tilt towards colder air with height while ridges align towards warmer air with height. This is a direct result of the thickness relation (i.e., Eq. 3.22) which states that the vertical distance between pressure surfaces is directly proportional to the mean temperature of the intervening layer.

### 3.7 Vorticity

An extremely valuable concept in describing synoptic atmospheric circulations is that of *vorticity*. Vorticity is defined as,

$$\vec{\nabla} \times \vec{V} \equiv \text{vorticity} = \xi,$$

and represents a measure of circulation. In synoptic meteorology, the vertical component of vorticity is of primary interest. This component can be written as:

$$\xi_z = \vec{k} \cdot \vec{\nabla} \times \vec{V} = \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \quad (3.26)$$

Using the Stokes theorem (e.g., see Kaplan 1952, pg. 275), Eq. (3.26) can be integrated over an area yielding:

$$\iint_S \xi_z ds = \iint_S \vec{k} \cdot \vec{\nabla} \times \vec{V} ds = \oint V \cdot d\vec{r} = C$$

where  $S$  is the area of integration and  $\oint$  represents a closed line integral around the perimeter of the area which is perpendicular to  $\vec{k}$ . The distance differential is represented by  $d\vec{r}$ , so that the circulation  $C$  is defined by the integrated velocity along the line integral. Therefore, circulation represents an area average of the vorticity.

An equation for vertical vorticity is obtained from Section 3.4. For convenience in the following derivation, the  $\hat{f}w$  term is neglected (as shown, for example, by Pielke 1984, pg. 37 – this term is generally much less in magnitude on the synoptic scale than  $fv$ ), and friction is ignored. Performing the partial derivative in  $y$  on the first equation and the partial derivative in  $x$  on the second equation in Eq. (3.2), after expanding  $\frac{d}{dt}$  into  $\frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}$ , and subtracting the resultant second equation from the first yields, after rearrangement:

$$\frac{d}{dt} (\xi_z + f) = - (f + \xi_z) \left[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right] + \left[ \frac{\partial w}{\partial y} \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \frac{\partial v}{\partial z} \right] - \frac{1}{\rho^2} \left[ \frac{\partial p}{\partial x} \frac{\partial \rho}{\partial y} - \frac{\partial p}{\partial y} \frac{\partial \rho}{\partial x} \right] \quad (3.27)$$

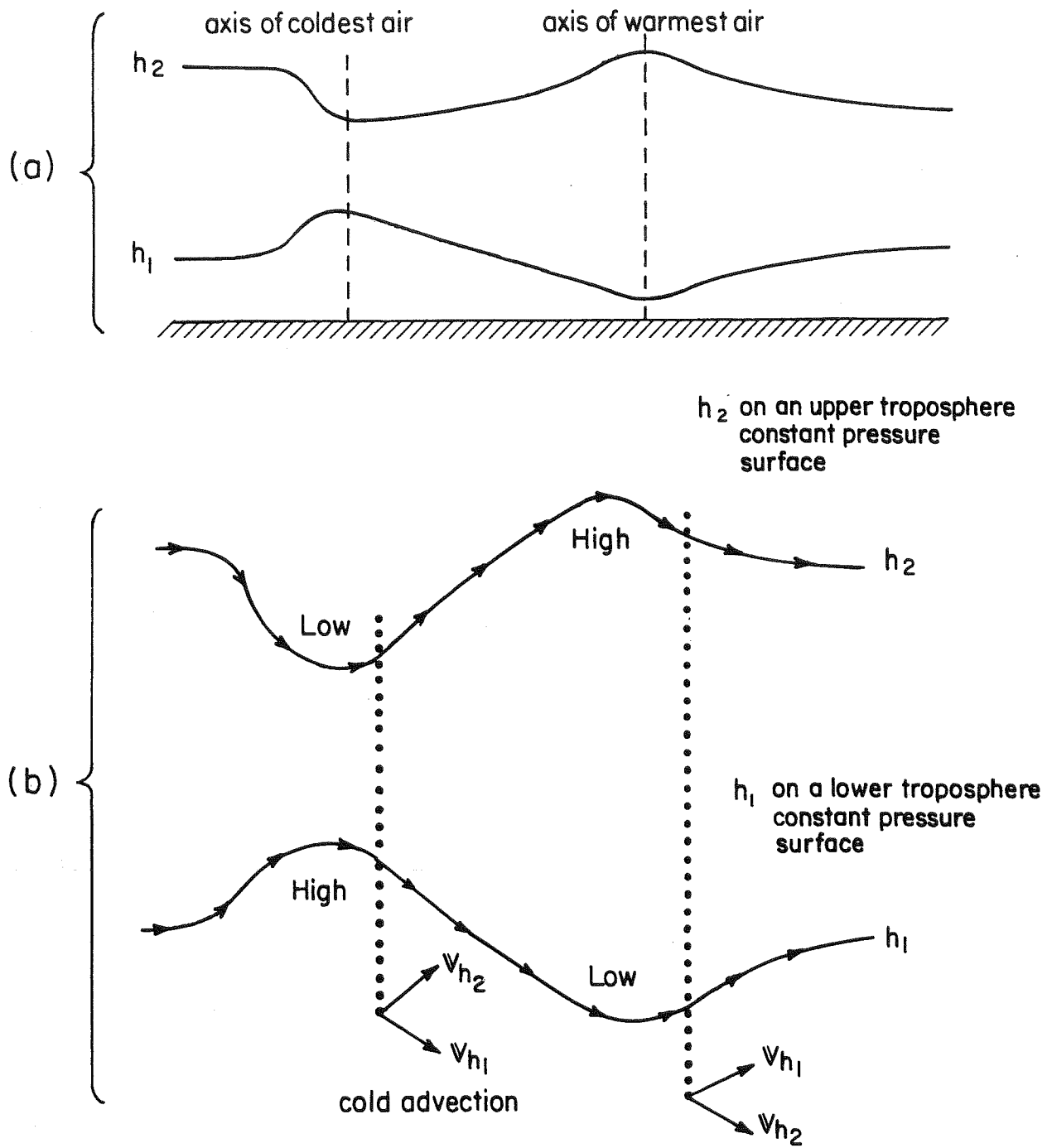


Figure 3.13: Schematic illustrating the reason that cold advection is associated with backing winds and warm advection with veering winds with height in the northern hemisphere. A vertical cross section is given in (a), a horizontal cross section in (b).



In obtaining Eq. (3.27), the observation that  $\frac{df}{dt} = v \frac{\partial f}{\partial y}$  is used. The quantity  $\xi_z + f$  is referred to as *absolute vorticity* with  $\xi_z$  called the *relative vorticity*. The Coriolis parameter  $f$  is the earth's vorticity which results because of the planet's rotation.

The terms in Eq. (3.27) are defined as follows:

$$\begin{aligned} \frac{d(\xi_z + f)}{dt} & : \text{ change of absolute vorticity, following a parcel.} \\ (f + \xi_z) \left[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right] & : \text{ represents changes of vertical absolute vorticity as a result of horizontal velocity divergence. To the extent that the atmosphere is incompressible, } \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -\frac{\partial w}{\partial z} \text{ can be substituted into this term.} \\ \left[ \frac{\partial w}{\partial y} \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \frac{\partial v}{\partial z} \right] & : \text{ represents changes of vertical absolute vorticity due to conversion from or to horizontal vorticity. This term is called the } \textit{tilting term}. \\ \frac{1}{\rho^2} \left[ \frac{\partial \rho}{\partial x} \frac{\partial p}{\partial y} - \frac{\partial \rho}{\partial y} \frac{\partial p}{\partial x} \right] & : \text{ represents changes of absolute vorticity as a result of differential heating or cooling. This term is referred to as the } \textit{solenoidal term}. \end{aligned}$$

Relative vorticity can also be expressed in so-called natural coordinates. Natural coordinates are defined with respect to the motion of a parcel. Using this approach:

$$\xi_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = \frac{V}{R_T} - \frac{\partial V}{\partial n} \quad (3.28)$$

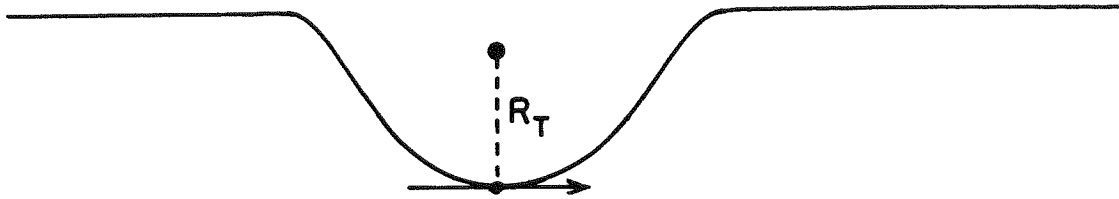
where  $V/R_T$  represents the angular velocity of solid rotation of an air parcel about a vertical axis with an instantaneous radius of curvature,  $R_T$ . The radius,  $R_T$ , is defined positive for counterclockwise rotation. The lateral shear term,  $-\partial V/\partial n$ , represents the effective angular velocity of an air parcel produced by distortion due to horizontal velocity differences at its boundaries. An illustration of the two terms on the right of Eq. (3.28) are given in Fig. 3.14. A useful interpretation of Eq. (3.28) is obtained by assuming a stick in an airstream represented by Fig. 3.14 with a pivot point midway along the stick. In both cases, for this example, the stick would rotate counterclockwise, indicating a cyclonic circulation which is represented by positive relative vorticity.

In order to illustrate the use of Eq. (3.27), the tilting and solenoidal terms are ignored, so that,

$$\frac{d(\xi_z + f)}{dt} = -(f + \xi_z) \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) = -(f + \xi_z) \text{div}_H \vec{V},$$

where the convention of writing  $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$  as  $\text{div}_H \vec{V}$  has been adopted. Clearly  $\text{div}_H V < 0$  indicates convergent horizontal winds, while  $\text{div}_H V > 0$  specifies divergent horizontal winds.

Rotational Vorticity  $\frac{V}{R_T}$



Shear Vorticity  $-\frac{\partial V}{\partial n}$

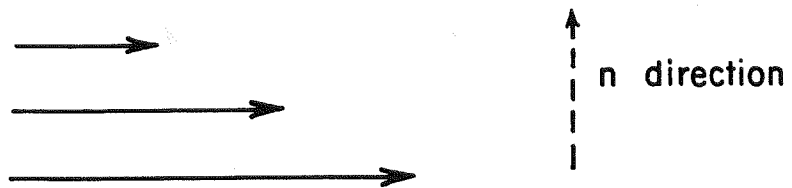


Figure 3.14: Examples of rotational and shear cyclonic vorticity illustrated in natural coordinates.

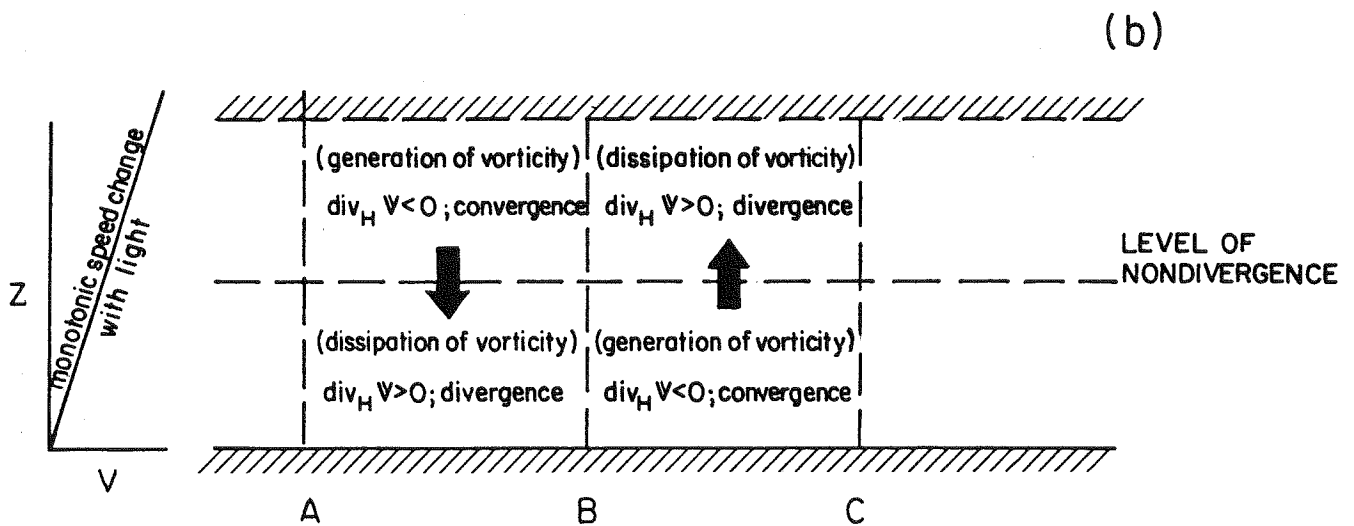
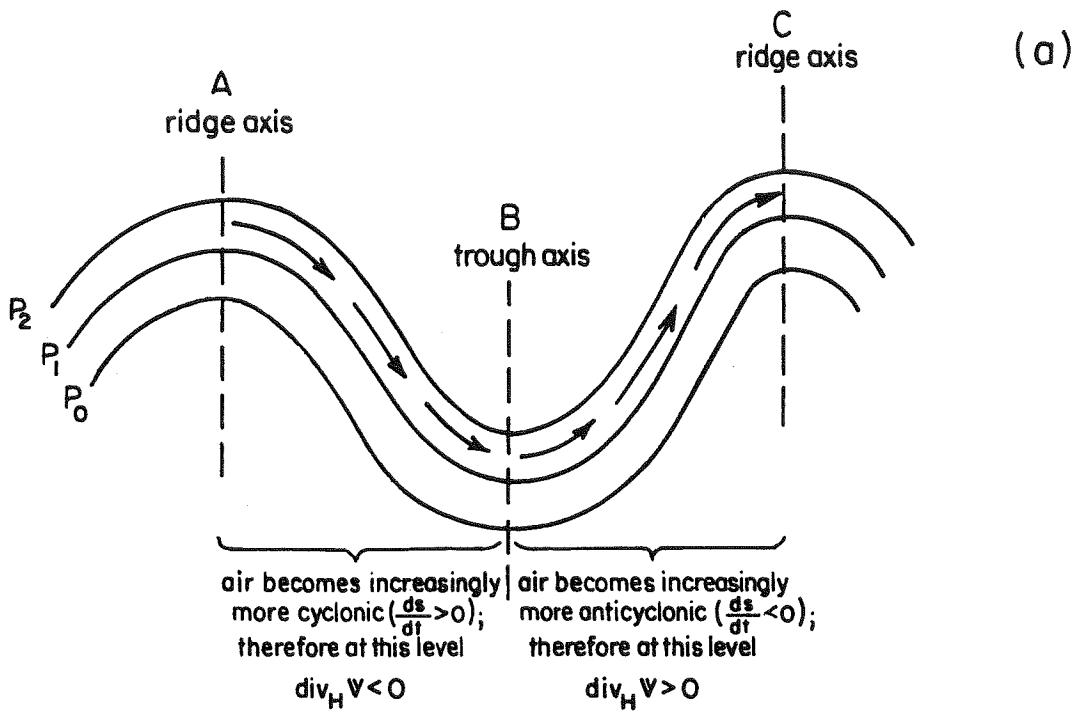


Figure 3.15: Schematic illustration of the inferred change of vorticity and resultant vertical motion (b) as an air parcel in gradient wind balance moves through a constant pressure gradient wind field in the upper troposphere given in (a).

Figure 3.15 illustrates a characteristic ridge-trough parcel trajectory in the upper troposphere. Since wind speeds in the westerlies in midlatitudes usually increase monotonically with height within the troposphere, the wind (and, therefore, the vorticity) field at the upper levels exerts a major control on the synoptic vertical motion field as represented by  $\text{div}_H \vec{V} \cong -\partial w / \partial z$ .

To the extent that the parcel trajectory is in gradient wind balance and, therefore, represented by Eq. (3.19) with  $C_D = 0$ , the parcel at the upper levels will decelerate as it moves from the ridge crest into the trough. Correspondingly, the parcel will accelerate as it approaches the ridge crest from the trough. Since, except for a modification due to the decrease of average air density with height,  $\text{div}_H \vec{V} \cong -\partial w / \partial z$  is a good approximation in the earth's troposphere, and the distribution of vertical velocities in Fig. 3.15b would result in order to conserve mass. On flat ground,  $w = 0$ , of course, while at the tropopause  $w \cong 0$  will be assumed in this analysis since the strong thermal stratification in the lower stratosphere strongly inhibits vertical motion.

The distribution of vertical motion in the midtroposphere, associated with gradient wind balance around ridges and troughs, provides one explanation for the observed preference for clouds east of a trough axis and west of a ridge crest (additional explanations are provided in Section 3.8). The level of nondivergence indicated in Fig. 3.15b occurs around 600 mb.

Values of realistic changes in gradient wind speed as a parcel moves through a ridge and trough are listed in Table 3.2. Assuming a height of 10 km, and a linear change of speed

Table 3.2: Estimate of induced vertical motion in  $\text{cm s}^{-1}$  at the level of nondivergence (a height of 5 km is used here) assuming steady flow and a wind speed which increases linearly with height ( $V$  at the surface is zero). The distance over which change takes place is on the left of the table. Analysis requires a large enough radius of curvature of parcel trajectory when the flow is anticyclonic such that the inequality given by Eq. (3.17) is satisfied.

Distance (km)	Change in gradient wind speed from ridge crest to trough axis in the upper troposphere ( $\text{m s}^{-1}$ )			Change in gradient wind speed from trough axis to ridge crest in the upper troposphere ( $\text{m s}^{-1}$ )		
	10	50	100	10	50	100
500	-10	-50	-100	10	50	100
1000	-5	-25	-50	5	25	50
2000	-2.5	-12.5	-25	2.5	12.5	25
5000	-1	-5	-10	1	5	10

with height (with  $|\vec{V}| = 0$  at the surface) yields the values of vertical velocity,  $w$ , at the level of nondivergence given in the table. As concluded by Palmén and Newton (1969, pg. 145),

“The magnitude of the gradient-wind divergence is greatest if the wave amplitude is large, the wavelength small, and the wind speed is large and significantly different from that at the level of nondivergence.”

As stated further by Palmén and Newton (1969), since the inferred vertical motion is larger when a more substantial vertical gradient wind shear exists, stronger thickness gradients associated with ridges and trough couplets are associated with more intense vertical motion patterns.

## 3.8 Extratropical Cyclones

### 3.8.1 Determination and Definition of Fronts

A front on the synoptic scale is characterized by the following three criteria.

- i) A front separates different air mass types.
- ii) A thickness gradient defines the approximate location of the front, which is located near the warm side of the gradient.
- iii) The type of front depends on the direction of movement of the colder air mass.

At the surface, the following indicators are applied to precisely locate a front, once the criteria listed above are satisfied:

- a) a wind shift line
- b) a pressure trough
- c) a temperature discontinuity
- d) a dewpoint temperature discontinuity
- e) the pressure tendency pattern
- f) horizontal variations in visibility
- g) horizontal variations in precipitation type

There are five basic types of fronts, i.e.,

- cold front
- warm front
- stationary front
- cold occlusion
- warm occlusion

Table 3.3: Characteristics of warm and cold fronts at the surface.

	<i>Cold Front</i>	<i>Warm Front</i>
A wind shift line	a) Ahead of the front in the warmer air, surface winds are southwesterly, often gusty close to the front. Behind the front, winds veer to the west or northwest and increase in strength as the cold advection destabilizes the air, thereby mixing the stronger winds aloft down to the surface.	Ahead of the front in the colder air, winds are southeasterly to northeasterly in direction with little gustiness, generally. Behind the front, winds veer to the southwest or south.
A pressure trough	b) The development of a pressure trough is associated with convergent synoptic-scale low-level winds which concentrate the thickness gradient, thereby strengthening the front. Frictional convergence into the trough enhances the gradient further.	Same as for cold fronts.
A temperature discontinuity	c) The air is generally colder at the surface behind the front in the air mass with lower thicknesses. An exception occurs, particularly in the summer when although the thickness is smaller behind a front so that the average temperature is colder, stronger vertical mixing and/or removal of cloud cover behind the front can result in warmer surface temperatures.	Colder air ahead of the warm front. The gradient of temperature at the surface is usually less ahead of a warm front than is the case for a cold front. This is attributed to the greater frictional retardation of the forward movement of cold air by the ground than is the case for the retreat of cold air ahead of the warm front.
A dewpoint temperature discontinuity	d) Lower dewpoint temperature air is generally found behind cold fronts since cold air can hold less moisture than warmer air.	Lower dewpoint temperature air is generally found ahead of warm fronts although the relative humidity is generally much higher ahead of the front.
The pressure tendency pattern	e) Pressure falls ahead of the front; rises behind the front; the rate of pressure change depends on the strength of the pressure trough associated with the front and its rate of movement. Pressure changes are generally more rapid with a cold front than a warm front of equal space because the temperature gradient (and therefore, horizontal pressure gradient) in low levels is larger for the reason mentioned in c) of these criteria.	Pressure falls comparatively slowly ahead of the warm front unless the trough associated with the front is intensifying rapidly; pressure rises slowly or is steady behind the front.
Horizontal gradient in visibility	f) Visibility is often excellent behind the cold front due to the enhanced vertical mixing.	Often poor visibility ahead of the warm front improving after the warm front passes.
Horizontal variation in precipitation type	g) Deep cumulus convection often occurs ahead of the cold front. Behind the cold front, if they occur, showers are usually more shallow in vertical extent.	Often steady precipitation ahead of the front, replaced by showers or no precipitation behind the front.

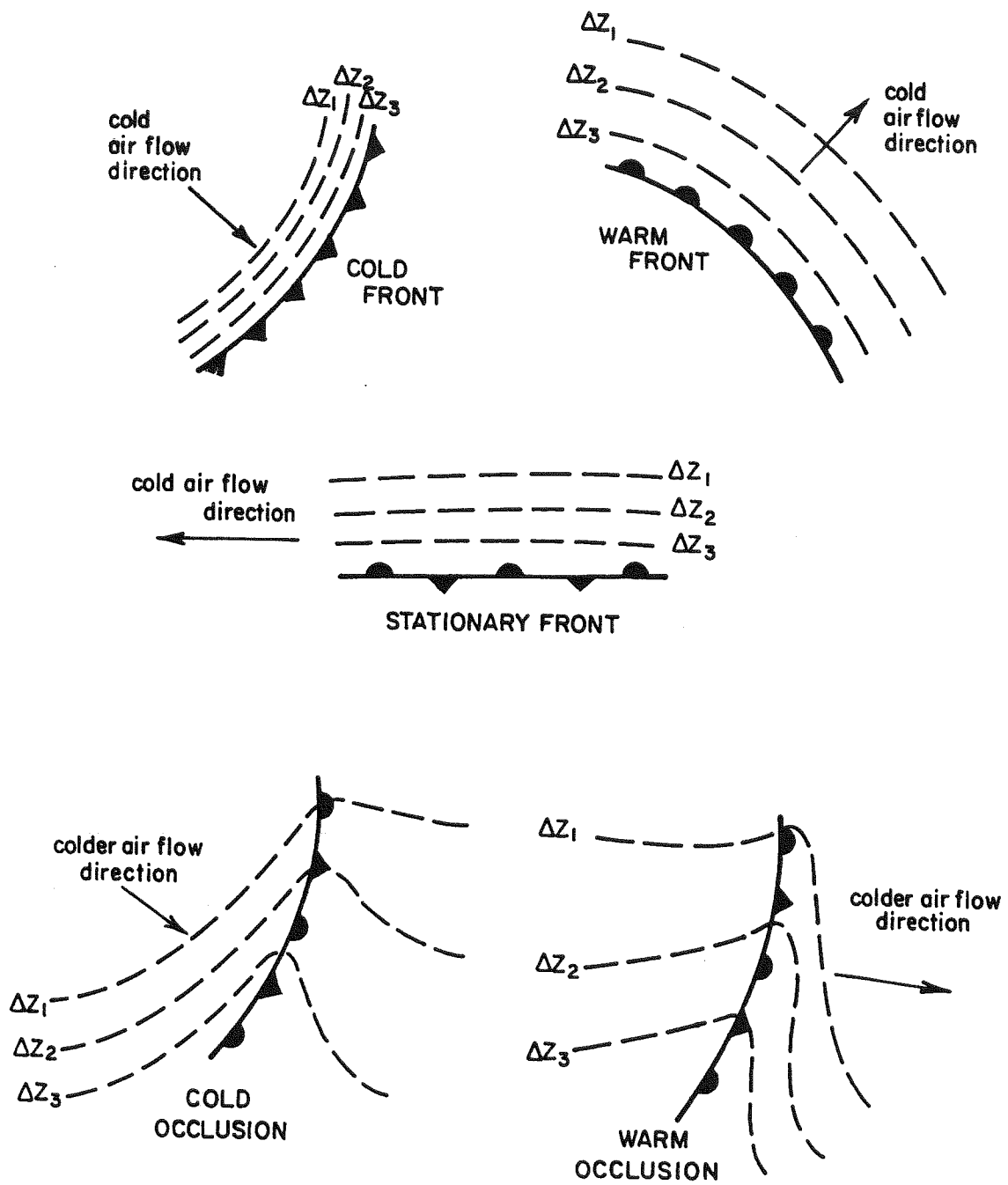


Figure 3.16: Schematic illustration of the different types of fronts. Fronts always move in the direction in which the more dense (i.e., colder) air mass is moving,  $\nabla_{z_3} > \nabla_{z_1}$ .

The symbols used on a weather map for each are shown (note that both types of occlusions use the same symbols). As an example, the common characteristics of criteria a)–g) for a cold and a warm front in the northern hemisphere are listed in Table 3.3.

An illustration of the relation between fronts and the thickness gradient is illustrated in Fig. 3.16.

The development of fronts are associated with low-level synoptic flow which is convergent in the presence of a thickness gradient in the low levels. The development of fronts is termed *frontogenesis*. In contrast, low-level synoptic flow which becomes divergent in the vicinity of an existing front is *frontolytic* (i.e., causing the front to weaken).

The two types of each front are:

- active fronts, and
- inactive fronts.

An active front exists when the warmer air mass is overrunning the cold air mass. This occurs when the warmer air mass has a wind component with respect to the frontal motion through a significant depth of the atmosphere which is blowing towards the front. This overrunning can result in clouds and precipitation if the overrunning is deep and extends high enough over the frontal surface to reach the lifting condensation level.

Figure 3.17 schematically illustrates the differences between active and inactive cold, warm, and stationary fronts. Occlusions can be defined in a similar fashion where the direction of movement of the low-level air on the warmer side determines whether it is an active or inactive occlusion.

Cross sections through cold and warm occlusions are illustrated in Fig. 3.18. The tongue of warm air aloft represented by the bulge in the thickness contours occurs when a cold front catches up with a warm front, thereby lifting the warmer air between the air which was originally between the two fronts. If the air behind the cold front is warmer than the air ahead of the warm front, a warm occlusion results. In the United States, warm occlusions are more common than cold occlusions. The surface frontal position closely corresponds to the position of the warm thickness bulge. This thickness bulge is generally associated with a minimum of pressure (i.e., the pressure trough associated with fronts). Cold occlusions tend to have the characteristics of a cold front, while warm occlusions are more similar to warm fronts.

### 3.8.2 Surface Depiction of Extratropical Storm Development

The existence of well-defined cyclonic circulations in mid and high latitudes (i.e., extratropical cyclones) were first defined at the surface where observations were sufficiently dense to resolve the feature. The association of the cyclone with fronts (and the existence of fronts) was originally noted by Norwegian meteorologists shortly after World War I (see Namias 1983 for a historical discussion of the discovery of fronts and the extratropical cyclone). The term front was adopted because of its association with the frontal and trench warfare of the war, in which well-defined defensive positions separated opposing armies.



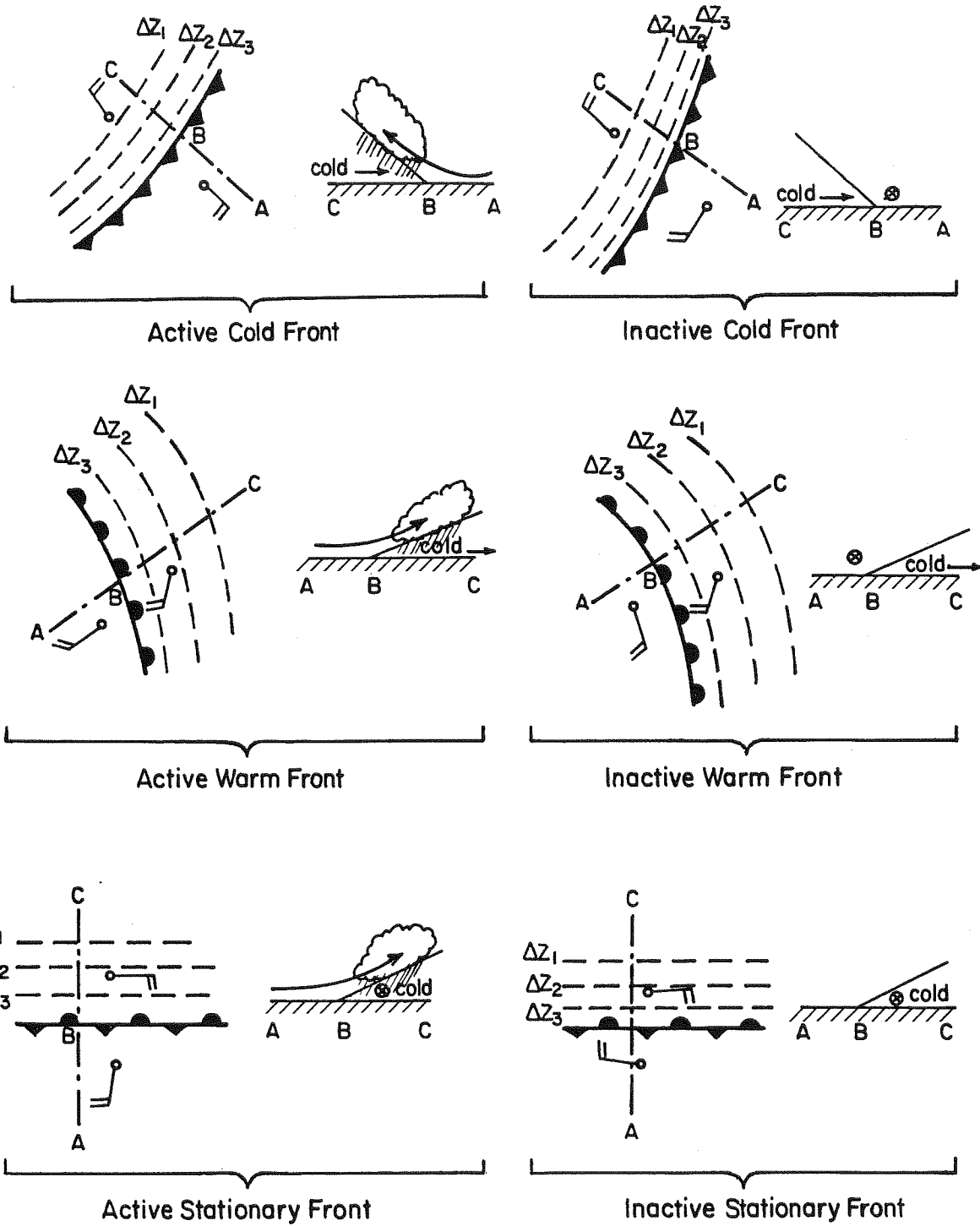
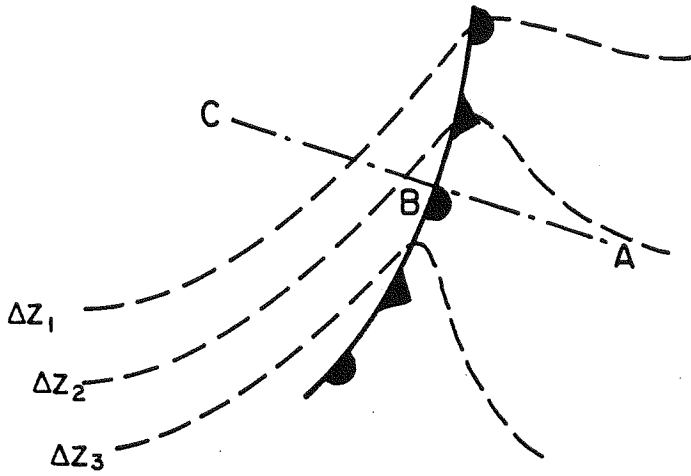


Figure 3.17: Schematic illustration of active and inactive cold, warm, and stationary fronts.

### Cold Occlusion



### Warm Occlusion

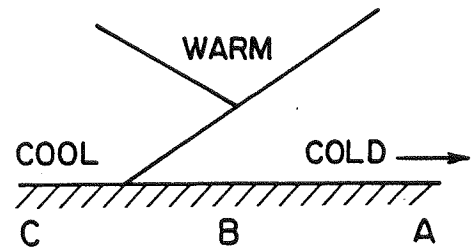
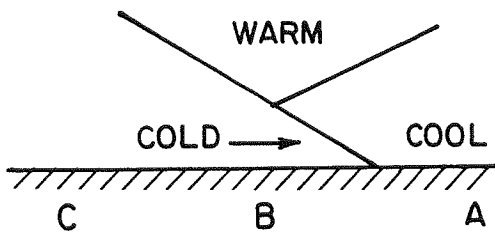
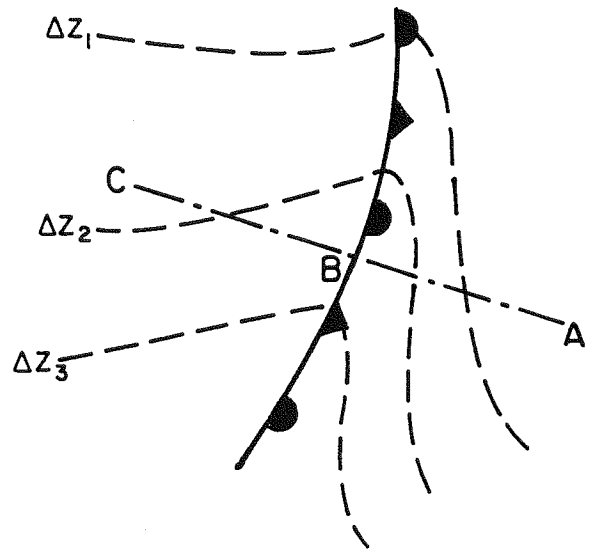


Figure 3.18: Schematic illustration of the juxtaposition of air masses in warm and cold occlusions. The movement of the cold air is indicated by the arrow.

Figure 3.19 illustrates three major stages in the evolution of a cyclone from a wave on a stationary front to its mature form. This process is referred to as cyclogenesis. All cyclones do not evolve through each stage, however. Many terminate at the initial stage and are termed *wave cyclones*. The difference in degree of cyclonic development as associated with the concept of *baroclinic instability* is discussed in more detail in Section 3.8.7. In simple terms, however, a cyclone evolves through all three stages when there is a continuous conversion of potential energy (as represented by the juxtaposition of cold and warm air) to kinetic energy (as represented by the cyclonic wind flow around the low pressure system). As an extratropical cyclone evolves through its different stages, its minimum pressure decreases and moves toward the colder air. The most rapid falls occur in the development stage – when the falls are excessive the extratropical storm is said to be undergoing *explosive cyclogenesis*.

The juncture of the warm, cold, and occlusion fronts during the mature stage is referred to as the *triple point*. Often a new low pressure center may develop at the triple point. This new development, referred to as *secondary cyclogenesis*, frequently occurs off the east coast of continents in midlatitudes during the winter as this zone of horizontal thickness gradient and associated cold air moves over warmer waters. The development processes associated with cyclogenesis are discussed in the next sections.

### 3.8.3 The Omega Equation

In order to describe the vertical motion pattern above the surface associated with extratropical cyclones and other types of synoptic weather features, it is useful to combine the vorticity equation and first law of thermodynamics into a single relation.

Using the same procedure to derive Eq. (3.26), except on a constant pressure surface, Eq. (3.7) can be used to derive a vorticity equation. Differentiating the top equation of Eq. (3.7) by  $\frac{\partial}{\partial y}$ , the bottom equation by  $\frac{\partial}{\partial x}$ , subtracting the resultant top expression from the bottom and neglecting the tilting and friction terms yields:

$$\frac{\partial \xi_p}{\partial t} + \vec{V} \cdot \vec{\nabla}_p (\xi_p + f) = (\xi_p + f) \frac{\partial \omega}{\partial p}, \quad (3.29)$$

where  $\xi_p$  is the relative vorticity on a constant pressure surface. The quantity  $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$  on a constant pressure surface is replaced by  $\frac{\partial \omega}{\partial p}$  with  $\omega = \frac{dp}{dt}$  (e.g., see Haltiner 1971, pp. 6-8).

Since  $\vec{V}_g = \frac{g}{f} \vec{k} \times \nabla_p z$ , a *geostrophic vorticity*, defined as  $\xi_g$ , can be obtained from:

$$\vec{\nabla} \times \vec{V}_g = \frac{g}{f} \nabla_p^2 z = \xi_g \quad (3.30)$$

A practical use of Eq. (3.30) is that vorticity can be estimated from the curvature of the height contours on a constant pressure analysis. Substituting Eq. (3.30) into Eq. (3.29), where  $\xi_p$  is set equal to  $\xi_g$ , yields:

$$\frac{\partial}{\partial t} \frac{g}{f} \nabla_p^2 z + \vec{V} \cdot \vec{\nabla}_p (\xi_g + f) = (\xi_g + f) \frac{\partial \omega}{\partial p}, \quad (3.31)$$

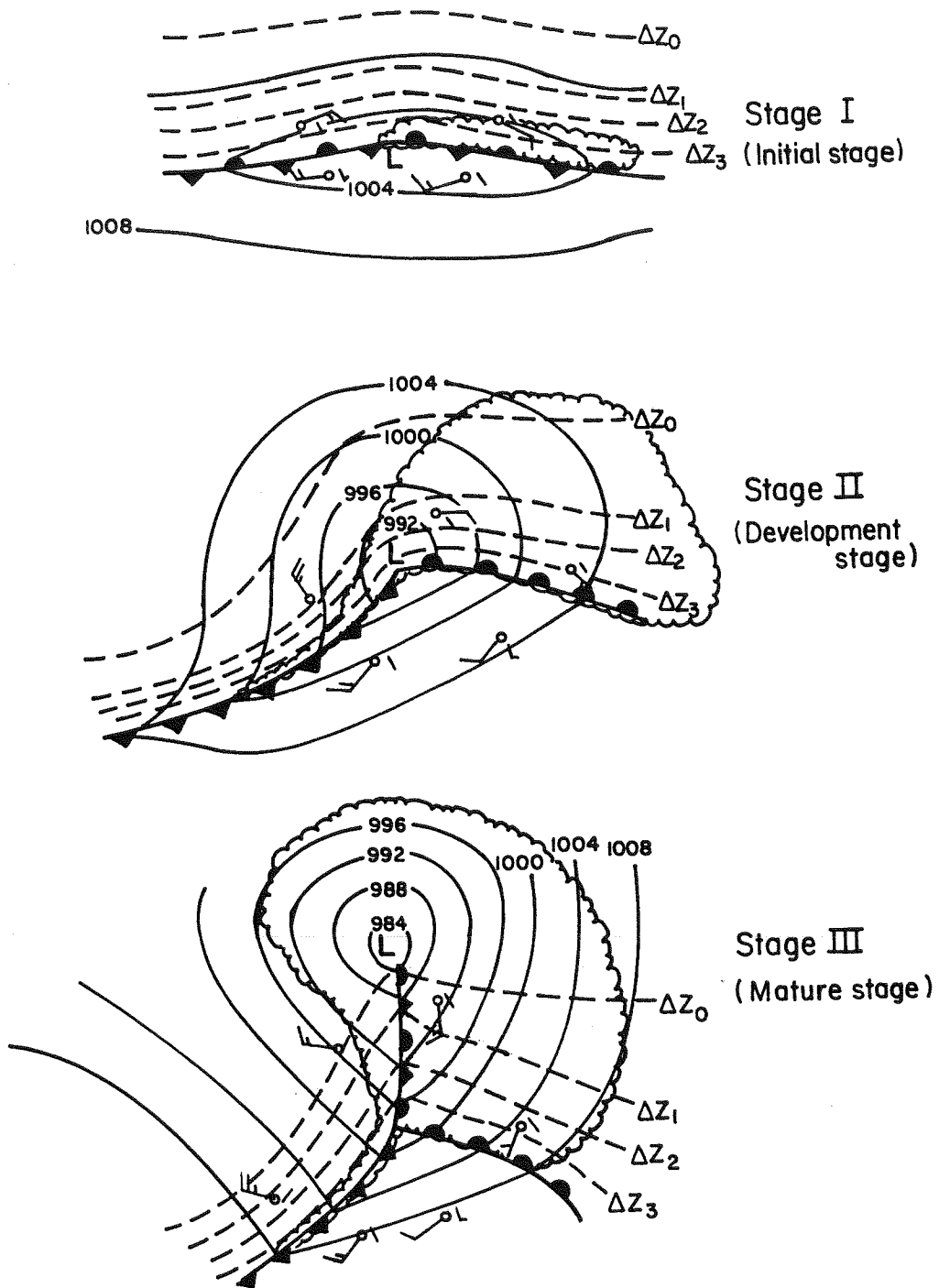


Figure 3.19: Schematic illustration of the evolution of an extratropical cyclone from a wave cyclone to a mature cyclone. The scalloped area represents cloud covered areas. Thickness is given by  $\Delta z$  where  $\Delta z_3 > \Delta z_0$ . Pressure is in millibars. Examples of station observations as plotted on U.S. surface map analyses are shown.

where  $\omega = dp/dt$ .

From Eq. (2.13a), the first law of thermodynamics can be written as:

$$C_p \frac{d \ln \theta}{dt} = Q/T \quad (3.32)$$

where  $Q$  represents changes of the sensible heat of a parcel (i.e., diabatic effects).  $Q$  can include explicit synoptic-scale phase changes of water as represented by  $-Ldw_s$  in Eq. (2.12), as well as radiative flux divergence and subsynoptic-scale phase changes of water due to cumulus clouds.

Equation (3.32) can be rewritten as:

$$C_p \left[ \frac{\partial \ln \theta}{\partial t} + u \frac{\partial \ln \theta}{\partial x} + v \frac{\partial \ln \theta}{\partial y} + \omega \frac{\partial \ln \theta}{\partial p} \right] = Q/T. \quad (3.33)$$

Since using the gas law:

$$\theta = T [1000/p]^{R_d/C_p} = \frac{p\alpha}{R_d} \left( \frac{1000}{p} \right)^{R_d/C_p}$$

then

$$\frac{\partial \ln \theta}{\partial x} = \frac{\partial \ln \alpha}{\partial x}; \quad \frac{\partial \ln \theta}{\partial y} = \frac{\partial \ln \alpha}{\partial y}; \quad \frac{\partial \ln \theta}{\partial t} = \frac{\partial \ln \alpha}{\partial t}$$

on a constant pressure surface and Eq. (3.33) can be written as:

$$C_p \left[ \frac{\partial \alpha}{\partial t} + u \frac{\partial \alpha}{\partial x} + v \frac{\partial \alpha}{\partial y} + \omega \alpha \frac{\partial \ln \theta}{\partial p} \right] = \frac{\alpha}{T} Q \quad (3.34)$$

From the hydrostatic relation in a pressure coordinate framework (i.e.,  $\frac{\partial z}{\partial p} = -\alpha/g$ ):

$$\alpha = -g \frac{\partial z}{\partial p}$$

so that Eq. (3.34) can also be written as:

$$C_p \left[ -\frac{\partial}{\partial t} \left( g \frac{\partial z}{\partial p} \right) - u \frac{\partial}{\partial x} \left( g \frac{\partial z}{\partial p} \right) - v \frac{\partial}{\partial y} \left( g \frac{\partial z}{\partial p} \right) + \omega \alpha \frac{\partial \ln \theta}{\partial p} \right] = \frac{\alpha}{T} Q \quad (3.35)$$

By convention:

$$\sigma = -\alpha \frac{\partial \ln \theta}{\partial p} = g \frac{\partial z}{\partial p} \frac{\partial \ln \theta}{\partial p}$$

is defined so that Eq. (3.35) becomes, after rearranging:

$$\frac{\partial}{\partial t} \left( -g \frac{\partial z}{\partial p} \right) - \vec{V} \cdot \vec{\nabla}_p \left( g \frac{\partial z}{\partial p} \right) - \omega \sigma = \frac{\alpha}{C_p T} Q = \frac{R_d}{p C_p} Q. \quad (3.36)$$

Performing the operation  $\partial/\partial p$  on Eq. (3.31) yields:

$$g\nabla_p^2 \frac{\partial}{\partial t} \frac{\partial z}{\partial p} + f \frac{\partial}{\partial p} [\vec{V} \cdot \nabla_p (\xi_g + f)] = f(f + \xi_g) \frac{\partial^2 \omega}{\partial p^2};$$

performing the operation  $\nabla_p^2$  on Eq. (3.36) and assuming that  $\sigma$  is a function of pressure only yields:

$$-g\nabla_p^2 \frac{\partial}{\partial t} \left( \frac{\partial z}{\partial p} \right) - \nabla_p^2 \left[ \vec{V} \cdot \nabla_p \left( g \frac{\partial z}{\partial p} \right) \right] - \sigma \nabla_p^2 \omega = \frac{R_d}{pC_p} \nabla_p^2 Q.$$

Adding the last two equations produces:

$$f \frac{\partial}{\partial p} [\vec{V} \cdot \nabla_p (\xi + f)] - \nabla_p^2 \left[ \vec{V} \cdot \nabla_p \left( g \frac{\partial z}{\partial p} \right) \right] - \sigma \nabla_p^2 \omega = \frac{R_d}{C_p p} \nabla_p^2 Q + f(f + \xi_g) \frac{\partial^2 \omega}{\partial p^2}.$$

Since  $\partial z/\partial p = -\alpha/g = -RT/gp$ , this relation can also be written as:

$$\sigma \nabla_p^2 \omega + f(f + \xi_g) \frac{\partial^2 \omega}{\partial p^2} = f \frac{\partial}{\partial p} [\vec{V} \cdot \vec{\nabla}_p (\xi_g + f)] + \frac{R_d}{p} \nabla_p^2 [\vec{V} \cdot \vec{\nabla}_p T] - \frac{R_d}{C_p p} \nabla_p^2 Q. \quad (3.37)$$

This equation is called the *Omega equation* and represents a diagnostic second order differential equation for  $\frac{dp}{dt}$ .

To illustrate the importance of the different terms in Eq. (3.37), note that the lefthand side of Eq. (3.37) is of the form  $\nabla^2 \omega$  (although it cannot be written so simply in a quantitative solution to Eq. (3.37) because the coefficient of  $\nabla_p^2 \omega$  is different from  $\partial^2 \omega/\partial p^2$ ). If  $\nabla^2 \omega$  has a wave form, i.e.,

$$\nabla^2 \omega = -k^2 A \sin kx$$

where  $A$  is a constant, and  $k = 2\pi/L$  where  $L$  is the wavelength, then:

$$\omega \sim A \sin kx$$

Since,

$$\omega = \frac{dp}{dt} = \frac{\partial p}{\partial t} + u \frac{\partial p}{\partial x} + v \frac{\partial p}{\partial y} + w \frac{\partial p}{\partial z} \cong w \frac{\partial p}{\partial z} = -w\rho g;$$

for typical synoptic values of pressure tendency and pressure gradient, then:

$$\omega \sim -w \quad \text{and} \quad w \sim \nabla^2 \omega.$$

In Eq. (3.37), the three terms on the right side represent the following:

$\frac{\partial}{\partial p} [\vec{V} \cdot \vec{\nabla}_p (\xi_g + f)] \longrightarrow$  vertical variation of the advection of absolute vorticity on a constant pressure surface.

$\nabla_p^2 [\vec{V} \cdot \vec{\nabla}_p T] \longrightarrow$  the curvature of the advection of temperature on a constant pressure surface.

$\nabla_p^2 Q \longrightarrow$  the curvature of diabatic heating on a constant pressure surface.

These three terms can be interpreted more easily.

Using the relation between  $\partial/\partial p$  and  $\partial/\partial z$ , and our observation that  $\nabla^2 \omega \sim w$ ,

$$w \sim \frac{\partial}{\partial p} [\vec{V} \cdot \vec{\nabla}_p (\xi_g + f)] \sim -\frac{\partial}{\partial z} [\vec{V} \cdot \vec{\nabla}_p (\xi_g + f)] \quad (3.38)$$

In most situations in the atmosphere, the vorticity advection is much smaller in the lower troposphere than in the middle and upper troposphere since  $\vec{V}$  and  $\xi_g$  are usually smaller near the surface. As shown in Section 3.6, on the synoptic scale, cold air towards the poles requires that  $\vec{V}$  becomes more positive with height.

Using this observation of the behavior of  $\vec{V}$  and  $\xi_g$  with height:

$$w \sim -\vec{V} \cdot \vec{\nabla}_p (\xi_g + f) \quad (3.39)$$

In other words, vertical velocity is proportional to vorticity advection. Since upper-level vorticity patterns are usually geographically the same as at midtropospheric levels (since troughs and ridges are nearly vertical in the upper troposphere; C. Kreitzberg, personal communication, 1970), the 500 mb level is generally chosen to estimate vorticity advection. This level is also close to the level of nondivergence (see Fig. 3.15) in which creation or dissipation of relative vorticity is small, so that the conservation of absolute vorticity is a good approximation.

Thus for the Northern Hemisphere where  $\xi_g > 0$  for cyclonic vorticity,

$w > 0$ if $-\vec{V} \cdot \vec{\nabla}_p (\xi_g + f) > 0$ positive vorticity advection (PVA)
$w < 0$ if $-\vec{V} \cdot \vec{\nabla}_p (\xi_g + f) < 0$ negative vorticity advection (NVA)

To generalize this concept to the southern hemisphere, PVA should be called cyclonic vorticity advection; NVA should be referred to as anticyclonic vorticity. The curvature of the advection of temperature on a constant pressure term can be represented as:

$$\nabla_p^2 [\vec{V} \cdot \vec{\nabla}_p T] \sim -k^2 B \sin kx$$

where  $B$  is a constant. Therefore,

$$\vec{V} \cdot \vec{\nabla}_p T \sim B \sin kx$$

Since:

$$w \sim \nabla_p^2 [\vec{V} \cdot \vec{\nabla}_p T]$$

then

$$w \sim -\vec{V} \cdot \vec{\nabla}_p T.$$

Thus,

$w > 0$ if $-\vec{V} \cdot \vec{\nabla}_p T > 0$ warm advection
$w < 0$ if $-\vec{V} \cdot \vec{\nabla}_p T < 0$ cold advection

The 700 mb surface is often used to evaluate the temperature advection patterns since the gradients of temperature are often larger at this height than higher up and the winds are significant in speed. The 850 mb height can be used (when the terrain is low enough) although the values of  $\vec{V}$  are often substantially smaller.

Finally, since  $\nabla_p^2 Q \sim -k^2 C \sin kx$  can be assumed in this form,  $w \sim -\nabla_p^2 Q$ , and  $Q \sim w$  results.

Therefore,

$w > 0$ diabatic heating
$w < 0$ diabatic cooling

An example of diabatic heating on the synoptic scale is deep cumulonimbus activity. An example of diabatic cooling is longwave radiative flux divergence.

In summary, the preceding analysis suggests the following relation between vertical motion, vorticity and temperature advection, and diabatic heating.

$$w > 0 \left\{ \begin{array}{l} \text{positive vorticity advection} \\ \text{warm advection} \\ \text{diabatic heating.} \end{array} \right. \qquad w < 0 \left\{ \begin{array}{l} \text{negative vorticity advection} \\ \text{cold advection} \\ \text{diabatic cooling.} \end{array} \right.$$

When combinations of terms exist which would separately result in different signs of the vertical motion (e.g., positive vorticity advection with cold advection), the resultant vertical



motion will depend on the relative magnitudes of the individual contributions. Also, remember that this relation for vertical motion is only accurate as long as the assumptions used to derive Eq. (3.37) are valid.

Using synoptic analyses the following rules of thumb usually apply:

- i) vorticity advection: evaluate at 500 mb.
- ii) temperature advection: evaluate at 700 mb; at elevations near sea level, also evaluate at 850 mb.
- iii) diabatic heating: contribution of major importance in synoptic weather patterns (particularly cyclogenesis) are areas of deep cumulonimbus. Refer to geostationary satellite imagery and radar for determination of locations of deep convection.

An article by Trenberth (1978) shows how the Omega equation, in a form close to that given by Eq. (3.37), can be rearranged in order to combine the vorticity and temperature advection terms. The reason to combine them is that the two terms can be opposite in sign with respect to their contribution to vertical velocity.

By rearranging the Omega equation, Trenberth shows that, as an approximation,

- upward motion occurs where there would be cyclonic vorticity advection by the thermal wind;
- descent occurs where there would be anticyclonic vorticity advection by the thermal wind.

Actual advection by the thermal wind, of course, does not occur since the thermal wind is a velocity vector difference and is not a true wind. Nonetheless, the combination of the vorticity advection and temperature advection terms in Eq. (3.37) permit an interpretation of vertical motion in the context of the advection of vorticity by a vertical shear of the horizontal geostrophic wind. This vertical shear, the thermal wind, is related to the thickness gradient as shown by Eq. (3.25).

### 3.8.4 Petterssen's Development Equation

Equation (3.27) can be written as:

$$\frac{\partial (\xi_z + f)}{\partial t} + \vec{V}_H \cdot \nabla_p (\xi_z + f) = 0 \quad (3.39a)$$

if vertical advection of absolute vorticity, the tilting term, and the solenoidal term are ignored, and Eq. (3.39a) is assumed valid at the level of nondivergence ( $\sim 500$  mb).  $\vec{V}_H$  is the wind on the pressure surface. Since, if the wind is in geostrophic balance:

$$\vec{V}_{H500} = \vec{V}_{H_{SFC}} + \Delta \vec{V}_g$$

where  $\Delta \vec{V}_g$  is the geostrophic wind shear (see Eq. 3.25). Thus,

$$(\xi_z + f)_{500} = (\xi_z + f)_{SFC} + (\xi_z + f)_T$$

since  $\nabla \times \vec{V}_{H500} = (\nabla \times \vec{V}_{HSFC}) + (\nabla \times \Delta \vec{V})$ . Equation (3.39a) can be written as:

$$\frac{\partial(\xi_z + f)_{SFC}}{\partial t} = -\vec{V}_{H500} \cdot \nabla_p(\xi_z + f)_{500} - \frac{\partial(\xi_z + f)_T}{\partial t} \quad (3.39b)$$

From Eq. (3.25),

$$\nabla \times \Delta \vec{V}_g = \frac{g}{f} \nabla_p^2 (\Delta z)$$

where  $\Delta z = z_{500} - z_G$  with  $z_{500}$  the 500 mb height and  $z_G$  the surface elevation so that,

$$\frac{\partial(\xi_z + f)_T}{\partial t} = \frac{g}{f} \nabla_p^2 \frac{\partial(\Delta z)}{\partial t} \quad (3.39c)$$

Integrating Eq. (3.36) between the surface pressure,  $p_{SFC}$ , and 500 mb yields, after rearranging:

$$-g \int_{p_{SFC}}^{500} \frac{\partial}{\partial t} \left( \frac{\partial z}{\partial p} \right) dp = -g \frac{\partial}{\partial t} \int_{z_G}^{z_{500}} dz = -g \frac{\partial(\Delta z)}{\partial t} = \int_{p_{SFC}}^{500 \text{mb}} \left( \vec{V} \cdot \nabla_p \left( g \frac{\partial z}{\partial p} \right) + \omega \sigma + \frac{R}{p C_p} Q \right) dp \quad (3.39d)$$

Performing  $\nabla_p^2$  on Eq. (3.39d), substituting into Eq. (3.39c) and then Eq. (3.39b) yields:

$$\frac{\partial(\xi_z + f)_{SFC}}{\partial t} = -\vec{V}_{H500} \cdot \nabla_p(\xi_z + f)_{500} + \frac{g}{f} \nabla_p^2 \int_{p_{SFC}}^{500} \vec{V}_H \cdot \nabla_p \left( \frac{\partial z}{\partial p} \right) dp + \frac{\nabla_p^2}{f} \int_{p_{SFC}}^{500} \omega \sigma dp + \frac{R \nabla_p^2}{f C_p} \int_{p_{SFC}}^{500} \frac{Q}{p} dp \quad (3.39e)$$

This is the Petterssen development equation for the change of surface absolute vorticity due to:

- $-\vec{V}_{H500} \cdot \nabla_p(\xi_z + f)_{500}$  : horizontal vorticity advection at 500 mb.
- $\frac{g}{f} \nabla_p^2 \cdot \int_{p_{SFC}}^{500} \vec{V}_H \cdot \nabla_p \left( \frac{\partial z}{\partial p} \right) dp = -\frac{R}{f} \nabla_p^2 \int_{p_{SFC}}^{500} \frac{\vec{V}_H \cdot \nabla_p}{p} (T) dp$  : proportional to a pressure-weighted horizontal temperature advection between the surface and 500 mb.
- $\frac{\nabla_p^2}{f} \int_{p_{SFC}}^{500 \text{mb}} \sigma \omega dp$  : proportional to vertical motion through the layer.
- $\frac{R \nabla_p^2}{f C_p} \int_{p_{SFC}} \frac{Q}{p} dp$  : proportional to a pressure-weighted diabatic heating pattern.

### 3.8.5 Upper-Level Flow Associated with Extratropical Storm Development

Throughout the troposphere, an extratropical cyclone is characterized by the following during its development stage:

- surface pressure falls,
- ageostrophic<sup>8</sup> wind convergence acceleration (i.e., isallobaric wind) toward the developing low pressure system, thereby generating kinetic energy,
- convergence generates cyclonic vorticity at low levels,
- midlevel ascent and associated cloudiness as a result of the convergence, and
- upper-level divergent geostrophic winds which generate anticyclonic relative vorticity, which builds the upper-level ridge downstream.

Figure 3.20 schematically illustrates the relation between 500 mb and 700 mb flows, the thickness gradient, and the surface front. Note that there are warm advection and positive vorticity advection ahead of the upper-level trough. In terms of estimating vorticity advection, the 500 mb flow is generally used as discussed in Section 3.8.3. Thickness advection is usually evaluated at 700 mb, although in areas near sea level the 850 mb flow is also used. Since surface pressure is falling, the divergence aloft must be removing mass more rapidly than it can be replaced by convergent inflow at low levels. This characteristic of developing low pressure systems implies that they are forced by upper tropospheric airflow patterns. The surface pressure field, to a first approximation at least, is a response to this upper-level forcing.

As an extratropical cyclone evolves into Stage II, the cold and warm advection patterns become very well defined. It is the juxtaposition of this temperature advection pattern that provides the energy associated with the increase in circulation (i.e., vorticity) of the cyclone. Warm air lifted over the cold air of the warm front results in higher heights aloft which results in a divergent component of the flow at that altitude ahead of the cyclone in the upper troposphere. This loss of mass aloft permits the surface cyclone to deepen further, thereby strengthening the warm advection further. To the rear of the surface cyclone, the cold advection and sinking as the air moves equatorward more rapidly than the thickness gradient propagates, generates convergence aloft and a subsequent building of the high pressure in the low troposphere. The higher pressure provides stronger cold advection. The lower heights tilt towards the cold air with decreasing pressure – a direct result of the thickness relation.

As the cyclone occludes in Stage III, the lower heights at all levels within the troposphere tend to become coincident, resulting in little or no temperature or vorticity advection. Near the triple point, however, where the fronts juncture, significant temperature and vorticity advection often remain such that this is a favorable area for secondary cyclogenesis.

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<sup>8</sup>The term used to refer to flow which is not in gradient balance is *ageostrophic*. This terminology is, of course, misleading since gradient winds and geostrophic winds, in general, are not equal. A more accurate term could be a gradient flow.

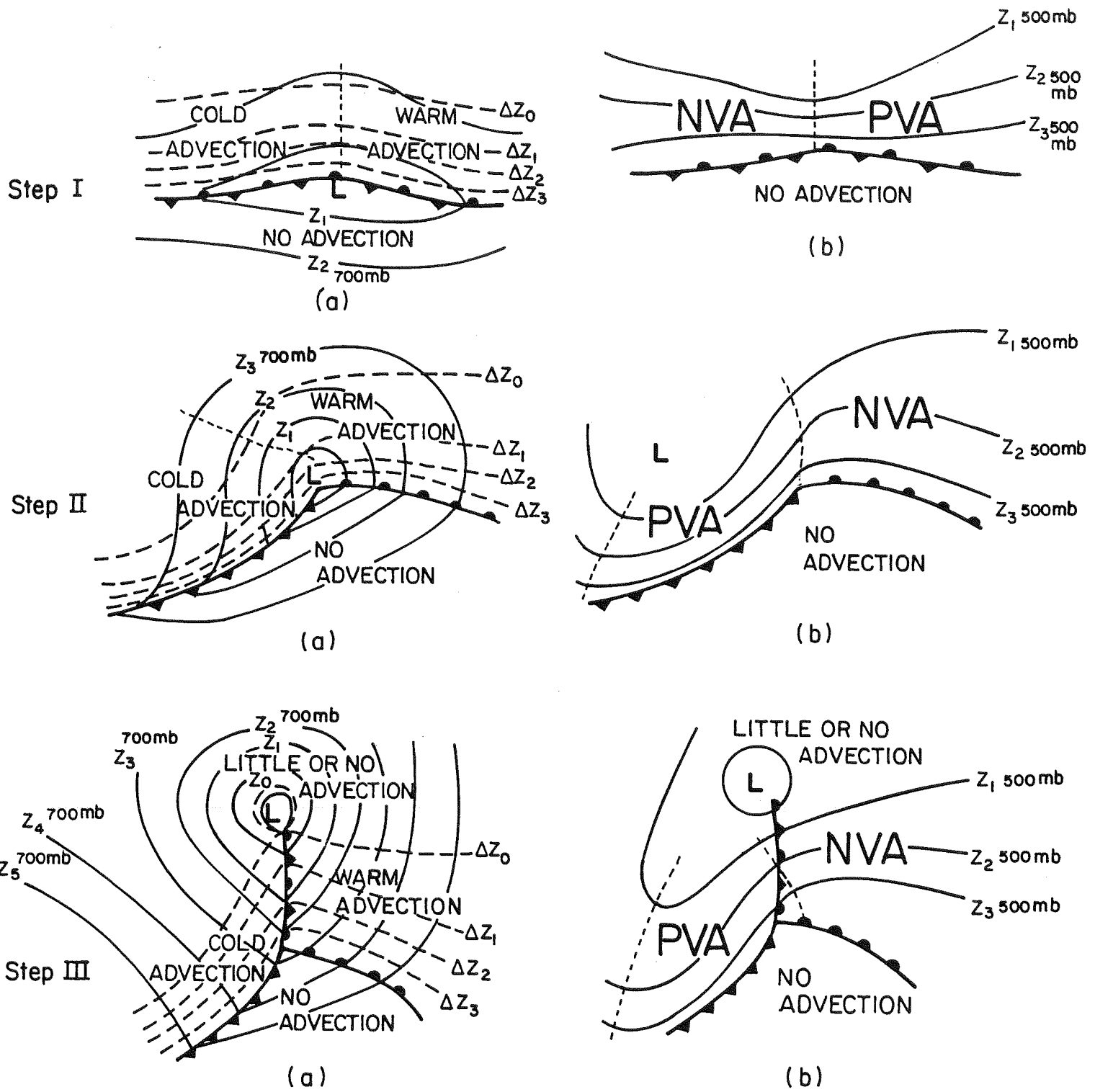


Figure 3.20: Schematic illustration of thickness advection and vorticity advection associated with extratropical cyclone development. The 700 mb height contours (solid lines), 1000-500 mb thickness contours (dashed lines), and surface frontal location are given in (a). The 500 mb height contours (solid lines) and surface frontal location are shown in (b).

Within the cyclone the strongest vertical motion within the low- and midtroposphere usually occurs when there is warm advection and positive vorticity advection combined. As seen in the schematic, for example, in Stage II the largest ascent (and likely greatest rate of stratiform precipitation) would be to the north and northwest of the cyclone center at 700 mb. Actual cyclones, of course, can have different advection patterns.

Subsiding air would occur in the mid and lower troposphere where they are both cold and have negative vorticity advection. The subsidence associated with the negative vorticity advection can often negate the de-stabilization that occurs because of the cold advection. A frequent satellite and surface observation is that the division between NVA and PVA in the area of cold advection is often denoted by a significant break in cloud type – towering cumulus and showers often occur in the air with PVA; the cumulus clouds, however, are frequently flattened at the top when NVA develops.

A summary of the conditions associated with the development of extratropical storms is presented below.

- Favorable conditions

- the existence of a thickness gradient in the lower troposphere (i.e., a front); particularly when it is anticyclonically curved;
- the presence of an upper-level trough with cold advection to its rear and warm advection ahead; and
- release of latent heat near the center of the surface low by deep cumulonimbus and stratiform precipitation.

- Unfavorable conditions

- a weakening thickness gradient as a result of low-level divergent flow; and
- the absence of an upper-level trough or a trough with cold advection ahead of it, and warm advection behind resulting in a trough which will decrease in intensity with time.

Extratropical cyclones are different from hurricanes and tropical storms because their energy is primarily from the juxtaposition of cold and warm air masses (i.e., a horizontal thickness gradient). Tropical cyclones, in contrast, derive their energy through heating around the central core as a result of deep cumulonimbus. In addition, the wind field of extratropical cyclones, although spread over a large area, has weaker maximum speeds since the pressure gradient is not as strong as found in a mature, well-developed hurricane. Oceanic extratropical cyclones are less of a danger to shipping than hurricanes because the seas are not as chaotic since the wind direction does not vary through 360° around a small center as it does for the tropical system.

### 3.8.6 Synoptic Momentum Transport Patterns

The north-south transport of planetary and air flow momentum on opposite sides of a trof will influence the subsequent evolution of the trof. As illustrated in Fig. 3.21, a positively tilted trof exports this momentum such that unless cold advection can maintain the region of low height, the trof will weaken.

### 3.8.7 Baroclinic Instability

A lucid and concise discussion of baroclinic instability is presented in Holton (1972, pp. 186-195). A *baroclinic* flow is defined as one in which a thickness gradient exists – the larger the gradient, the greater the baroclinicity. *Baroclinic instability* occurs when a small disturbance formed in a region of thickness gradient will grow exponentially.

From Holton (1972, pg. 191), a solution of baroclinic instability for a two-layer model is presented in Fig. 3.22. Holton's analysis suggests that the region of maximum instability corresponds to a horizontal wavelength of about 4000 km. This scale closely corresponds to the size of extratropical cyclones. It has been concluded for years that baroclinic instability is the primary mechanism for extratropical cyclone development. The analysis of Holton also concludes that the critical wavelength for baroclinic instability increases with static stability.

## 3.9 Miscellaneous Characteristics of Airflow

### 3.9.1 Post-Cold Frontal Cloudiness

From Holton (1972, pg. 69), the conservation of potential vorticity can be written as:

$$\frac{d}{dt} \left[ (\xi_z + f) \frac{\partial \theta}{\partial p} \right] = 0 \quad (3.40)$$

Since,

$$\frac{df}{dt} = v \frac{\partial f}{\partial y} = v\beta,$$

with southward-moving air, as with a cold arctic outbreak in the northern hemisphere:

$$v < 0 ; \beta v < 0$$

and

$$\begin{aligned} \frac{d\xi_z}{dt} &< 0 \text{ for anticyclonic curvature to the air parcel trajectories} \\ \frac{d\xi_z}{dt} &> 0 \text{ for cyclonic curvature to the air parcel trajectories.} \end{aligned}$$

Two cases can be examined with  $\beta v < 0$ . In both cases the flow will be assumed to be in the lower troposphere.

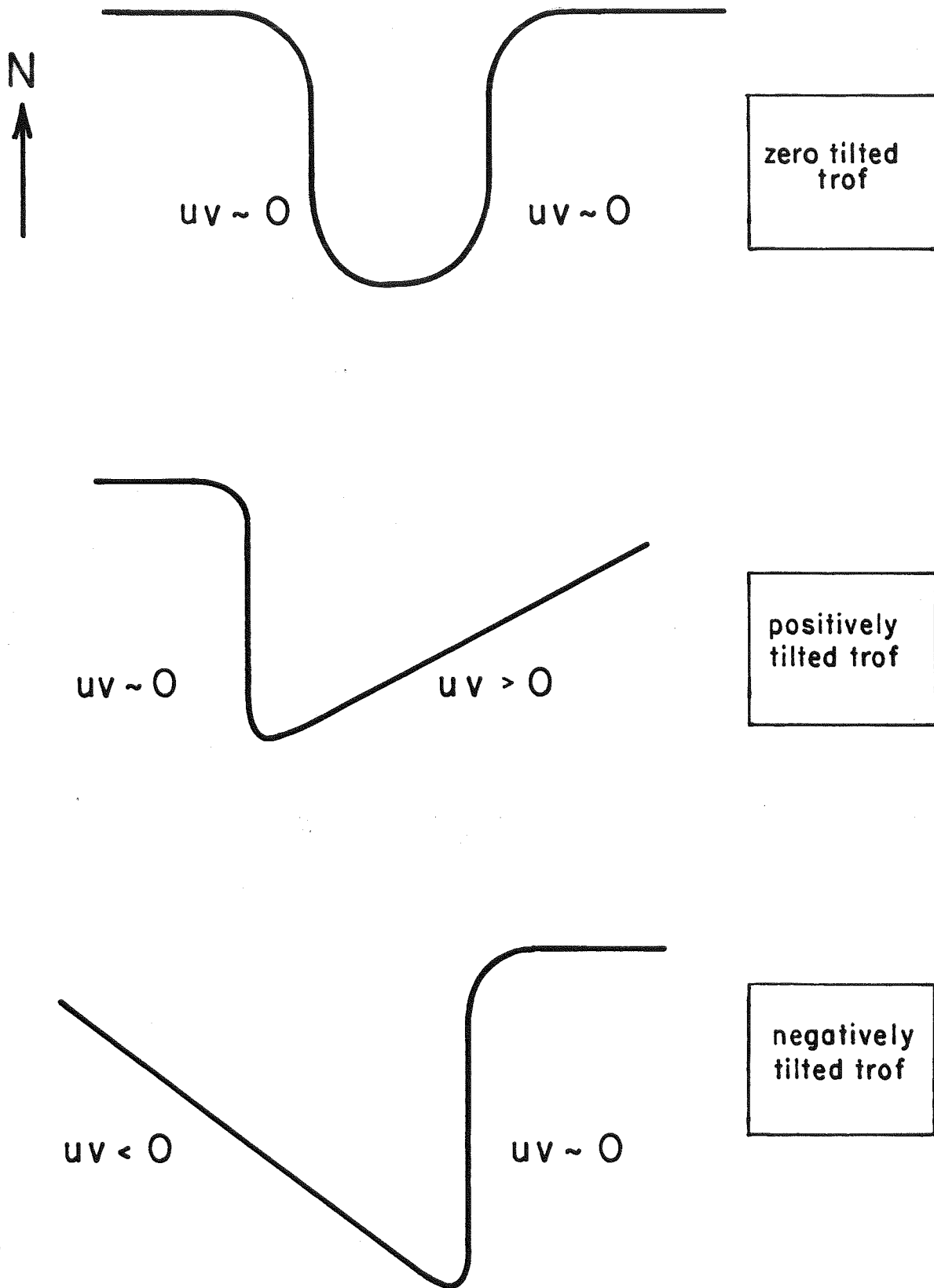


Figure 3.21: Influence of trof structure on its evolution over time.

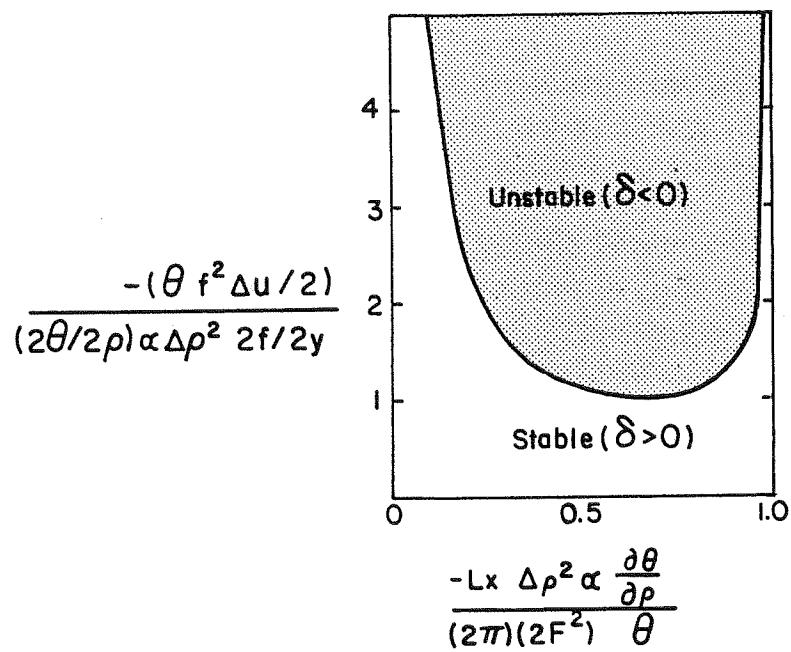


Figure 3.22: Neutral stability curve as obtained from Holton's (1972) two-level baroclinic model. Crosshatched area represents a baroclinically unstable region.



- a) For  $\frac{d\xi_z}{dt} < 0$ ,  $\frac{d}{dt} \left( \frac{\partial\theta}{\partial p} \right) > 0$  in order to maintain  $(\xi_z + f) (\partial\theta/\partial p)$  as a constant.  $d(\partial\theta/\partial p)/dt > 0$  indicates that surfaces of constant  $\theta$  are being brought closer together. Since  $w = 0$  at the ground surface, this requirement on  $\partial\theta/\partial p$  implies sinking motion.

Stratocumulus clouds, if any, that form in this environment as a result of the destabilizing effect of cold advection, tend to be flattened at the top as a result of the sinking air. This subsidence also exerts a warming component on the atmosphere by compression, thereby counteracting to some extent the cold advection.

- b) for  $\frac{d\xi_z}{dt} > 0$  there exists a region where,

$$\left| \frac{d\xi_z}{dt} \right| > |\beta v|$$

so that  $d(\xi_z + f)/dt$  is increasing. Therefore,  $\frac{\partial\theta}{\partial p}$  must decrease following a parcel. With  $w = 0$  at the ground surface, the spreading of potential temperature surfaces with respect to pressure require that ascent occur.

In this region the destabilizing effect of cold advection and the ascent required by the conversion of potential vorticity provide an ambient atmosphere conducive to towering cumulus and showers. The demarcation between the regions where  $|d\xi_z/dt|$  is greater than and less than  $|\beta v|$  is often characterized by a sharp break in cloud type visible from both satellite and from the ground. Deep cumulus extend from this demarcation toward the surface low center, while flattened cumulus or clear skies occur in the opposite direction. Figure 3.23 schematically illustrates this characteristic of the flow and associated clouds.

### 3.9.2 Troughing East of Mountains

It is observed on surface weather maps that troughs tend to form downwind of large-scale elongated mountain barriers when a substantial wind blows over the barrier. Such troughs, referred to as *lee-side troughs*, can be explained in terms of the conservation of potential vorticity.

As illustrated in Fig. 3.24a for the northern hemisphere, since vertical motion is inhibited by the stable stratification above the tropopause as it crosses the barrier,  $\partial\theta/\partial p$  must become larger using Eq. (3.40), resulting in a reduction of relative vorticity (i.e.,  $d\xi_z/dt < 0$ ). If the initial flow is straight and without horizontal shear,  $\xi_z$  therefore becomes anticyclonic and the parcel motion is as depicted in Fig. 3.24b<sup>9</sup>. The turn to anticyclonic flow occurs as soon as the ground begins to elevate.

Upon reaching the lee slope, the parcel direction is from the northwest and moves to the south of its original latitude. When reaching its original latitude at the edge of the lee slope,  $\xi_z$ , and therefore  $\partial\theta/\partial p$  return to their original values. Moving further south, however,  $f$

<sup>9</sup>If the flow were not uniform in the direction perpendicular to the barrier, the parcel could have attained anticyclonic shear vorticity instead of just anticyclonic curvature vorticity.

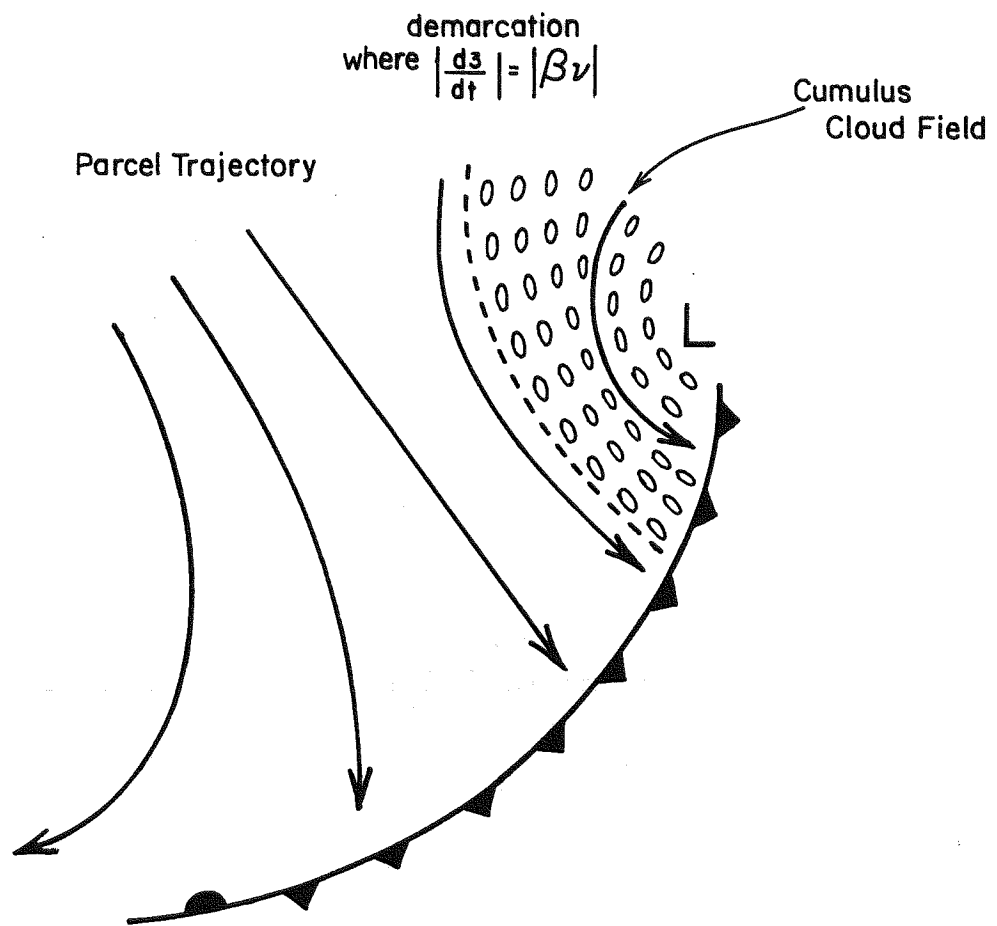


Figure 3.23: Schematic of the relation between parcel trajectory and the cloud field behind a cold front.

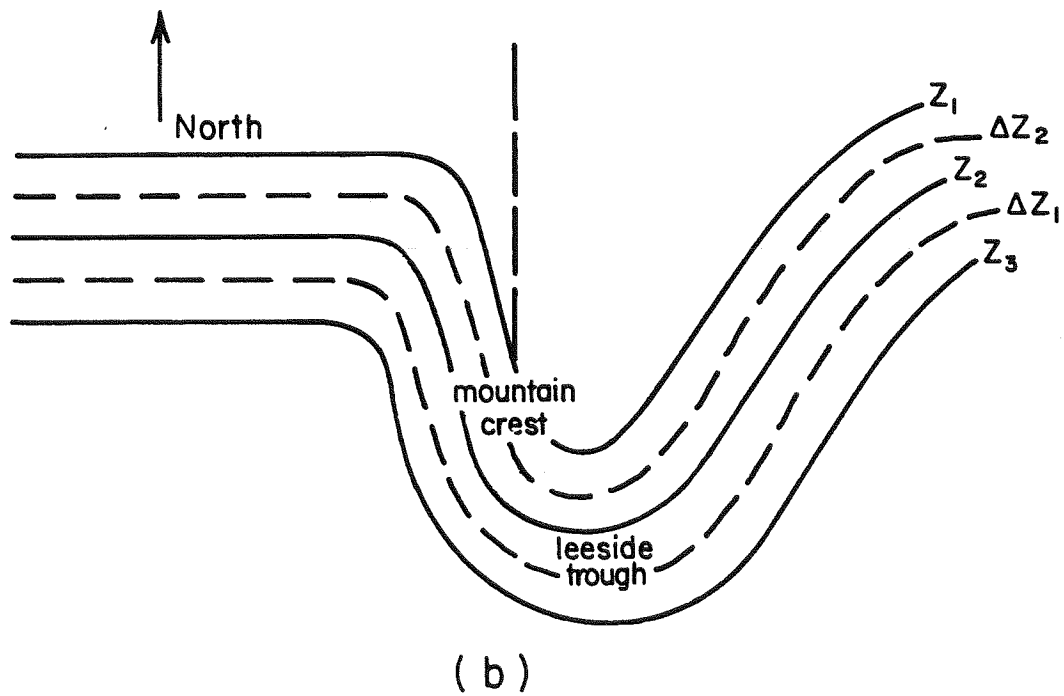
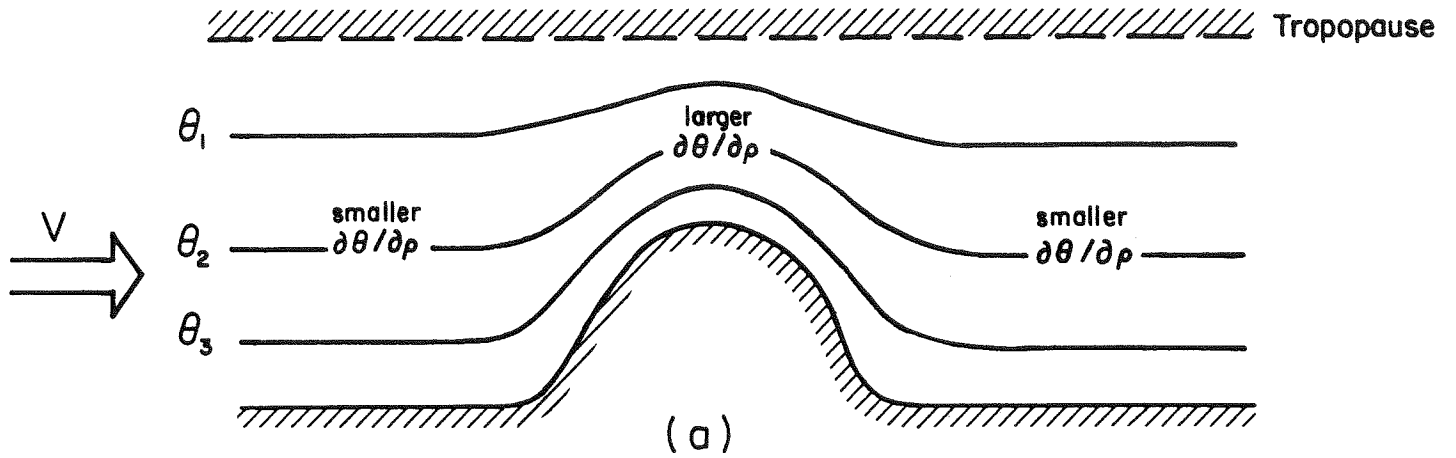


Figure 3.24: (a)  $x-z$ , and (b)  $x-y$  cross section of particle trajectories across a large-scale elongated ridge. Stratification, height, and thickness are drawn and steady-state flow is assumed.

decreases so  $\xi_z$  becomes cyclonic, eventually attaining enough curvature so that the parcel turns northward.

In the absence of friction, a series of troughs and ridges would extend downstream from the barrier indefinitely.

In the real world, the tendency for lee side troughing provides a thickness gradient (due to the resultant displacement of temperature contours by advection) which is conducive to cyclogenesis, as illustrated in Fig. 3.24b.

The path of a parcel crossing the ridge can be discussed using the conservation of potential vorticity, i.e.,

$$\frac{\partial\theta}{\partial p}(\xi_z + f) = \text{constant.}$$

If we assume all of the relative vorticity is due to curvature of the flow then:

$$\xi_z = V/R_T$$

where  $R_T$  is the radius of the air parcel trajectory and  $V$  is the wind speed. If a subscript "1" denotes the upstream value and "2" indicates its modification by the ridge then for east-west flow:

$$(\xi_1 + f) \left. \frac{\partial\theta}{\partial p} \right|_1 = (\xi_2 + f) \left. \frac{\partial\theta}{\partial p} \right|_2 \quad (3.41)$$

For nonsheared upstream flow  $\xi_1 = 0$ . As the airflow becomes more stratified, as it passes over the ridge,  $\left. \frac{\partial\theta}{\partial p} \right|_2$  can be written as:

$$\left. \frac{\partial\theta}{\partial p} \right|_2 = \alpha \left. \frac{\partial\theta}{\partial p} \right|_1 \quad \alpha > 1$$

Using these definitions Eq. (3.41) can be written, after rearranging as:

$$\xi_2 = \frac{V}{R_T} = \frac{f(1 - \alpha)}{\alpha}$$

which can be rearranged to solve for  $R_T$  yielding:

$$R_T = \frac{\alpha}{(1 - \alpha)f} V$$

Since  $\alpha > 1$  and  $V > 0$ ,  $R_T < 0$  which requires that the flow be anticyclonic upon rising over the ridge.

As an example let  $\alpha = 2$  and  $f = 10^{-4}\text{s}^{-1}$ ; thus,

$$R_T = -2 \times 10^4 V \left( -2 \times 10^4 \text{ has units of seconds} \right)$$

For  $V = 10 \text{ m s}^{-1}$ ,  $50 \text{ m s}^{-1}$ , and  $100 \text{ m s}^{-1}$ ,  $R_T = -200 \text{ km}$ ,  $-1000 \text{ km}$ , and  $-2000 \text{ km}$ , respectively. For the light wind, it appears that the flow would not even be able to cross the ridge if it was greater than 200 km to the crest! For real-world situations, of course,  $V$  and  $\left. \frac{\partial\theta}{\partial p} \right|_1$  would change and must permit the air to eventually cross the crest, otherwise mass would build-up indefinitely on the upwind side.

### 3.9.3 Conversion of Cold Fronts into Shear Lines

As a cold front moves over a warmer surface, thickness warming can occur from below. Such warming is particularly pronounced when cold air moves over warmer water with its large thermal inertia. Over land, surface cooling after cold frontal passage can diminish the rate of thickness modification.

After the thickness gradient is removed, however, the low-level wind convergence can remain particularly if deep cumulus convection resulting from the low-level convergence reinforces the convergence. This conversion of a front into a convergence zone frequently occurs in the winter in the tropics where the conditionally unstable lower tropospheric air provides the buoyant energy for cumulus convection, and the rate of conversion of the low-level wind to gradient balance is slow as a result of the low latitude.

Figure 3.25 illustrates schematically the conversion of a cold front to a convergence zone. Since the winds are opposing in direction across the zone, this region is also called a *shear line*.

A satellite visualization of this conversion process is shown in Anderson et al. (1974, pg. 3-B-3).

### 3.9.4 Backdoor Cold Fronts

If cold air masses are stably stratified, their forward motion will be impeded by mountain barriers unless they have sufficient kinetic energy to go over the barrier. If the flow is *blocked*, however, the airflow will decrease in speed and move towards lower pressure. This can occur even when the airflow above the cold air moves in the opposite direction. Substantial warm advection can occur above the cold air mass so that the atmosphere becomes even more stable.

A measure as to whether blocking will occur is the Froude number (e.g., see Pielke 1984, pg. 474). Defined as:

$$Fr = \bar{V} / \left[ z_{Gmax} \left( \frac{g}{\theta} \frac{\partial \theta}{\partial z} \right)^{1/2} \right],$$

flows tend to become blocked when  $Fr < 0.75$  to 1.5 or so. Greater stratification (i.e., large  $\partial \theta / \partial z$ ), higher terrain (i.e.,  $z_{Gmax}$ ), and lighter winds (i.e.,  $\bar{V}$ ) are associated with blocking.

This blocking is a common occurrence east of the Appalachians and Rocky Mountains particularly in the cooler seasons. In the case of the Appalachians, such blocking of the westward movement of a cold air mass and resultant southward flow is called a *backdoor cold front*. It is referred to as backdoor because it comes from an unusual direction (i.e., from the northeast or north) and is associated with a synoptic extratropical cyclone pattern which would suggest warm advection.

Figure 3.26 schematically illustrates the development and movement of a backdoor cold front due to the presence of a mountain barrier. Since the cold air frequently undercuts a region of ascending warm advection aloft which has a layer of above freezing temperatures, precipitation often falls as sleet or freezing rain after passing through below 0°C air near the

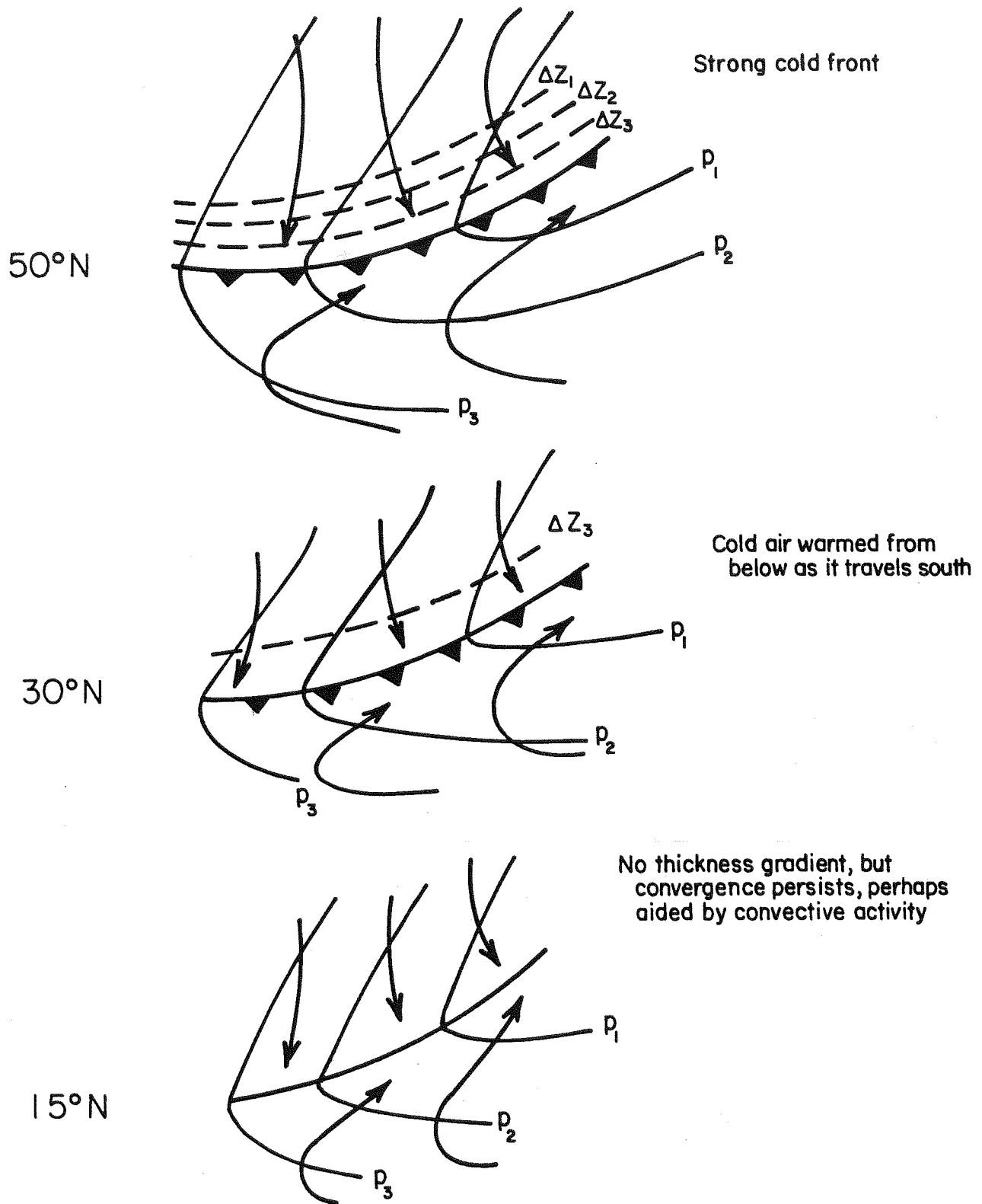


Figure 3.25: Schematic of the conversion of a cold front to a shear line as a front moves equatorward. Parcel trajectories are indicated by arrows.

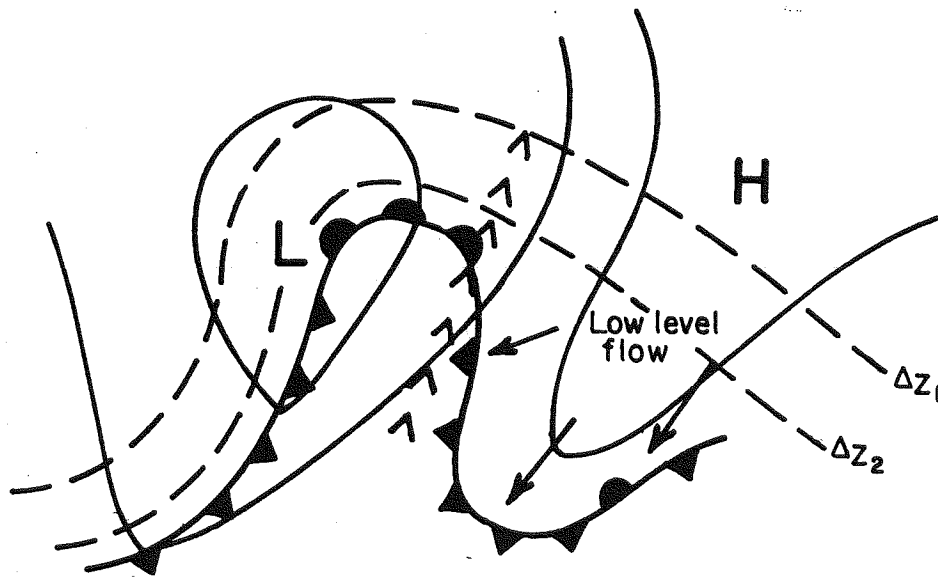
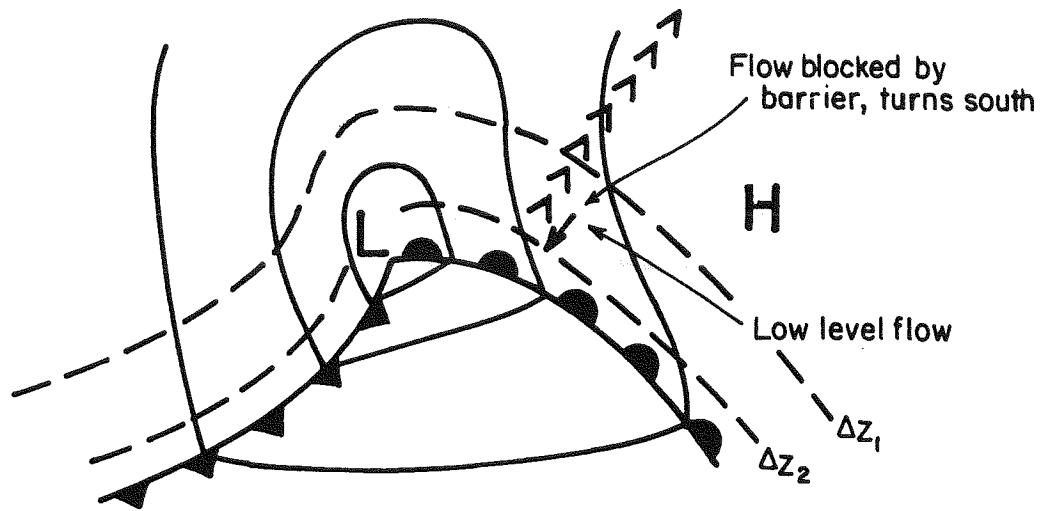


Figure 3.26: Generation of a backdoor cold front as a result of blocking. 1000-500 mb thickness,  $\nabla z$ , continue to move northward since most of the flow in the 1000-500 mb layer is above the cold domes.

surface. Fog and low visibilities are also often associated with the cold, stable, near surface air mass which is capped by warm air aloft.

Anderson et al. (1974, pp. 3-B-15 to 3-B-18) illustrate the cloud pattern associated with a backdoor cold front.

### 3.9.5 Depiction of Fronts in the Southern Hemisphere

While the dynamics of meteorological flows must be identical in the southern hemisphere, their visualization is different since  $f < 0$  south of the equator. One can look at a mirror image turned upside down of a northern hemisphere weather map to see how the identical features would appear in a southern hemisphere representation. Alternatively, turn a northern hemisphere analysis over, invert it, and look at it through a light table.

Figure 3.27 illustrates the form that the same extratropical cyclone would have in both hemispheres.

In the context of geostrophic and gradient balance, winds in the southern hemisphere blow clockwise around cyclones, counterclockwise around anticyclones. Cold advection is associated with veering winds, warm advection with backing winds in the southern mid and high latitudes.

### 3.9.6 Circulation Around an Anticyclone

Equation (3.40) can be used to describe expected vertical motion around a large lower tropospheric anticyclone. As illustrated in Fig. 3.28, equatorward moving air east of the high pressure region requires  $\beta v < 0$ . Thus, if the anticyclone is circular such that  $d\xi_z/dt = 0$ ,  $d(\partial\theta/\partial p)/dt > 0$  results. In contrast, west of the anticyclone,  $\beta v > 0$ , so that  $d(\partial\theta/\partial p)/dt < 0$  results in ascent west of the high.

Therefore, one should expect general subsidence east of a symmetric ridge and ascent on the west side. Precipitation would be expected to be more likely on the west.

In the subtropics, subtropical anticyclones are often configured as more-or-less symmetric high pressure regions. These synoptic realizations of the Hadley cell develop in this form over the ocean areas, as a result of lower pressure caused by surface heating over the land surfaces. The eastern subtropical oceans are characterized by net subsidence and low boundary layer inversions which, to a large extent, can be related to the requirement for a conservation of potential vorticity. In the western subtropical oceanic areas, average ascent tends to eliminate the inversion and to provide an atmosphere which is more conducive to precipitation.

### 3.9.7 Upper-Level Fronts

Figure 3.29 illustrates the influence of horizontal convergence in the upper troposphere on the generation of an upper-level strong air flow. Referred to as the *subtropical jet*, the convergence at these heights is a direct result of poleward moving air associated with the Hadley cell which is the prime planetary circulation associated with poleward transport of warm air from equatorial regions. Palmén and Newton (1969, pp. 112-113) discuss this



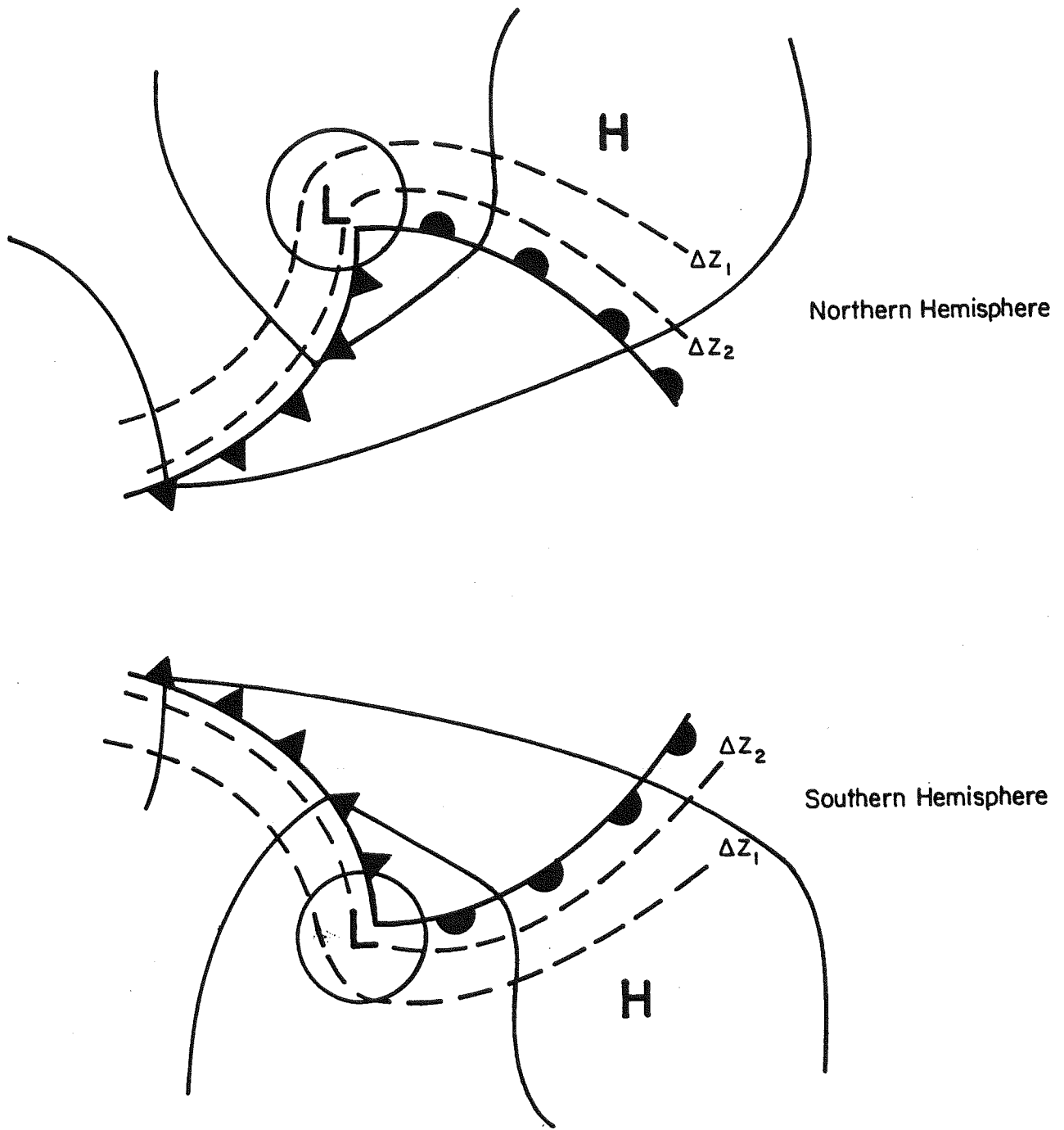


Figure 3.27: Representation of the same extratropical cyclone as would appear in northern and southern hemispheric analyses.

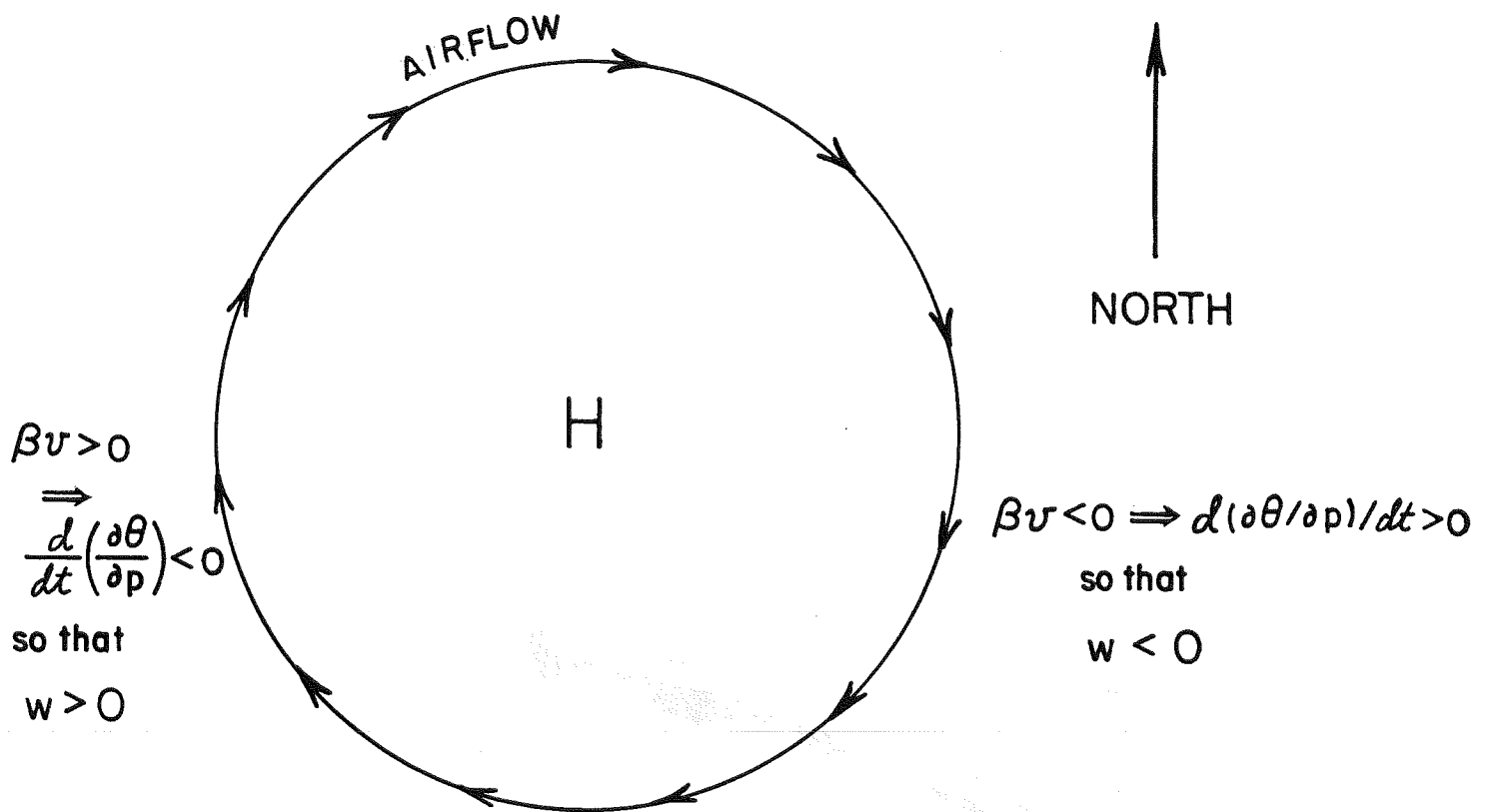


Figure 3.28: Schematic flow around an anticyclone in which  $\frac{d\xi}{dt} = 0$ .

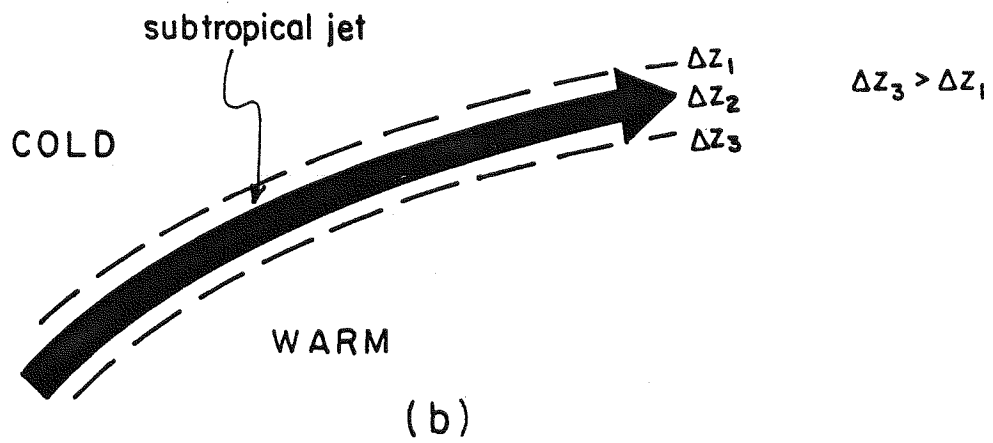
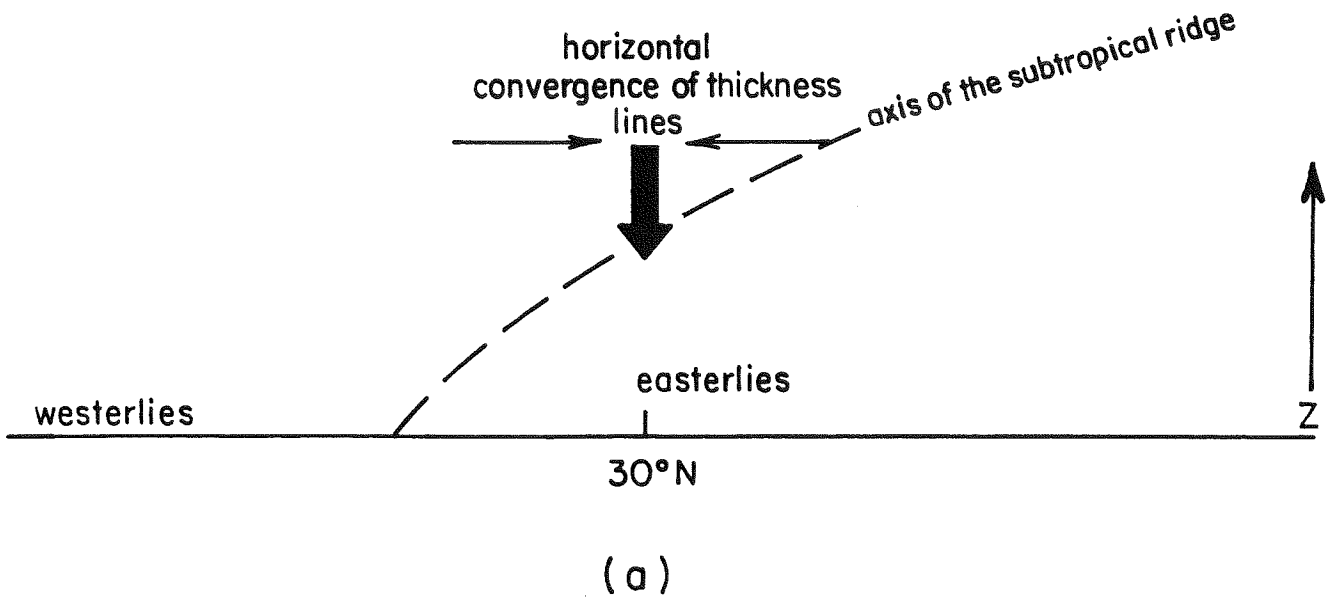


Figure 3.29: Illustration of the mechanisms of generation of the subtropical jet for (a) a vertical cross section, and (b) a horizontal cross section.

jet in more detail. Since the horizontal gradient of thickness only occurs in the layers where the horizontal convergence occurs, the subtropical jet is an upper tropospheric feature exclusively. It directly influences low-level flows only when it becomes coupled through deep cumulus convection and/or interactions with the polar jet. Since cold air is on the poleward side of the gradient, the jet is westerly, as explained by the thermal wind relation (i.e., see Fig. 3.12).

### 3.9.8 Orientation of Cumulus Convection with Respect to the Wind Shear

The patterning of shallow to moderate depth cumulus, as viewed from satellite imagery, can often be used to estimate the wind shear, and therefore, the thickness gradient through the layer of the cloud. Two schematic illustrations of cloud patterning associated with cold and warm advection are shown in Fig. 3.30.

Shallow and moderate depth cumulus clouds are oriented in the direction of the shear because at low levels they tend to move in the direction of the wind at that level. As they develop vertically, to the extent that ambient air is entrained within the cumulus clouds, the movement tends to be in the direction of the wind at that level. The appearance of the clouds as viewed from aloft is in the direction of the shear because of the turning of the cloud with height. With cold advection, cumulus clouds back with height (Fig. 3.29a), while cumulus clouds tend to veer with height under warm advection (Fig. 3.29b).

### 3.9.9 Inertial Instability

Equation (3.7) can be written as:

$$\begin{aligned}\frac{\partial u}{\partial t} &= fv - v \frac{\partial u}{\partial y} = v \left( f - \frac{\partial u}{\partial y} \right) \\ \frac{\partial v}{\partial t} &= -fu\end{aligned}\tag{3.42}$$

if variations in  $x$  and  $z$  are ignored, and the pressure gradient and frictional forces are neglected. The top equation in Eq. (3.42) can be rewritten as:

$$\begin{aligned}f \frac{\partial u}{\partial t} &= fv \left( f - \frac{\partial u}{\partial y} \right) \\ \text{or } \frac{\partial^2 v}{\partial t^2} + fv \left( f - \frac{\partial u}{\partial y} \right) &= 0 \\ \text{since } -f \frac{\partial u}{\partial t} &= \frac{\partial}{\partial t} (fu) = \frac{\partial^2 v}{\partial t^2}.\end{aligned}\tag{3.43}$$

For a fixed value of  $\frac{\partial u}{\partial y}$ , Eq. (3.43) can be treated as an ordinary differential equation of the form:

$$\left[ \frac{d^2}{dt^2} + f \left( f - \frac{\partial u}{\partial y} \right) \right] v = 0$$

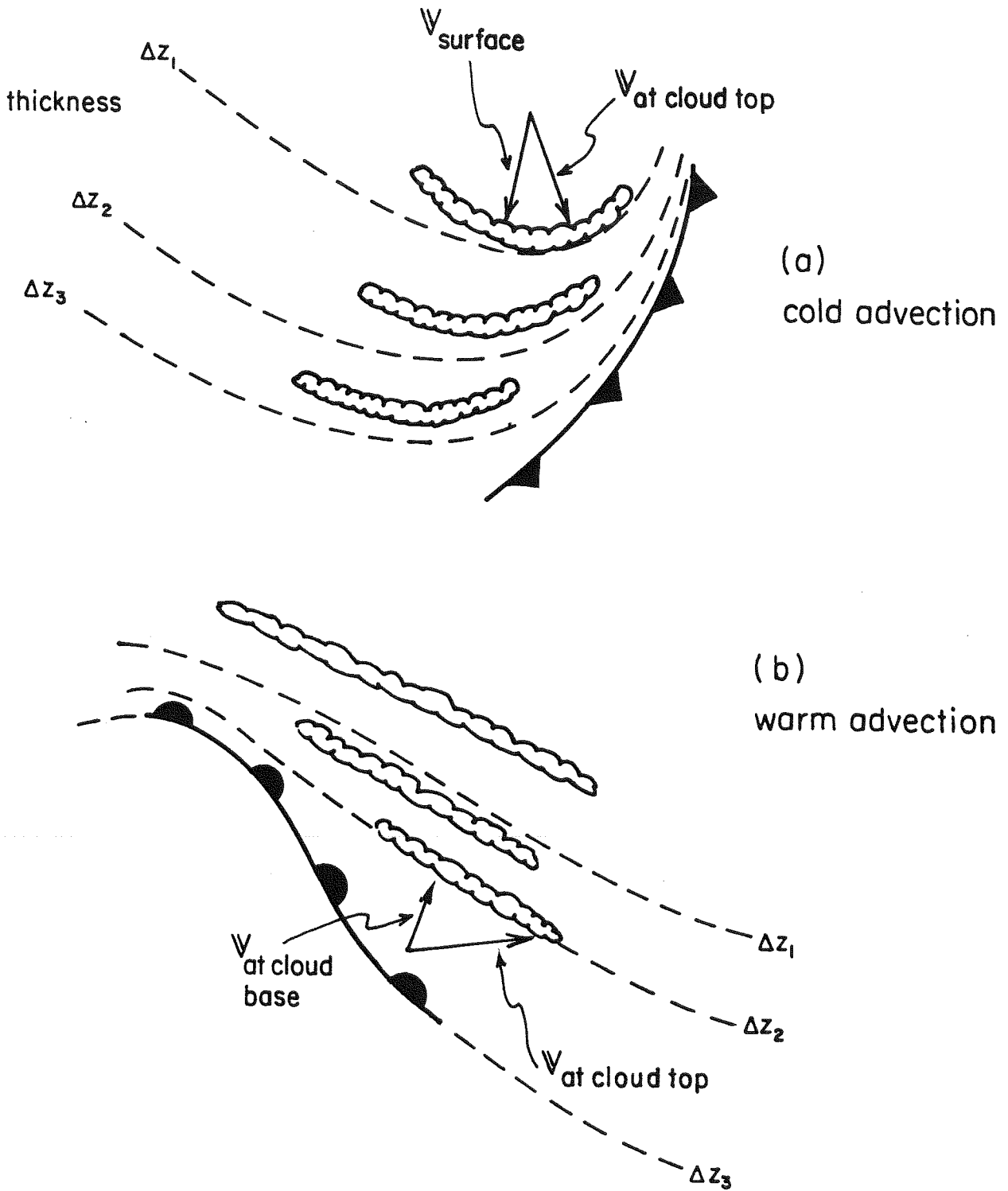


Figure 3.30: Schematic illustration of the relation between cumulus cloud orientation, wind shear, and thickness for (a) cold advection, and (b) warm advection.

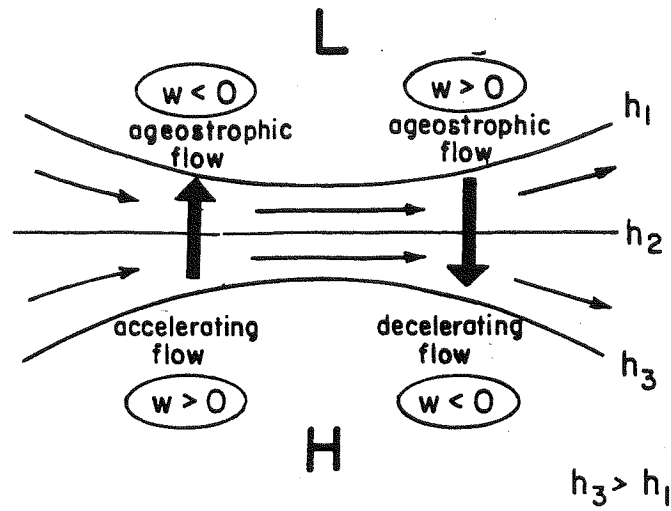


Figure 3.31: An idealized jet streak with associated vertical motion pattern.

which has a periodic solution if  $f > \partial u / \partial y$ , but an exponential solution if  $f < \frac{\partial u}{\partial y}$  (Spregil 1967, Chapter 4).

In the synoptic atmosphere, values of  $\partial u / \partial y$  are largest south of the polar jet (i.e., anticyclone shear); hence, this region would correspond to a location where we would expect preferred amplification of waves along the jet due to this mechanism of *inertial instability*.

### 3.9.10 Jet Streaks

Jet streaks represent localized regions of stronger winds embedded within the jet stream. The jet stream itself results from the horizontal gradient of thickness, as discussed in Section 3.6 (i.e., see Equation 3.25). Jet streaks on the synoptic scale would, therefore, be expected to be associated with locations of particularly strong horizontal temperature gradients.

Figure 3.31 illustrates an idealized jet streak, and the associated vertical motion pattern, as the wind flow geostrophically adjusts to the different horizontal height field. In the entrance region of the jet streak, the ageostrophic flow is towards lower heights as the air accelerates, but requires a period of time to come into balance with the tighter horizontal gradient of height. In this portion of the jet streak, the actual wind speed is less than the gradient wind. The result is descent in the troposphere on the lower height side of the jet with ascent on the higher height side of the jet. In the exit region of the jet, the opposite pattern occurs as the flow decelerates in response to the weaker horizontal gradient of the

height field, but requires time to again achieve gradient balance. In this region, the actual wind speed is greater than the gradient wind.

This pattern of ascent and descent would occur on the synoptic scale in the absence of tropospheric temperature advection. Carlson (1991) discusses jet dynamics in detail, including how temperature advection modifies the upward/downward motion couplet shown in Fig. 3.31. Uccellini et al. (1987) describes how jet streaks are intimately involved in cyclogenesis along the east coast of the United States.

## 4. Thermodynamic Analyses

### 4.1 Basic Concepts

#### 4.1.1 Dry Adiabatic Lapse Rate

If no heat is added to or removed from a parcel, the potential temperature must be constant as shown in Section 2 and elsewhere (e.g., Pielke 1984, Chapter 2). Therefore, for this situation,

$$\frac{d\theta}{dz} = 0 \quad (4.1)$$

is a statement that there is no heat changes for a vertically displaced parcel. From the definition<sup>10</sup> of  $\theta$  [ $\theta = T (1000 \text{ mb}/p)^{R_d/C_p}$ ], therefore, after differentiating logarithmically with height:

$$\frac{1}{\theta} \frac{d\theta}{dz} = 0 = \frac{1}{T} \frac{dT}{dz} - \frac{R_d}{C_p p} \frac{dp}{dz} \quad (4.2)$$

is an equivalent statement of Eq. (4.1). Assuming hydrostatic balance (i.e.,  $dp/dz = -\rho g$ ), Eq. (4.2) after rearranging, becomes:

$$\frac{dT}{dz} = \frac{-R_d T \rho}{p} \frac{g}{C_p} = -\frac{g}{C_p} = -\gamma_d \quad (4.3)$$

where the ideal gas law ( $p = \rho RT$ ) has been applied. For the earth's troposphere  $g/C_p \cong 1^\circ\text{C}/100 \text{ m}$ . The variable  $\gamma_d$  is referred to as the *adiabatic lapse rate*.

On a thermodynamic diagram, lines of constant  $\theta$  correspond to a temperature lapse rate equal to  $-1^\circ\text{C}/100 \text{ m}$ .

#### 4.1.2 Wet Adiabatic Lapse Rate

When a parcel is lifted, temperature decreases as evident from Eq. (4.3). Since air cannot hold as much water vapor at colder temperatures, (e.g., see Wallace and Hobbs 1977, pg. 73) sufficient lifting will result in condensation (deposition) when the vapor pressure of the water vapor,  $e$ , becomes equal to the saturation vapor pressure,  $e_s$ , with respect to water (e.g., ice). Since  $e/e_s = 1$  corresponds to  $w/w_s = 1$ , where  $w$  is the mixing ratio defined in Section 2, the height where  $w = w_s$  is first calculated on a thermodynamic diagram is referred to as the *lifting condensation level* (LCL).

The value of  $w$  for the parcel is determined by measuring the *dewpoint temperature*. The dewpoint temperature is defined as the temperature at which condensation first occurs as a result of cooling *at constant pressure*. An analogous temperature (*the frost point*) is defined for the first occurrence of deposition due to cooling at constant temperature.

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<sup>10</sup>The appropriate temperature to use is the virtual temperature, defined as  $T = T_{\text{dry}} (1 + 0.61w)$  where  $w$  is the mixing ratio. See Pielke (1984, pg. 8) for a derivation of virtual temperature.  $T_{\text{dry}}$  is the thermometer temperature.



The temperature of the parcel determines the maximum amount of water vapor that can be contained without condensation or sublimation. This relation between saturation mixing ratio and temperature is given for realistic tropospheric conditions as:

$$w_s \cong \frac{3.8}{\bar{p}} \exp \left[ \frac{21.9 (\bar{T} - 273.2)}{\bar{T} - 7.7} \right] \quad (\text{for liquid water}) \quad (4.4)$$

$$w_{s_i} \cong \frac{3.8}{\bar{p}} \exp \left[ \frac{17.3 (\bar{T} - 273.2)}{\bar{T} - 35.9} \right] \quad (\text{for ice}) \quad (4.5)$$

(from Pielke 1984, pg. 234). Lines of constant saturation mixing ratio from a formulation such as Eq. (4.4) are usually drawn on thermodynamic diagrams as dashed or dotted lines.

Since water vapor content up to the LCL is constant,  $w$  is a constant as a parcel ascends or descends below the LCL. It is important to recognize, however, that a constant value of  $w$  does not indicate that the dewpoint temperature is constant with height. As the parcel ascends, expansion results in a reduction in the vapor pressure,  $e$ , with height as seen from the ideal gas law (i.e.,  $e = \rho_v R_v T$  where  $\rho_v$  is the density and  $R_v$  is the gas constant of the water vapor). Expansion requires that  $\rho_v$  become less and Eq. (4.3) indicates that temperature decreases as well. Thus, the temperature to which a parcel must be cooled *isobarically* in order to achieve condensation (sublimation) becomes lower at higher heights (i.e., lower pressures) since  $e$  decreases with height. Therefore while  $w = \rho_v / \rho$  is constant with height below the LCL,  $d T_D / dz$  is less than zero.

The phase change of water at and above the LCL permits a source of a heat. Equation (4.2) can be generalized to represent this source term as:

$$\frac{1}{\theta} \frac{d\theta}{dz} = \frac{1}{T} \frac{dT}{dz} - \frac{R_d}{C_p p} \frac{dp}{dz} = -\frac{L}{C_p T} \frac{dw_s}{dz} \quad (4.6)$$

where  $dw_s/dz$  is the change of saturation mixing ratio with height which when negative represents the amount of water vapor converted to another phase. The latent heat of phase change is given by  $L$ .

Rearranging Eq. (4.6), and substituting the hydrostatic relation yields:

$$\frac{dT}{dz} = -\frac{L}{C_p} \frac{dw_s}{dz} - \frac{R_d T \rho g}{p C_p} = -\frac{L}{C_p} \frac{dw_s}{dz} - \frac{g}{C_p} \quad (4.7)$$

where the gas law has been applied to simplify the last term on the right. By the chain rule of calculus,  $dw_s/dz$  can be written as:

$$\frac{dw_s}{dz} = \frac{dw_s}{dT} \frac{dT}{dz} \quad (4.8)$$

Substituting Eq. (4.8) into Eq. (4.7) and rearranging yields:

$$\frac{dT}{dz} = -\frac{g}{C_p} \left/ \left[ 1 + \frac{L}{C_p} \frac{dw_s}{dT} \right] \right. = \frac{-\gamma_d}{\left[ 1 + \frac{L}{C_p} \frac{dw_s}{dT} \right]} = -\gamma_m \quad (4.9)$$

where  $\gamma_m$  is referred to as the *moist adiabatic lapse rate*. (Note that  $\gamma_m \leq \gamma_d$  because of the heat liberated by the phase change of water.) When the phase change is from water vapor to liquid water,  $L$  corresponds to the latent heat of condensation ( $L \cong 2.5 \times 10^6 \text{ J kg}^{-1}$ ) and  $w_s$  is the saturation mixing ratio with respect to liquid water (e.g., Eq. 4.4) and  $\gamma_m$  is often called a *water adiabat*. When the phase change is to ice,  $L$  is the latent heat of deposition ( $L \cong 2.88 \times 10^6 \text{ J kg}^{-1}$ ) and  $w_s$  is the saturation mixing ratio with respect to ice (e.g., Eq. 4.5). On most thermodynamic diagrams, except those specifically designed for the upper troposphere where, for instance, the prime forecast consideration is the analysis for jet contrails, water adiabats are the ones most frequently plotted.

From Eq. (4.9), irrespective of which moist adiabat is used, since  $dw_s/dT$  is positive:

$$\gamma_m \leq \gamma_d$$

in all circumstances. Also, since  $dw_s/dT$  becomes small for colder temperatures,  $\gamma_m \cong \gamma_d$  in cold air. Lines of  $\gamma_m$  are often indicated on thermodynamic diagrams as dashed lines in the same color as the solid lines of  $\gamma_d$ .

There are two interpretations of moist ascent along a  $\gamma_m$  lapse rate. If the liquid water or ice is carried along with the parcel, then during subsequent descent this water can convert back to water vapor (i.e., evaporation for liquid water, sublimation for ice). For this situation, the phase change process is completely reversible and the lines of  $\gamma_m$  are referred to as *saturated adiabats*. On the other hand, if the liquid water or ice is interpreted to precipitate out of the parcel, a subsequent descent of the parcel will not permit the attainment of the original water vapor content. With this interpretation, the lines of  $\gamma_m$  are referred to as *pseudo-adiabats* and the process of lifting above the LCL is considered *irreversible*.

Two additional quantities are used to describe the moist thermodynamic stratification of the atmosphere – the *equivalent potential temperature* and the *wet bulb potential temperature*. To illustrate these two quantities, they will be derived in their approximate forms. Iribarne and Godson (1973) provide more precise derivations. Equation (4.6) can be written in the form:

$$\frac{1}{\theta} \frac{d\theta}{dz} = -\frac{L}{C_p T} \frac{dw_s}{dz} \cong -\frac{L}{C_p} \frac{d}{dz} \left( \frac{w_s}{T} \right) \quad (4.10)$$

as long as the approximation  $T^{-1} |dw_s/dz| \gg w_s T^{-2} |dT/dz|$  is valid (which it is for reasonable atmospheric conditions within the troposphere). The saturation mixing ratio corresponds to the value of  $w$  of a saturated parcel of air. Saturation of the parcel will only occur when it is cooled sufficiently so that the saturation value of  $w$  is attained.

Since at low temperatures saturation mixing ratio goes to zero more rapidly than temperature,  $w_s/T$  approaches zero at absolute zero. Therefore, treating  $L$  and  $C_p$  as constants, Eq. (4.10) can be integrated from an observed temperature to absolute zero yielding the

approximate formula.<sup>11</sup>

$$\theta_{es} = \theta \exp\left(\frac{Lw_s}{C_p T}\right). \quad (4.11)$$

The equivalent potential temperature, therefore, represents the potential temperature that would occur if *all* of the water was condensed (when  $L$  corresponds to the latent heat of condensation) and the resultant heat is used to warm the parcel to a higher potential temperature.

The wet bulb potential temperature is also derived from Eq. (4.10). Equation (4.10) can be rewritten in its approximate form as:

$$\frac{d(\ln \theta)}{dz} = -\frac{L}{C_p} \frac{d}{dz} \left[ \frac{w_s}{T} \right]. \quad (4.12)$$

Equation (4.12) can be integrated between current values of  $\theta$  and  $w_s$  and values of potential temperature,  $\theta_W$ , and saturation mixing ratio,  $w'_s$ , it would have if water vapor were added to the air parcel so as to cause saturation. This yields:

$$\int_{\theta}^{\theta_W} \frac{d}{dz} \ln \theta \, dz = -\frac{L}{C_p} \int_{w_s}^{w'_s} \frac{d}{dz} \left[ \frac{w_s}{T} \right] dz$$

or

$$\ln \frac{\theta_W}{\theta} = -\frac{L}{C_p} \left[ \frac{w_s}{T} - \frac{w'_s}{T_W} \right]$$

or

$$\theta_W = \theta \exp \left[ -\frac{L}{C_p} \left( \frac{w_s}{T} - \frac{w'_s}{T_W} \right) \right]. \quad (4.13)$$

The value of the wet bulb temperature in Eq. (4.13) can be obtained for an isobaric process from the first law of thermodynamics in the form:

$$C_p dT = -Ldw_s,$$

which after integrating over the same limits as applied to obtain Eq. (4.13), yields:

$$C_p (T - T_W) = -L[w_s - w'_s]$$

or

$$T_W = T - \frac{L}{C_p} (w'_s - w_s). \quad (4.14)$$

Since moistening an air parcel elevates the dewpoint temperature, while the evaporation of water cools the temperature,  $T_D \leq T_W \leq T$ .

$\theta_E$  and  $\theta_W$  correspond to lines of constant moist adiabatic lapse rate,  $\gamma_m$ . Both  $\theta_E$  and  $\theta_W$  are derived so as to account for the decrease in temperature with height of a saturated air parcel, as latent heat is continually released.

<sup>11</sup>A more exact form of  $\theta_{es}$  can be obtained from  $T_{es} = T_v + \frac{L}{C_p} w_s$  where  $T_e$  is the isobaric equivalent temperature and, thus,  $\theta_{es} = T_{es} \left( \frac{1000}{p} \right)^{Rd/cp}$  can be used to compute  $\theta_{es}$ .

### 4.1.3 Lifting Condensation Level

An air parcel ascends dry adiabatically ( $\frac{d\theta}{dz} = 0$ ) until saturation is attained. The moisture content of a parcel is specified by the mixing ratio as discussed previously. The height at which the ascending parcel first becomes saturated is called the *lifting condensation level* (LCL). Below the LCL  $\theta$ ,  $\theta_E$ , and  $\theta_W$  remain constant in the absence of entrainment of air with different thermodynamic properties. All three forms of potential temperature, therefore, are conserved with respect to dry air motions. Above the LCL, however, only  $\theta_E$  and  $\theta_W$  of a parcel remain constant in the absence of entrainment. Therefore, only  $\theta_E$  and  $\theta_W$ , and not  $\theta$ , are conserved with respect to saturated air motions.

### 4.1.4 Concept of Static Stability

Since force is equal to a mass times an acceleration (i.e., Newton's second law), the vertical equation of motion in the atmosphere can be written as:

$$\frac{d^2z}{dt^2} = \frac{dw}{dt} = -\frac{1}{\rho} \frac{\partial p}{\partial z} - g. \quad (4.15)$$

where, in Eq. (4.15),  $w$  is vertical motion. The two forces on the right side of Eq. (4.15) are the vertical pressure gradient force and gravitational acceleration. When these two forces are equal and opposite, the atmosphere is said to be in hydrostatic balance. Correspondingly, an imbalance of the two forces results in an acceleration.

In terms of an air parcel, it is convenient to write the hydrostatic version of Eq. (4.15) for the ambient (i.e., surrounding) atmosphere (denoted by a subscript "e") and the complete form of Eq. (4.15) (denoted by a subscript "p") for the parcel.

The relation of the parcel to the surrounding atmosphere is schematically illustrated in Fig. 4.1:

$$\left. \begin{aligned} \frac{\partial p}{\partial z} \Big|_e &= -\rho_e g \\ \frac{dw}{dt} &= -\frac{1}{\rho_p} \frac{\partial p}{\partial z} \Big|_p - g \end{aligned} \right\} \quad (4.16)$$

In applying Eq. (4.16), it is assumed that the vertical pressure gradient acting on the parcel is identical to the vertical pressure gradient of the atmosphere at the same level, i.e.,

$$\frac{\partial p}{\partial z} \Big|_e = \frac{\partial p}{\partial z} \Big|_p = \frac{\partial p}{\partial z}.$$

The bottom expression in Eq. (4.16) can then be written, after rearranging, as:

$$\frac{dw}{dt} = g \left[ \frac{\rho_e - \rho_p}{\rho_p} \right]. \quad (4.17)$$

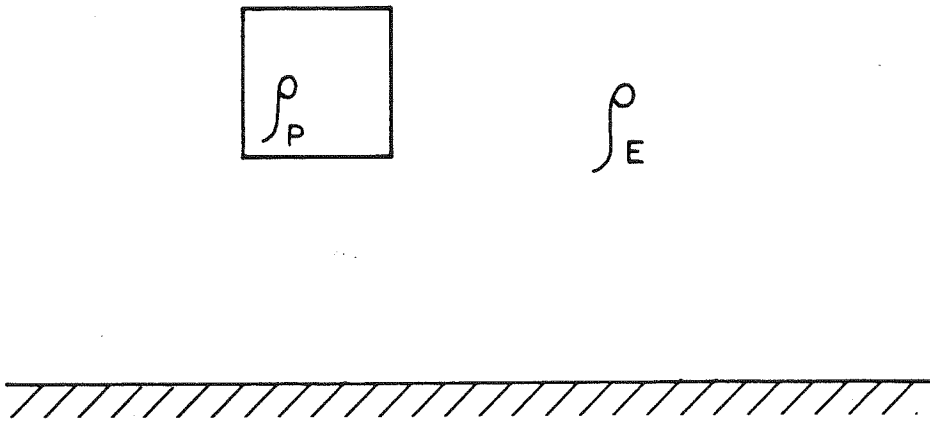


Figure 4.1: Schematic of the relation between a parcel and the surrounding atmosphere.

Thus, a parcel starting at rest will accelerate upward if it is less dense than the surrounding air. If  $\rho_e = \rho_p$ , a parcel at rest will stay at rest, while a parcel in motion will continue to move at a constant speed.

Using the ideal gas law for the parcel and for the ambient atmosphere:

$$\rho_e = p/R_d T_e \ ; \ \rho_p = p/R_d T_p,$$

Eq. (4.17) can be rewritten as:

$$\frac{dw}{dt} = g \frac{T_p - T_e}{T_e}. \quad (4.18)$$

Therefore, a parcel, starting at rest, will accelerate upward if it is warmer than the surrounding air.

Using a Taylor series expansion, the response of a parcel to forced motion from its height of origin in the atmosphere can be evaluated:

$$T_e = T_o + \left. \frac{dT}{dz} \right|_e \delta z + \frac{1}{2} \left. \frac{d^2 T}{dz^2} \right|_e (\delta z)^2 + \dots$$

$$T_p = T_o + \left. \frac{dT}{dz} \right|_p \delta z + \frac{1}{2} \left. \frac{d^2 T}{dz^2} \right|_p (\delta z)^2 + \dots$$

where  $T_o$  is the temperature at the level at which the parcel originated.

If  $\delta z$  is small,

$$T_e \cong T_o - \gamma \delta z \ ; \ T_p \cong T_o - \gamma_d \delta z$$

where  $\gamma = -dT/dz|_e$  is the lapse rate of the environment and  $\gamma_d$  is the lapse rate of a parcel undergoing dry adiabatic motion (i.e.,  $\gamma_d = \frac{g}{c_p} = -\left. \frac{dT}{dz} \right|_p$ ; see Eq. 4.3). Equation (4.18) can therefore be approximated by:

$$\frac{dw}{dt} \cong g \frac{(\gamma - \gamma_d)}{T_e} \delta z \quad (4.19)$$

In terms of Eq. (4.19), the following definitions are used when referring to a dry atmosphere,

- an unstable equilibrium exists when  $\gamma > \gamma_d$
- a neutral equilibrium exists when  $\gamma = \gamma_d$
- a stable equilibrium exists when  $\gamma < \gamma_d$ .

In the atmosphere,  $\gamma < \gamma_d$  at almost all locations except,

- a) near the ground on sunny days,
- b) over water when colder air advects over it, and

c) at the top of clouds, particularly at sunset.

Since values of constant potential temperature  $\theta$  are equivalent to  $\gamma_d$ ,

$$\left. \begin{array}{l} \gamma > \gamma_d \\ \gamma = \gamma_d \\ \gamma < \gamma_d \end{array} \right\} \text{ is equivalent to } \left\{ \begin{array}{l} \frac{\partial \theta}{\partial z} < 0 \\ \frac{\partial \theta}{\partial z} = 0 \\ \frac{\partial \theta}{\partial z} > 0 \end{array} \right. \quad (4.20)$$

Partial derivatives are used here to emphasize that the potential temperature lapse rate is referred to rather than the value of  $\theta$  following a parcel. When  $\partial\theta/\partial z < 0$ , the lapse rate  $\gamma$  is said to be *superadiabatic*.

Corresponding definitions can be made for a saturated environment except  $\gamma_d$  is replaced by  $\gamma_m$ . If the air is saturated,

- $\gamma > \gamma_m$  is unstable and cumuliform clouds result,
- $\gamma = \gamma_m$  is neutral and cumuliform clouds occur,
- $\gamma < \gamma_m$  is stable and stratiform clouds result.

Since values of constant equivalent and wet bulb potential are equivalent to constant values of  $\gamma_m$ , a general terminology relating lapse rates and the different  $\theta$  forms of potential temperature can be derived. These relationships are summarized in Table 4.1.

Up to this point, thermodynamic stability has referred to parcel motion. Often, however, entire layers of the atmosphere are lifted as a result of large-scale ascent. As will be illustrated in the following discussion, this lifting can result in significant changes in the atmospheric lapse rates,  $\gamma$ .

Figures 4.2a and b schematically represent two basic types of atmospheric stratification. In Fig. 4.2a,  $\partial\theta_E/\partial z > 0$  so the atmosphere is absolutely stable, while  $\partial\theta_E/\partial z < 0$  in Fig. 4.2b which is a conditionally unstable atmosphere as long as  $\partial\theta/\partial z > 0$ . The stable atmosphere is characterized by relatively dry air capped by relatively wetter air aloft. The converse is true for the conditionally unstable atmosphere.

The changes in stratification due to the lifting of the layer A-B to A'-B' are shown in the figure. The equivalent potential temperatures,  $\theta_{E_A}$  and  $\theta_{E_B}$  at the heights A and B, and which are invariant under both dry and moist ascent, are also illustrated. The lifting of the layer proceeds adiabatically (i.e., constant  $\theta$ ) until saturation is achieved, whereupon values of constant  $\theta_E$  are followed.

As evident in the figure, when  $\partial\theta_E/\partial z > 0$ , the layer becomes more stable, while when  $\partial\theta_E/\partial z < 0$ , the stratification becomes less stable.

Table 4.1: Relation between lapse rates.

Thermodynamic stability	Lapse rate relationship	Potential temperature relationship	Parcel behavior
Absolutely stable	$\gamma < \gamma_m$	$\frac{\partial\theta_w}{\partial z} = \frac{\partial\theta_E}{\partial z} > 0$	Regardless of whether saturation occurs in the absence of entrainment, the parcel will move back to its original position if displaced.
Conditionally stable	$\gamma_m \leq \gamma < \gamma_d$	$\frac{\partial\theta_w}{\partial z} = \frac{\partial\theta_E}{\partial z} < 0$ but $\frac{\partial\theta}{\partial z} > 0$	The parcel accelerates away from its original position if displaced and if saturated. If not saturated it will move back to its original position. In addition, even if the parcel is displaced sufficiently such that saturation occurs, the parcel will still move back towards its original position until further saturated ascent overcomes the temperature deficit that resulted from the earlier dry adiabatic upward motion.
Absolutely unstable	$\gamma \geq \gamma_d$	$\frac{\partial\theta}{\partial z} \leq 0$	Parcel will accelerate away from its original position when displaced.



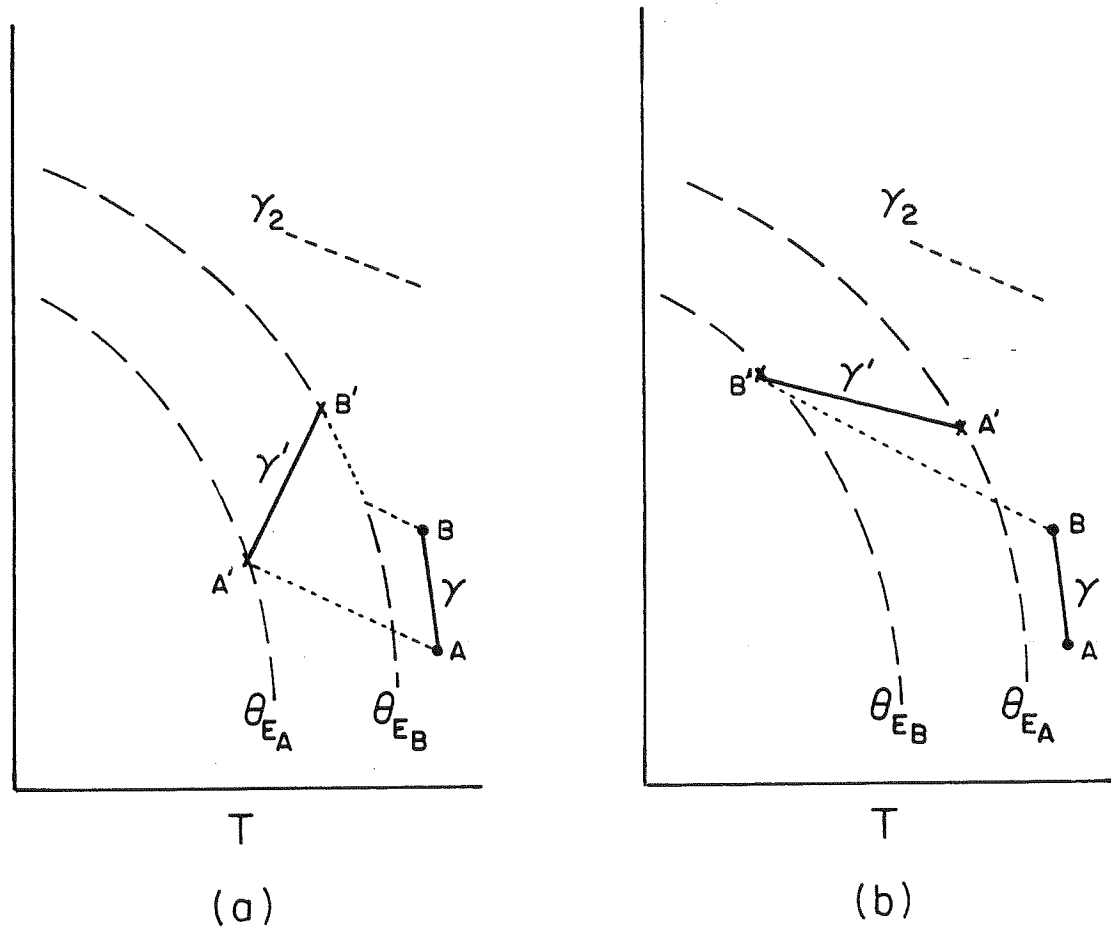


Figure 4.2: Schematic of (a) a convectively stable, and (b) convectively unstable air mass which is lifted from heights A-B to A'-B'. The original lapse rate is  $\gamma$  and the new lapse rate after lifting is  $\gamma'$ .

When  $\partial\theta_E/\partial z$  becomes more negative, the atmosphere becomes more conducive to cumiform convection.

When  $\partial\theta_E/\partial z < 0$ , the layer is variously referred to as:

- i) convectively unstable – since cumulus convection results when saturation is realized in such an atmosphere.
- ii) potential instability – since organized lifting must occur before saturation is actually realized.
- iii) layer instability – since it is the lifting of a layer of the atmosphere that increases the instability and permits saturation to occur.

As a qualitative guide, dry air above moist air is a fingerprint of a convectively unstable atmosphere, and is one criteria looked for in predicting severe thunderstorm outbreaks.

In using these thermodynamic definitions, it is important to remember that conditional instability refers to a parcel, while convective instability refers to a layer.

#### 4.1.5 Convective Parameters

There are several derived thermodynamically-related parameters that are valuable in estimating if and when convection will occur, and how intense it will be. These are:

- a) Equilibrium Level (EL) – This is the height in the atmosphere at which the temperature of an air parcel,  $T_p$ , equals the temperature of the environment at that level,  $T_e$ . Below this height for some distance,  $T_p > T_e$ .

This height closely corresponds to the average heights of cumulus cloud tops. Cumulus clouds which exceed this height are referred to as *overshooting* tops since they exceed their equilibrium level.

- b) Convective Temperature ( $T_c$ ) – This is a temperature near the surface corresponding to a dry adiabatic environmental lapse rate (created as a result of surface heating by solar insolation and resultant mixing) which is high enough so that parcel ascent from the shallow superadiabatic layer near the surface reaches a height at which condensation occurs. It often closely corresponds to the maximum daytime surface temperature.

- c) Convective Condensation Level (CCL) – This is the height of condensation associated with  $T_c$ . Condensation at this height is manifested initially by shallow cumulus clouds which represent the tops of buoyant turbulent eddies within the boundary layer. Once the CCL is attained, surface temperatures generally do not exceed  $T_c$  as a result of the shading of the ground by the clouds and the increased winds near the surface as the cumulus clouds themselves begin to enhance mixing within the layers below the CCL. The CCL is always higher than or equal to the LCL. The most accurate way to

compute the CCL is to compute the average  $w$  within a height  $z_i$  from the surface. The depth  $z_i$  corresponds to the height of the layer with a near adiabatic lapse rate. When  $z_i$  reaches a height such that the value of the average  $w$  over the depth  $z_i$  attains its saturated value at  $z_i$ , then  $z_i$  corresponds to the CCL.

- d) Level of Free Convection (LFC) – This is the height at which a parcel mechanically lifted from near the surface will initially attain a temperature warmer than the ambient air. The parcel will subsequently rise from its own buoyancy.
- e) Positive Buoyant Energy – This energy is proportional to the temperature excess of a parcel between the LFC and the EL. The mechanical energy required to lift a parcel to the LFC is termed a negative buoyant energy. Positive buoyant energy is also called Convective Available Potential Energy (CAPE).
- f) Convective Inhibition (CIN) – This is the heat energy that must be added to the lower levels of the profile in order to make the potential temperature at the LFC equal to the potential temperature near the surface (i.e.,  $\partial\theta/\partial z = 0$ ). This energy removes the negative buoyant energy.
- g) Lifted Index (LI) – This measure of stability is defined as:

$$LI = T_{500\text{mb}} - T_{p500\text{mb}}$$

where  $T_{p500\text{mb}}$  is the temperature of a parcel lifted at a constant  $\theta$  to the LCL and at a constant  $\theta_E$  to 500 mb.  $T_{500\text{mb}}$  is the observed temperature at 500 mb. Values of  $LI > 0$  are generally associated with no significant cumulus convection;  $0 > LI > -4$  with showers;  $-4 > LI > -6$  thunderstorms; and  $LI < -6$  with severe thunderstorms.

- h) K-Index (K) – This measure of stability is defined as:

$$K = T_{850\text{mb}} + T_{d_{850\text{mb}}} - T_{500\text{mb}} - (T_{700\text{mb}} - T_{d_{700\text{mb}}});$$

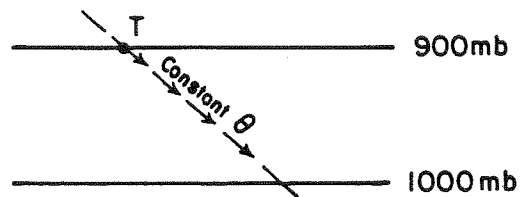
$K > 30$  is generally associated with thunderstorms. The formula needs to be modified for use in higher elevations of the western United States.

- i) Mixing Condensation Level (MCL) – This is the height that condensation will occur as a result of strong winds mixing a layer so as to attain uniform with altitude potential temperature and mixing ratio. The MCL is the minimum height at which uniform mixing of  $\theta$  and  $w$  results in saturation. The effect of surface heating is ignored.
- j) Precipitable Water (P) – Vertical integral of water depth if all water vapor in a column were condensed out. Defined in terms of  $\text{g/cm}^2 \equiv 1 \text{ cm}$  of water depth as:

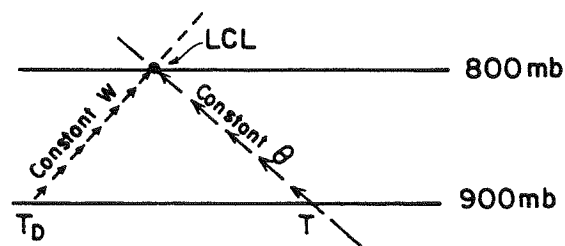
$$P = \int_{\text{surface}}^{\infty} \rho_v dz = \int_{\text{surface}}^{\infty} w \rho dz$$

## 4.2 Schematic Illustration of the Calculation of Variables on a Thermodynamic Diagram

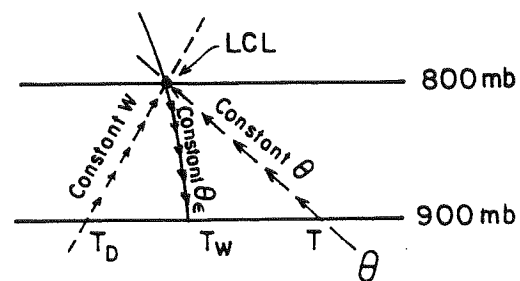
### 4.2.1 Potential Temperature, ( $\theta$ )



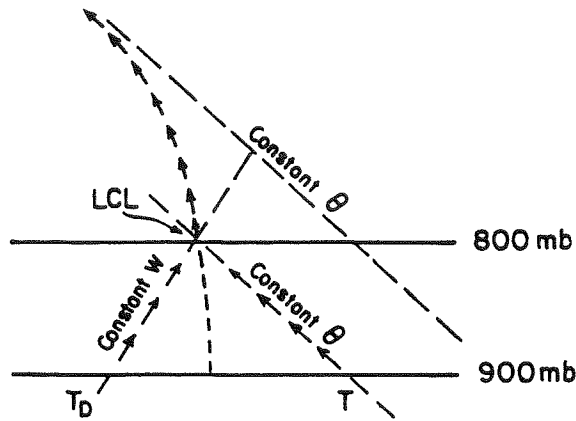
### 4.2.2 Lifted Condensation Level (LCL)



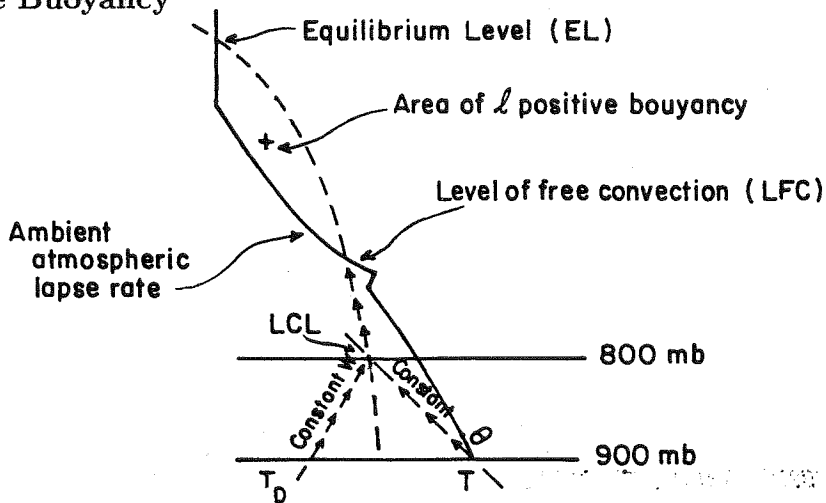
### 4.2.3 Wet Bulb Potential Temperature ( $\theta_w$ ) and Wet Bulb Temperature ( $T_w$ )



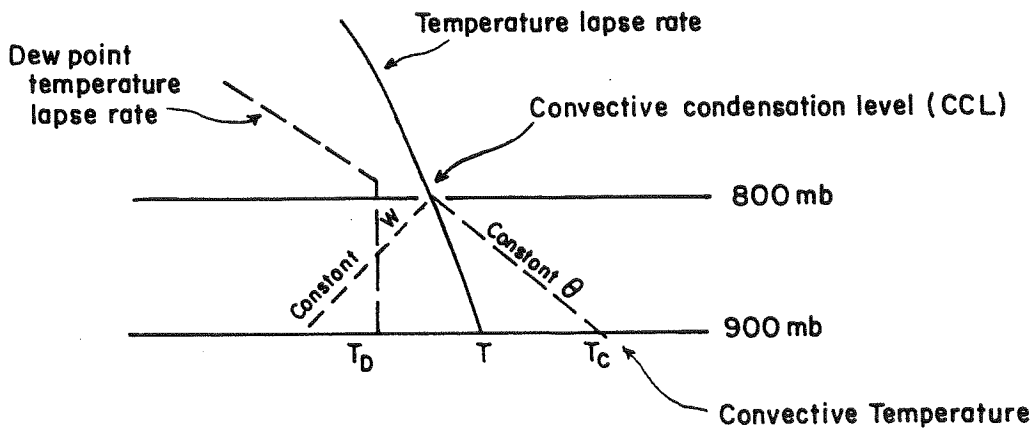
4.2.4 Equivalent Potential Temperature ( $\theta_E$ )



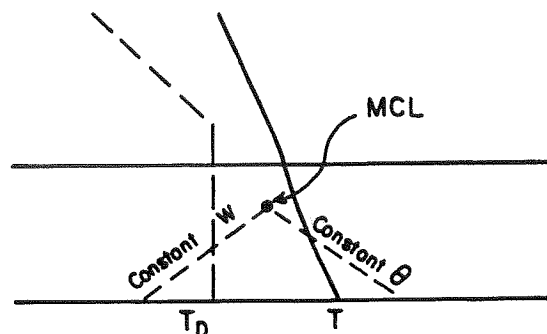
4.2.5 Level of Free Convection (LFC), Equilibrium Level (EL), and Area of Positive Buoyancy



4.2.6 Convective Temperature ( $T_c$ ) and Convective Condensation Level (CCL)



#### 4.2.7 Mixing Condensation Level (MCL)



The MCL is the minimum height at which uniform mixing of  $\theta$  and  $w$  results in saturation.

A summary of the uses of the common thermodynamic parameters is presented in Table 4.2.

#### 4.3 Severe Storm Indices

#### 4.4 Conditional Symmetric Instability

#### 4.5 Thermodynamic Cross Sections

As discussed in Table 4.2, since potential temperature is conserved with respect to dry motions<sup>12</sup>, when  $\frac{\partial \theta}{\partial z} > 0$ ,  $\theta$  can be used as a parcel tracer in an atmosphere without saturation. An additional requirement is that the parcel not entrain adjacent air with different values of  $\theta$ .

Similarly, the equivalent potential temperature and wet bulb potential temperature can be used as a parcel tracer as long as  $\partial \theta_E / \partial z = \partial \theta_W / \partial z > 0$ . These temperatures, unlike  $\theta$ , are also conserved under saturated motion.

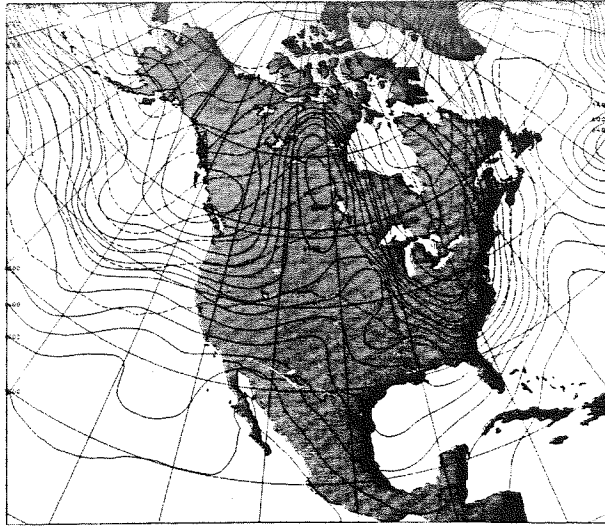
It therefore appears useful to use these quantities to estimate atmospheric trajectories. In a dry atmosphere, for example, air parcels would tend to move along  $\theta$  surfaces, such as illustrated in Fig. 4.3 reproduced from Nagle (1979). In a moist atmosphere, parcels would tend to move along  $\theta_W$  surfaces.

The application of these surfaces to estimate trajectories in a dry environment are most useful when the atmosphere is absolutely stable (i.e.,  $\partial \theta / \partial z > 0$ ) and radiative flux divergence effects are small as mentioned in Footnote 13. Such thermodynamic structure generally occur above the planetary boundary layer in the remaining portion of the troposphere and in the stratosphere. Near the surface, of course, particularly during sunny days, superadiabatic layers often occur resulting in values of  $\theta$  which are multi-valued with height. Therefore, a determination of the appropriate layer near the ground surface to follow a trajectory is unclear. In addition, strong vertical mixing as a result of the superadiabatic layer can produce substantial parcel entrainment of air with different values of  $\theta$ .

<sup>12</sup>Heat changes due to radiative flux divergence must also be small over the period of interest.

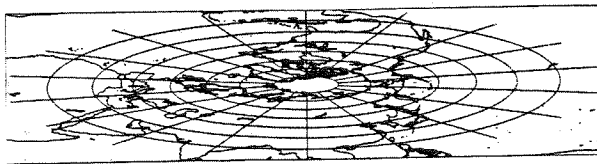
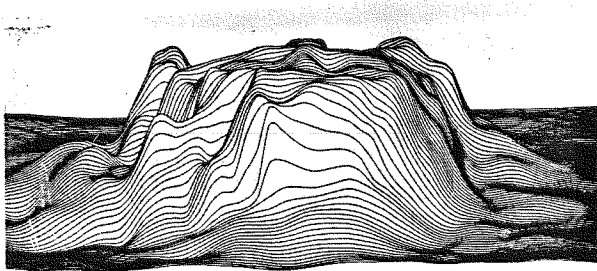
Table 4.2: Uses of common thermodynamic parameters.

PARAMETER	USE
$\theta$	Used as a tracer for dry motions where $\partial\theta/\partial z > 0$ (therefore, most useful in the mid and upper troposphere).
$\theta_E, \theta_W$	Used as a tracer for both dry and wet motions. Major problem with its use as a tracer is that $\theta_E$ and $\theta_W$ are often multi-valued with height (i.e., $\partial\theta_E/\partial z = \partial\theta_W/\partial z$ often change sign one or more times with height).
LCL	Provides an estimate of stratiform cloud base as a result of forced lifting over mountains or along frontal surfaces.
CCL	Provides an estimate of cumulus cloud base due to surface heating.
MCL	Provides an estimate of cloud base when winds increase so as to mix a layer near the ground.
LFC	Provides an estimate of the depth to which forced ascent is required before cumuliform clouds will spontaneously grow.
EL	Provides an estimate of average cumulus cloud top within a region. Over-shooting cumulus tops will be higher than the EL.
Area of positive buoyancy	Provides a quantitative measure of the intensity of cumulus growth if clouds reach the CCL.
Precipitable water	Provides a liquid water equivalent if all the water vapor in a column was condensed. Used to estimate average precipitation potential over an area.
LI	LI > 0: no deep cumulus clouds expected; 0 > LI > -4: showers expected; -4 > LI > -6: thunderstorms expected; LI < -6: severe thunderstorms expected.
K	Used to estimate whether or not cumulus convection will occur.
$\frac{\partial\theta_E}{\partial z}, \frac{\partial\theta_W}{\partial z}$	Determines layers in which forced lifting will destabilize the layer resulting in more intense cumulus convection if it develops ( $\frac{\partial\theta_E}{\partial z} = \frac{\partial\theta_W}{\partial z} < 0$ ).
$T_W$	Provides an estimate for the observed temperature when precipitation falls into a layer, evaporating as it falls.
$T_D$	Provides an estimate of the temperature that must be reached on clear nights before frost or dew will form ( $T_D$ with respect to deposition or condensation are close enough for the purposes of this estimate). Except, due to advection, nighttime temperatures seldom fall much below $T_D$ , since heat is released at the surface through the phase change of water.

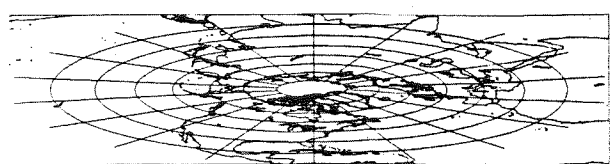
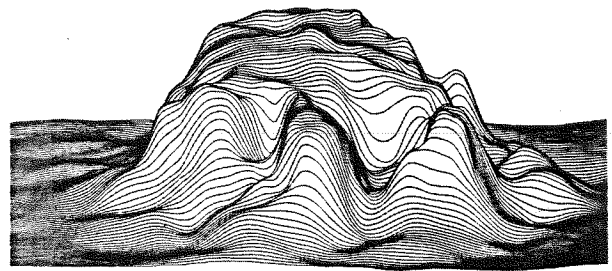


a) The conventional 313 K isentropic chart for North America and adjacent regions, 1200 GMT, 12 November 1977, is shown for comparison with the three-dimensional pattern in Fig. b. Solid lines are contours of height; broken lines, the Montgomery streamfunction.

The Montgomery streamfunction is defined by the righthand side expression in Eq. (3.12).



c) (Above) Three-dimensional pattern of the 313 K isentropic surface over the Northern Hemisphere as viewed from 100°E longitude, 1200 GMT, 12 November 1977. (Below) A polar stereographic map viewed from the same perspective as the isentropic dome in the top illustration.



b) (Above) Three-dimensional pattern of the 313 K isentropic surface over the Northern Hemisphere as viewed from 80°W longitude, 1200 GMT, 12 November 1977. (Below) A polar stereographic map viewed from the same perspective as the isentropic dome in the top illustration.

Figure 4.3: Illustration of northern hemispheric  $\theta$  surfaces as viewed from two different perspectives (from Nagle 1979).



In a saturated environment, in the absence of significant entrainment of air with different thermodynamic properties, trajectories will follow surfaces of constant  $\theta_W$  and  $\theta_E$ . If the saturated air has a structure such that  $\partial\theta_W/\partial z = \partial\theta_E/\partial z < 0$ , however, the same problem occurs as when  $\partial\theta/\partial z < 0$ , namely  $\theta_W$  and  $\theta_E$  are multi-valued in height. In such a saturated atmosphere in which conditional instability is realized, cumulus convection will occur with the resultant vertical mixing making trajectory assessments ambiguous. In contrast to profiles of  $\theta$ , therefore,  $\theta_W$  and  $\theta_E$  are often multi-valued even above the planetary boundary layer. Such multi-valued profiles most often occur in air of tropical origin.

In summary, the use of dry and moist isentropic surfaces to estimate trajectory motion are most useful when:

- dry motion: •  $\partial\theta/\partial z > 0$   
 • heating or cooling due to radiative flux divergence is small.
- moist motion: •  $\partial\theta_E/\partial z = \partial\theta_W/\partial z > 0$   
 • heating or cooling due to radiative flux divergence is small.
- (4.21)

Since regions of large horizontal thickness gradient also have a large horizontal gradient of  $\theta$ ,  $\theta_E$ , and  $\theta_W$ , significant parcel ascent or descent occurs in such regions. The application of  $\theta$  surfaces in dry air or  $\theta_W$  surfaces ( $\theta_E$  surfaces) in saturated air, therefore, provides excellent resolution of parcel motion in such an atmosphere, providing the criteria listed in Eq. (4.21) are satisfied.

In applying these surfaces to estimate parcel motion:

- use  $\theta$  surfaces when the relative humidity of the parcel is less than 100%. The simultaneous occurrence of regions with  $\partial\theta_E/\partial z = \partial\theta_W/\partial z < 0$  is of no relevance *as long as the parcel remains unsaturated*.
- use  $\theta_W$  ( $\theta_E$ ) surfaces when the relative humidity of the parcel reaches 100%. Precipitation can be estimated from the condensation that must occur with continued ascent after a relative humidity of 100% is reached for the first time.

If  $\partial\theta_E/\partial z = \partial\theta_W/\partial z \leq 0$ , however, the use of  $\theta_E$  ( $\theta_W$ ) surfaces is of little value, unless the region of conditional instability is very narrow.

An early, effective discussion of the application of isentropic trajectories is presented in Rossby (1941, pp. 637-641). Artz et al. (1985) provide an evaluation of differences obtained when an isentropic trajectory analysis is used instead of a constant height evaluation.

## 5. Climatology

### 5.1 Global Climate

The primary driving force for the horizontal structure of the earth's atmosphere is the amount and distribution of solar radiation which impinges on the planet. The orbit of the earth around the sun is an ellipse with a perihelion (closest approach) of  $1.47 \times 10^8$  km in early January, and a aphelion (farthest distance) of  $1.52 \times 10^8$  km in early July. The time between the *autumnal equinox* and following *vernal equinox* in the northern hemisphere (about 22 September to about 21 March) is approximately one week shorter than the remainder of the year as a result of the earth's elliptical orbit, resulting in shorter winters in the northern hemisphere than south of the equator.

The earth rotates every 24 hours around an axis that is tilted at an angle of  $23\text{-}1/2^\circ$  with respect to the plane of its orbit. As a result of this tilt, during the summer season in either the northern or southern hemisphere, sunshine is more direct on a flat surface at a given latitude than it is during the winter season. Poleward of  $66\text{-}1/2^\circ$  of latitude, the tilt of the earth is such that for at least one complete day (at  $66\text{-}1/2^\circ$ ) and as long as six months (at  $90^\circ$ ), the sun is above the horizon during the summer season and below the horizon during the winter.

As a result of this asymmetric distribution of solar heating, during the winter season high latitudes become very cold in the troposphere as a result of the long nights. In the summer at high latitudes, the troposphere warms significantly as a result of the long hours of daylight, although due to the oblique angle of the sunlight, the temperatures remain, in general, relatively cool compared to regions in the summer midlatitudes. Equatorward of  $30^\circ$  or so, however, substantial and similar radiational heating from the sun occurs during both winter and summer. The tropical troposphere, therefore, has comparatively little variation in temperature during the year.

In the troposphere, the demarcation between the cold polar air and warmer tropical atmosphere is usually well-defined by the *polar front* – poleward of the front the air is of polar origin, equatorward it is of tropical origin. The colder polar air is denser than the tropical air, with over a 30% difference in densities at the surface possible for extreme wintertime contrasts. During the winter season, the polar front is generally located at lower latitudes and is stronger than in the summer.

The region of greatest solar heating at the surface in the humid tropics results in areas of deep cumulonimbus convection. These cumulonimbus clouds occur because upon condensation the clouds are warmer than the surrounding ambient atmosphere. These clouds transport water substance, sensible heat, and the earth's rotational momentum to the upper portion of the troposphere. The troposphere in these latitudes is around 17 to 18 km as a result of the vigorous mixing of the atmosphere by the convection.

Since motion upward into the stratosphere is inhibited by a very stable thermal stratification, the air transported upward by the convection diverges poleward in the upper troposphere. This divergence aloft results in a minimum of pressure at the surface, which is

referred to as the *equatorial trough*. As the air is transported poleward it is deflected towards the right in the northern hemisphere and left in the southern hemisphere, since it tends to retain the angular momentum of the near equatorial region. At low latitudes the angular momentum is large as a result of the earth's rotation.

Upon reaching around 30° of latitude poleward of its region of origin, the air is traveling primarily towards the east. Since motion upward is constrained by the stratosphere, the air must descend. The resultant compressional warming as the air descends creates vast regions of strong stable thermodynamic stability within the troposphere. The sparse precipitation in these regions, a result of stabilization and subsidence, is associated with the great arid regions of the world such as the Sahara, Atacama, Kalahari, and Sonoran deserts. The accumulation of air as a result of the convergence in the upper troposphere causes deep high pressure systems, referred to as *subtropical ridges*, to occur in these regions. Locally, these ridges or high pressure systems are given names such as the Bermuda High, the Azores High, and the North Pacific High.

Upon reaching the lower troposphere, the presence of the earth's surface requires that the air diverge, with some air moving poleward, and the remainder moving equatorward. In either direction the air is deflected to the right in the northern hemisphere and to the left in the southern hemisphere. The tendency of an air parcel to conserve its momentum results in this horizontal deflection. This deflection occurs because according to Newton's first principle, a parcel in motion in a certain direction will retain the same motion unless acted on by an exterior force. With respect to a rotating earth, therefore, a moving parcel which is conserving its momentum (i.e., not acted on by an exterior force) will appear to be deflected with respect to fixed points on the rotating earth. As seen from a fixed point in space, a parcel which is conserving its momentum would be moving in a straight line. This apparent force on air motion is called the *Coriolis effect*. Air tends to rotate counterclockwise around large-scale low pressure systems, clockwise around large-scale high pressure systems in the northern hemisphere as a result of the Coriolis effect. In the southern hemisphere, the flow direction is reversed. In the equatorward moving flow, this deflection results in northeast winds north of the equator and southeast winds south of that latitude. These low-level winds are called the *trade winds* since in the seventeenth and eighteenth centuries, sailing vessels used them to travel to the Americas. The low-level convergence region of the northeast and southeast trade winds from the two hemispheres is called the *Intertropical Convergence Zone* (ITCZ). The ITCZ corresponds to the equatorial trough and is the mechanism which helps generate the deep thunderstorms in this pressure trough.

The circulation of ascent in the equatorial trough, poleward movement in the upper troposphere, descent in the subtropical ridges, and equatorward movement in the trade winds is a *direct heat engine*, called the *Hadley cell*. It is a persistent circulation feature whereby heating from the latitudes of greatest solar insolation is transported to the latitudes of the subtropical ridges. The geographic location of the Hadley circulation moves north and south with the seasons with the equatorial trough lagging the latitude of greatest surface solar heating by about two months. This lag results because of the thermal inertia of the

earth's surface in which the highest daily temperatures are achieved after the time of greatest insolation since time is required to heat the ocean surface waters and the soil.

Poleward of the subtropical ridges in the lower troposphere, as a result of the tendency for air motions to conserve absolute angular momentum, southwesterlies in the northern hemisphere and northwesterlies in the southern hemisphere tend to occur.

Since warm air is being moved poleward at low levels, however, the wind flow is no longer associated with a direct heat engine. The transport of the heat which originated in the equatorial trough is consequentially transported farther poleward by large, horizontal low pressure eddies which are called *extratropical cyclones*.

Figure 5.1 schematically illustrates the distribution of surface winds and a vertical cross section of average motion in the troposphere on the earth. A rotating dishpan experiment in which dry ice is inserted in the center, and the rim is heated can produce a number of the features of the general circulation of the earth including a direct thermal circulation analogous to the Hadley cell and vortices along the boundary of the cold and warm air which corresponds to the polar front. A schematic of a dishpan experiment is shown in Fig. 5.2.

These extratropical cyclones develop on the polar front (which delineates air of polar origin from that of tropical sources) when a sufficiently large horizontal gradient of temperature in the lower troposphere develops across the front. The intensity of this temperature gradient is referred to as the *baroclinicity* of the front. Extratropical cyclones are found to have three stages of development: the *developing stage* in which an undulating wave develops along the front; the *mature stage* in which sinking cold air sweeps equatorward west of the surface low and ascending warm air moves poleward east of the cyclone; and the *occluded stage* in which the warm air has become entrained within and moved above the air of polar origin and cut off from the source region of the tropical air. Cyclones which develop no further than the developing stage are referred to as *wave cyclones*, while extratropical lows that reach the mature and occluded stages are baroclinically unstable waves. Extratropical storm development is referred to as *cyclogenesis*. Surface pressure falls of greater than about  $24 \text{ mb day}^{-1}$  which occasionally occur with rapid extratropical cyclone development is referred to as *explosive cyclogenesis* and is often associated with major winter storms. Theoretical analysis has shown that the occurrence of baroclinically unstable waves is directly proportional to the magnitude of the temperature gradient with maximum growth for wavelengths of 3000 to 5000 km.

*Cold fronts* occur at the leading edge of the equatorward moving polar air, while *warm fronts* are defined at the equatorward surface position of the polar air as it retreats poleward east of the extratropical cyclone. The equatorward moving air behind the cold front occurs in pools of cold, dense, polar and arctic surface high pressure systems. Arctic highs are defined to distinguish air of an origin even deeper within the high latitudes than are polar highs. When the polar air is neither retreating or advancing, the polar front is called a *stationary front*. In the occluded stage, where the cold air west of the surface low pressure center advances more rapidly eastward around the cyclonic circulation than the warm air east of the center moves poleward, the warm, less dense tropical air is forced aloft. The

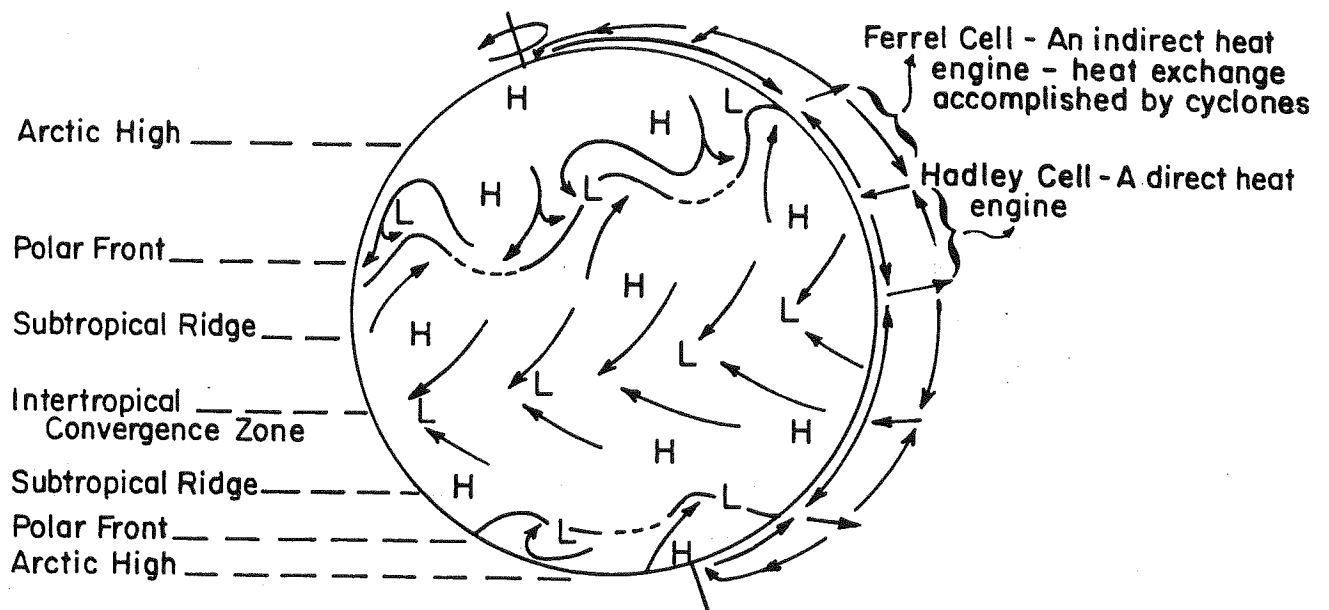


Figure 5.1: Schematic of the general circulation of the earth in the northern hemisphere winter. There is average subsidence in the subtropical ridge and arctic high, and average ascent in the intertropical convergence zone and the polar front region. The ITCZ, jet streams, and subtropical ridges move north and south with the seasons. The height of tropopause corresponds to the upper branch of arrows in the cross section.

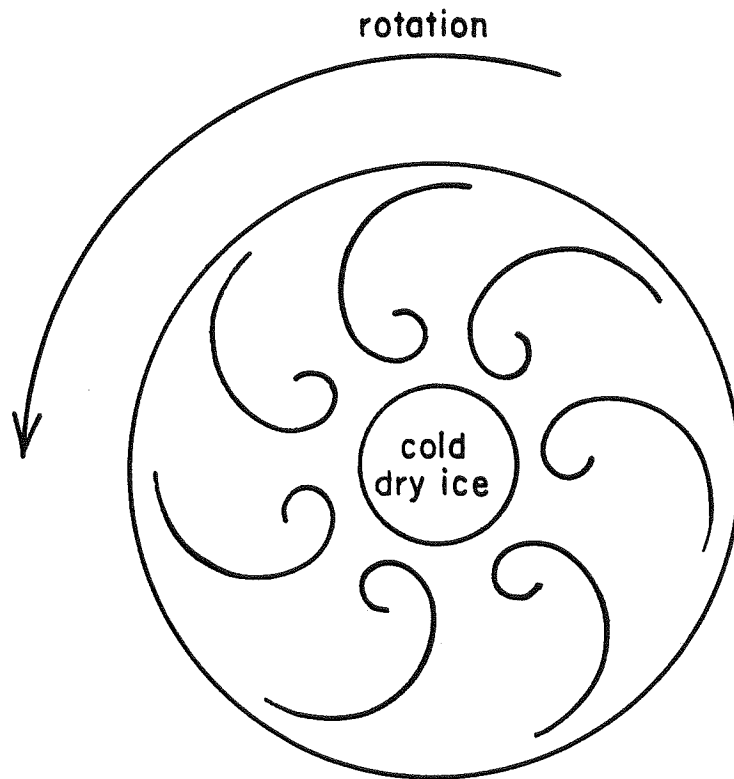


Figure 5.2: A schematic illustrating the dishpan experiments where a flat circular pan is rotated about its center in a horizontal plane. The pan is cooled at its center, analogous to the poles, and warmed at the rim of the pan, analogous to the equator.

resultant frontal intersection is called an *occluded front*. Fronts of all types always move in the direction towards which the colder air is moving.

Clouds and precipitation often occur poleward of the warm and stationary fronts whenever the poleward moving, less dense tropical air north of subtropical ridges reaches the latitude of the polar front, and is forced upward over the colder air near the surface. Such fronts are defined as *active fronts* and rain and snowfall from them form a major part of the precipitation received in mid and high latitudes particularly during the winter.

The position of the polar front slopes towards the colder air with height. This occurs because cold air, being more dense, tends to undercut the warmer air of tropical origin. Since the cold air is more dense, pressure decreases more rapidly with height poleward of the polar front than on the warmer side. In the mid and upper troposphere, the resultant large horizontal pressure gradient between the polar and tropical air creates strong westerly winds as air circulates around the region of low pressure in the higher latitudes at these heights. The center of this low pressure region is called the *circumpolar vortex*. The region of strongest winds, which occurs at the juncture of the tropical and polar air masses, is called the *jet stream*. Since the temperature contrast between the tropics and the high latitudes is greatest in the winter, the jet stream is stronger during that season. In addition, since the midlatitudes also become colder during the winter, while tropical temperatures are relatively unchanged, the westerly jet stream tends to move equatorward during the colder season.

The jet stream reaches its greatest velocities at the tropopause. Above that level, lower tropopauses in the polar region than in the tropics result in a reversal of the horizontal temperature gradient in the stratosphere from that found in the troposphere, with relatively warmer temperatures at high latitudes. This causes a weakening of the westerlies with height. At intervals of 20 to 40 months with a mean of 26 months, for reasons that are not completely understood, a reversal of wind direction occurs at low latitudes so that easterly flow develops. This feature is called the *quasi-biennial oscillation*. A phenomena called *sudden stratospheric warming*, apparently a result of strong downward motion, also occurs in the late winter and spring at high latitudes which can significantly influence the chemical balance of ozone and other reactive gases in the stratosphere.

Preferred geographic locations exist for the development, movement, and decay of extratropical cyclones, and for the presence of centers of the subtropical ridge. In the winter in mid and high latitudes, continents tend to become lower tropospheric high pressure reservoirs of cold air as heat is radiated out to space during the long nights. In contrast, oceans lose heat less rapidly as a result of the large thermal inertia of water, its ability to overturn as the surface cools and becomes negatively buoyant, and the existence of ocean currents such as the Gulf Stream and Kuroshio Currents which transport heat from lower latitudes poleward. The lower troposphere over the warmer oceanic areas, therefore, tends to be a region of relative low pressure. As a result of this juxtaposition of cold and warm air, east sides of continents and the western fringes of oceans in mid and high latitudes are preferred locations for extratropical storm development. Over the Asian continent, in particular, the

cold high pressure system is sufficiently permanent that a persistent offshore flow called the *winter monsoon* occurs.

An inverse type of flow develops in the summer as the continents heat more than adjacent oceanic areas. Continental areas tend to become regions of relative low pressure, while high pressure in the lower troposphere becomes more prevalent offshore. Persistent lower tropospheric onshore flow that develops over large land masses as a result of the heating is referred to as the *summer monsoon*. The leading edge of this monsoon is associated with a trough of low pressure called the *monsoon trough*. Tropical moisture brought onshore by the monsoon often results in copious rainfall. Cherrapunji in India, for instance, recorded over 9 meters of rain in a month (July, 1861) due to the Indian summer monsoon.

The subtropical ridge is segmented into surface high pressure cells as a result of the continental effect. In the subtropics, large land masses tend to be relative centers of low pressure as a result of the strong solar heating. Persistent high pressure cells, therefore, such as the Bermuda and Azores highs occur over the oceans. The oval shape to these high pressure cells cause different thermal structure in the lower troposphere on their eastern and western sides. On the east, subsidence from the Hadley circulation is enhanced as a result of the tendency for air to preserve its angular momentum on the rotating earth. This concept<sup>13</sup> can be illustrated using the relation:

$$\frac{\xi_z + f}{\Delta p} = \text{constant}$$

where the left side is called *potential vorticity*. Vorticity,  $\xi_z + f$ , is a measure of the circulation over an area and  $\Delta p$  is the difference in pressure between the top and bottom of the planetary boundary layer. The quantity  $f$ , called the *Coriolis parameter* and equal to  $2\pi \text{ day}^{-1} \sin \phi$ , represents the circulation of air due to the rotation of the earth at latitude  $\phi$ . The variable  $\xi_z$ , the *relative vorticity* is the rotation imposed on air as a result of pressure gradient and frictional forces, which can be expressed as:

$$\xi_z = \frac{\Delta V}{\Delta n} + \frac{V}{R_T}$$

where  $\Delta V/\Delta n$  is the horizontal gradient of velocity perpendicular to the flow direction and  $R_T$  is the apparent radius of the trajectory of an air parcel with velocity  $V$ .

To the extent that the subtropical high pressure systems are circular and symmetric,  $V/R_T$  and  $\Delta V/\Delta n$ , and therefore,  $\xi_z$ , are constant, while  $f$  decreases moving equatorward on their east side, but increases moving poleward on the west side. Since  $(\xi_z + f)/\Delta p$  needs to be a constant if potential vorticity is conserved,  $\Delta p$  must become smaller through descent in the lower troposphere on the east and become greater through ascent in the west since pressure remains essentially constant in time at the surface. As a result of the enhanced descent in the eastern oceans, land masses adjacent to these areas tend to be deserts such as found in northwest and southwest Africa and along western coastal Mexico. In contrast,

<sup>13</sup>See also Section 3.8.4.



despite being under the descending branch of the Hadley cell, western continental fringes of the subtropical oceans have precipitation since the stabilization effect of the subsidence portion of the Hadley cell is minimized by the upward vertical velocity associated with the circular subtropical high pressure cells.

The aridity found along the west coasts of continents in subtropical latitudes is further enhanced by the influence of the equatorward surface flow around the high pressure cells on the ocean currents. This flow exerts a shearing stress on the ocean surface which results in the deflection to the right in the northern hemisphere and to the left in the southern hemisphere of the layer of water above the oceanic thermocline. This deflection is a result of the tendency for the water to conserve its angular momentum and therefore to move westward when displaced toward the equator. Cold, lower-level water from below the thermocline rises to the surface to replace this offshore ocean flow. Called *upwelling*, these areas of cold, coastal surface waters result in enhanced atmospheric stability in the lower troposphere and an even further reduction in the likelihood for precipitation although fogs and low stratus clouds are common. Upwelling regions are also associated with enriched sea life as the cold, oxygen- and nutrient-rich bottom ocean waters are transported up to near the surface.

North-south oriented mountain barriers and large massifs, such as the Rocky Mountains, Scandanavian Mountains, and Tibetan Plateau also influence the atmospheric flow. By imposing a barrier to the general westerly flow in midlatitudes, air tends to be blocked and transported poleward west of the terrain and equatorward east of the obstacle. Air that is forced up the barrier often is sufficiently moist to produce considerable precipitation on windward mountain slopes, while subsidence on the lee slopes produces more arid conditions. The elevated terrain affects the atmosphere as if it were an anticyclone, with the result that warm air is transported further towards the pole west of the terrain. It is also difficult for cold air in the interior to move westward of the terrain, therefore, relatively mild weather for the latitude exists, for example, along the west coast of North America. East-west mountain barriers such as the Alps, in contrast, offer little impediment to the general westerly flow resulting in maritime conditions extending far inland.

A major focus of weather forecasting in the mid and high latitudes is to forecast the movement and development of extratropical cyclones, polar and arctic highs, and the location and intensity of subtropical ridges. Spring and fall frosts, for example, are associated with the equatorward movement of polar highs behind a cold front, while droughts and heat waves in the summer are associated with unusually strong subtropical ridges.

## 5.2 Continental United States Climate

The sources of air masses into the continental United States is illustrated schematically in Fig. 5.3. The symbols have the following definitions:

<i>m</i> : maritime	<i>T</i> : tropical
<i>c</i> : continental	<i>P</i> : polar
	<i>A</i> : arctic

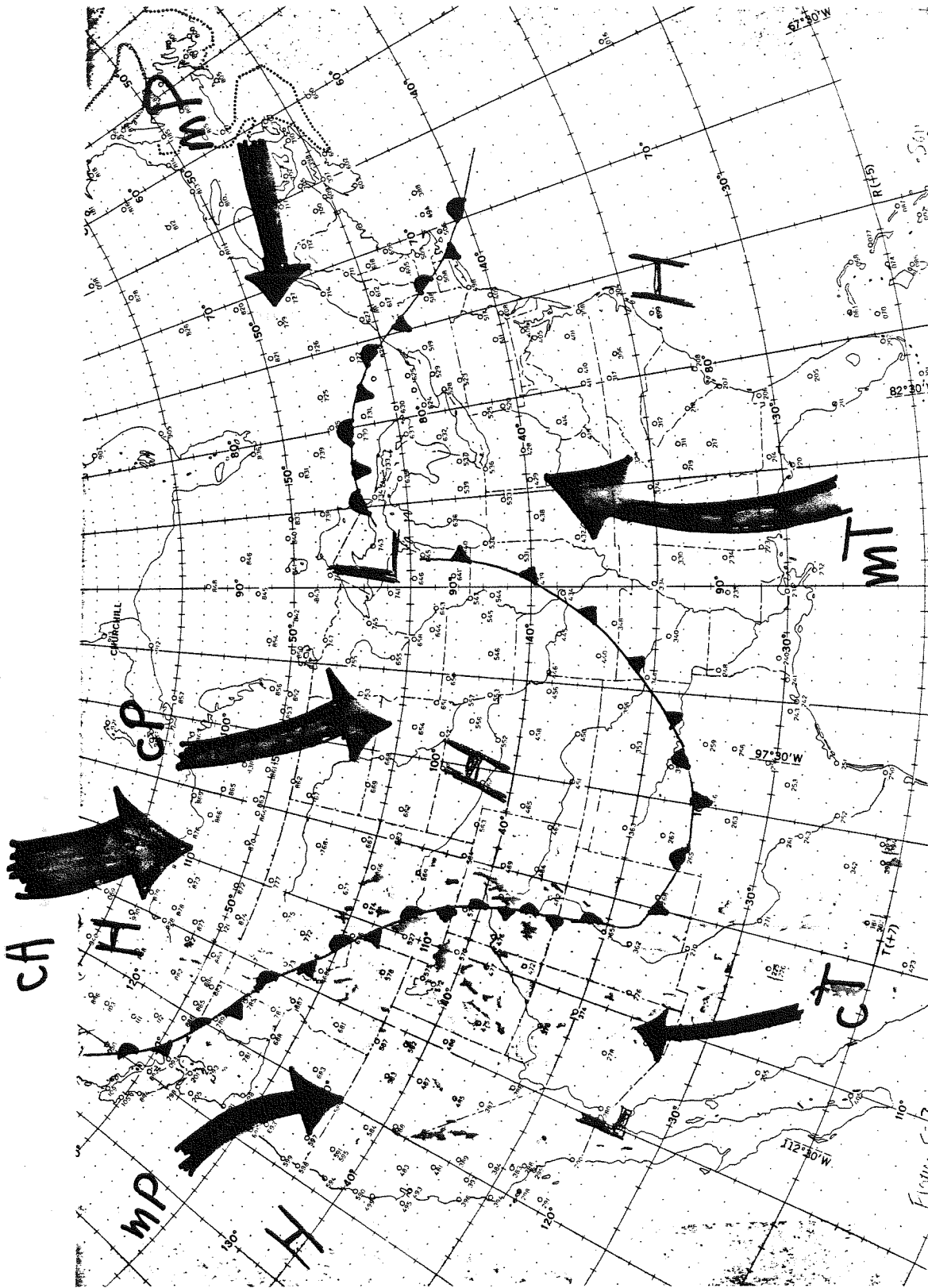


Figure 5.3: The sources of air masses into the United States with the following symbols defined. *m*: maritime; *c*: continental; *T*: tropical, *P*: polar; and *A*: arctic.

The maritime polar air ( $mP$ ), of course, has its origins over the north Pacific and Atlantic Oceans where cold surface waters exist, while the maritime tropical ( $mT$ ) air originates in the much warmer Gulf of Mexico and in the Atlantic Ocean off of the southeast U.S. coast over the Gulf Stream. Continental polar air ( $cP$ ) develops over the prairies of central and north-central Canada, while continental arctic air ( $cA$ ) originates farther north, often from as far away as Siberia. When tropical air overruns polar air, such as occurs north of a warm or stationary front, the symbolism, e.g.,

$$\frac{mT}{cP} \text{ or } \frac{mT}{mP}$$

is used. When a conversion of one air mass type to another is ongoing then the notation, e.g.,

$$cP \implies mP$$

is applied.

As discussed in Section 3, it is the juxtaposition of cold and warm air masses, resulting in a large horizontal thickness gradient, that results in extratropical storm development. Therefore, regions where equatorward moving polar air collides with poleward moving tropical air would be expected to be a preferred region of cyclogenesis.

In the continental United States, these regions include:

- the Gulf of Mexico,
- lee of the central Rockies,
- lee of the Alberta Rockies, and
- off the east coast.

These extratropical cyclones, of course, are a major mechanism of heat and moisture exchange between the tropics and polar regions.

In the tropical ( $mT$ ) air masses,  $\frac{\partial \theta_E}{\partial z} < 0$ , generally, in the lower troposphere particularly during the summer, so that clouds, if formed, are usually cumuliform. Low-layered clouds in these air masses under such conditions are infrequent.

Using this characterization of air mass type and the components of the Omega equation from Section 3.8.3, a surface weather map can be categorized as illustrated in Fig. 5.4a using surface information alone. The reasons for the separate classifications and a number of their characteristics are summarized in Tables 5.1 through 5.3.

If upper-air information were available, Category 2 would naturally be decomposed into two separate classes – one with positive vorticity advection, the other with negative vorticity advection. Both would be associated with warm advection in the lower troposphere.

The atmospheric dispersion characteristics of the different categories, based on the vertical thermodynamic structure and wind flow patterns, are schematically illustrated in

Table 5.1: Synoptic classification scheme used when integrating a mesoscale model using climatological data (modified from Lindsey 1980).

Category	Air mass	Reason for categorization <sup>†</sup>
I	$mT$	<i>In the warm sector of an extratropical cyclone.</i> In this region the thickness and vorticity advection is weak with little curvature to the surface isobars. There is limited low-level convergence with an upper-level ridge tending to produce subsidence. Southerly low-level winds are typical.
II	$mT/cP$ , $mT/cA$ , $mP/cA$ ,	<i>Ahead of the warm front in the region of cyclonic curvature to the surface isobars.</i> Warm air advecting upslope over the cold air stabilizes the thermal stratification, while positive vorticity advection and low-level frictional convergence add to the vertical lifting close to the low center. Further from the low center, negative vorticity advection, and resultant subsidence, enhance the stabilization of the temperature profile. Because of the warm advection, the geostrophic winds veer with height. Low-level winds are generally northeasterly through southeasterly.
III	$cP$ ; $cA$	<i>Behind the cold front in the region of cyclonic curvature to the surface isobars.</i> Positive vorticity advection and negative thermal advection dominate, with the resultant cooling causing strong boundary layer mixing. The resulting thermal stratification in the lower troposphere is neutral, or even slightly, superadiabatic. Gusty winds are usually associated with this sector of an extratropical cyclone. Because of the cold advection, the geostrophic winds back with height. Low-level winds are generally from the northwest through southwest.
IV	$cP$ ; $cA$	<i>Under a polar high in a region of anticyclonic curvature to the surface isobars.</i> Negative vorticity, weak negative thermal advection and low-level frictional divergence usually occur, producing boundary layer subsidence. Because of relatively cool air aloft, the thermal stratification is only slightly stabilized during the day, despite the subsidence. At night, however, the relatively weak surface pressure gradient associated with this category causes very stable layers near the ground on clear nights due to longwave radiational cooling. The low-level geostrophic winds are usually light to moderate varying slowly from northwesterly to southeasterly as the ridge progresses eastward past a fixed location.
V	$mT$	<i>In the vicinity of a subtropical ridge</i> where the vorticity and thickness advection and the horizontal pressure gradient at all levels are weak. The large upper-level ridge, along with the anticyclonically curved low-level pressure field, produces weak but persistent subsidence. This sinking causes a stabilization of the atmosphere throughout the troposphere. Low-level winds over the eastern United States associated with these systems tend to blow from the southeast through southwest.

<sup>†</sup> This discussion applies to the northern hemisphere.

Table 5.2: Relation of synoptic category to aspects of airflow related to synoptic trajectories.

Feature	Category 1	Category 2	Category 3	Category 4	Category 5
Low-level wind direction	S to SW	ESE to NE	N to W	NW to SW (light speeds)	SE to SW
Midlevel wind direction	S to SW	S to SW	W to SW	W to NW	SW to NW (light speeds)
Low-level thermodynamic stability	summer: convectively unstable, $\partial\theta_E/\partial z < 0$ ; winter: often convectively stable, $\partial\theta_E/\partial z > 0$	$\frac{\partial\theta_E}{\partial z} > 0$	$\frac{\partial\theta_E}{\partial z} \cong 0$	$\frac{\partial\theta_E}{\partial z} > 0$	$\frac{\partial\theta_E}{\partial z} > 0$
Midlevel thermodynamic stability	summer: $\frac{\partial\theta_E}{\partial z} < 0$ winter: usually $\frac{\partial\theta_E}{\partial z} > 0$	summer: usually $\frac{\partial\theta_E}{\partial z} < 0$ winter: usually $\frac{\partial\theta_E}{\partial z} > 0$	$\frac{\partial\theta_E}{\partial z} \sim 0$	$\frac{\partial\theta_E}{\partial z} > 0$	$\frac{\partial\theta_E}{\partial z} > 0$
Cold advection			yes		
Warm advection	yes but weak	yes		yes, aloft	yes but weak
Positive vorticity advection	yes but weak	yes, close to the low center	yes		
Negative vorticity advection		yes, further from the low center		yes	
Expected mesoscale influence, if any	squall lines	lake effect	lake effect	lake breezes urban circulations	mesoscale convective systems
Direction of source of air low level:	from S to SW	from ESE to NE	from N to W	local	from SE to SW
midlevel:	from S to SW	from S to SW	from W to SW	from W to NW	from SW to NW
Type of precipitation, if any	convective	summer: convective and/or stratiform; winter: usually stratiform	light stratiform near Category 2; shallow, convective showers, Category 3, if any	none	convective
Expected trajectory model to be used	summer: ARL above; winter: MiTa PBL; ARL: below PBL	summer: ARL above; winter: MiTa inversion; ARL: below inversion	MiTA: above PBL; ARL: below PBL	MiTA: above PBL; ARL: below PBL	ARL
Average ascent or descent of air, $w$ low level:	$\bar{w} \sim 0$	$\bar{w} \sim 0$	$\bar{w} \lesssim 0$	$\bar{w} \sim 0$	$\bar{w} \lesssim 0$
midlevel:	$\bar{w} \gtrsim 0$	$\bar{w} > 0$	$\bar{w} > 0$	$\bar{w} < 0$	$\bar{w} < 0$

Table 5.3: Overview of meteorological aspects of the 5 synoptic categories illustrated in Fig. 5.4 which can be directly obtained from synoptic surface analyses (Northern Hemisphere). (Adapted from Forbes and Pielke 1985; and Pielke et al. 1987.)

Category Characteristics	Category 1	Category 2	Category 3	Category 4	Category 5
Category class	<i>mT</i> : In the warm sector of an extra-tropical cyclone	<i>mT/cP</i> , <i>mT/cA</i> , <i>mP/cA</i> : Ahead of the warm front in the region of cyclonic curvature to the surface	<i>cP cA</i> : Behind the cold front in the region of cyclonic curvature to the surface isobars	<i>cP cA</i> : Under a polar high in a region of anti-cyclonic curvature to the surface	<i>mT</i> : In the vicinity and west of a subtropical ridge
Surface winds	Brisk SW surface winds	Light to moderate SE to ENE surface winds	Strong NE to W surface winds	Light and variable winds	Light SE to SW winds
Vertical motion	Weakening synoptic descent as the cold front approaches	Synoptic ascent due to warm advection and negative vorticity advection aloft becomes positive vorticity advection aloft closer to low center, resulting in enhanced vertical motion	Synoptic ascent due to positive vorticity advection aloft (in this region this ascent more than compensates for the descent due to cold advection)	Synoptic descent (due to warm advection and/or negative vorticity advection aloft)	Synoptic subsidence (descending branch of the Hadley cell). Becomes stronger as you approach the ridge axis
Temperature advection	Little temperature advection at the surface	Warm advection above the frontal inversion	Cold advection at the surface	Weak temperature advection at the surface	Weak temperature advection at the surface
Inversion	Weak synoptic subsidence inversion caps planetary boundary layer	Boundary layer capped by frontal inversion	Deep planetary boundary layer	Synoptic subsidence inversion and/or warm advection aloft create an inversion which caps the planetary boundary layer	Synoptic subsidence inversion
Diurnal variation in boundary-layer stability	Moderate diurnal variability in the boundary-layer stability	Little diurnal variability in the boundary-layer stability because of cloud cover	Little diurnal variability in the boundary-layer stability because of strong winds and destabilizing of boundary-layer by cold advection	In the absence of snow cover because of clear skies and light winds there is large diurnal variability in boundary-layer stability	Moderate diurnal variability in boundary-layer stability

Table 5.3: Continued.

Category Characteristics	Category 1	Category 2	Category 3	Category 4	Category 5
Humidity near the surface	Often humid in relative and absolute sense	Often dry in absolute sense, but humid in relative sense	Dry in the absolute sense: usually dry in the relative sense	Dry in the absolute sense, humid in the relative sense at night/dry in relative sense during the day except when ground is snow covered	Humid in relative and absolute sense
Cloud cover	Clear to partly cloudy skies except near squall lines	Mostly cloudy to cloudy	Clear to scattered or broken shallow to medium depth convective clouds	Clear except tendency for fog at night	Day: scattered fair weather cumulus; Night: clear (except near the mesoscale systems listed below)
Dominant mesoscale systems	Squall lines	Embedded lines of convection	Forced airflow over rough terrain systems: lake effect storms	Mountain-valley flows, land-sea breezes, urban circulations (thermally-forced systems)	Mountain-valley flows, land-sea breezes, urban circulations (thermally-forced systems)
Precipitation types	Organized lines of convective precipitation	Often stable cloud types and precipitation. Overcast in general	Medium to shallow depth convective clouds, showery precipitation	No precipitation	Shallow low convective clouds with deeper convective clouds and precipitation organized by thermally-forced mesoscale systems such as listed above
Ventilation	Moderate to good ventilation	Poor ventilation of low-level (i.e. below frontal inversion) emissions	Excellent ventilation	Night or snow-covered ground: poor ventilation; Day: poor to moderate ventilation	Day: moderate to good ventilation; Night: moderate to poor ventilation
Deposition	Dry deposition except wet deposition in showers	Dominated by wet deposition	Dry deposition except in showers	Dry deposition	Dry deposition except wet deposition in showers and thunderstorms
Transport	Long range	Long range above inversion	Long range	More local as you approach the center of the polar high	More local as you approach the center of the subtropical high
Visibility	Moderate	Moderate to poor, in general	Excellent	Becomes less as you approach the center of the polar high	Becomes less as you approach the center of the subtropical high

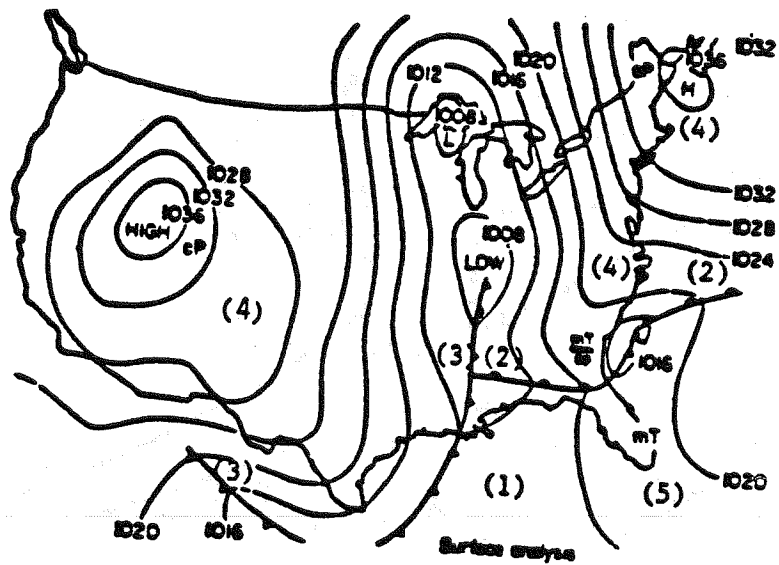


Figure 5.4: (a). Example of a surface analysis chart (for 9 January 1964) showing the application of the synoptic climatological model for the five synoptic classes listed in Table 5.1 (reproduced from Pielke 1982).



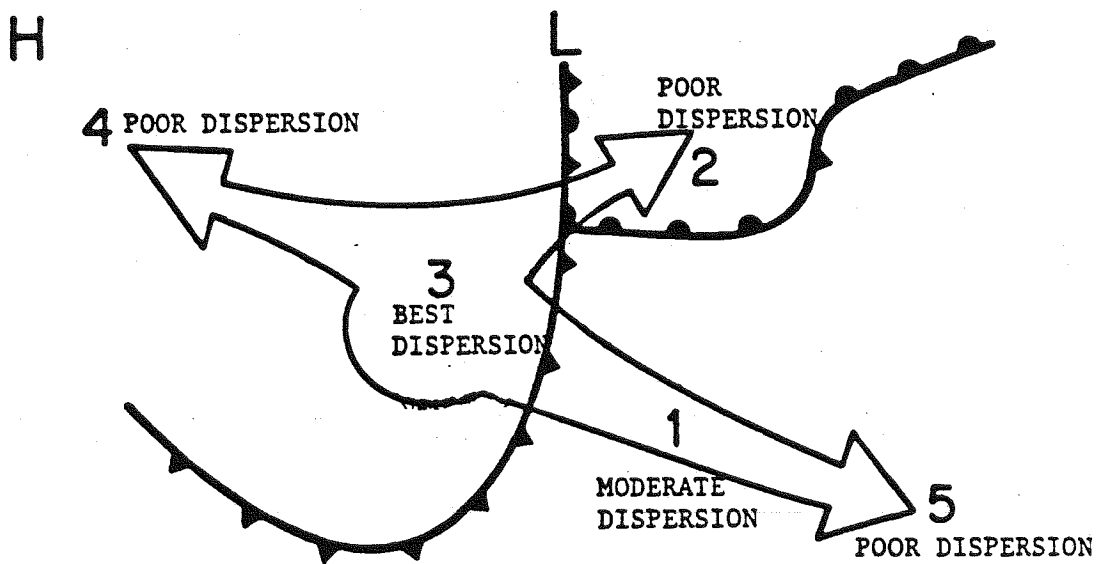


Figure 5.4: (b). Schematic illustration of the relative ability of different synoptic categories to disperse pollutants emitted near the ground (from Pielke et al. 1985).

Fig. 5.4b. Poor dispersion would normally be associated with poor visibility if pollution or water sources occur within the air mass.

Pielke et al. (1987) discusses an approach to define meteorologically-based seasons using these synoptic classes and the frequency of locations poleward and equatorward of the polar front. This procedure is discussed in the following text.

The definition of seasons for meteorological applications, in midlatitudes particularly, is usually made with respect to either the astronomical calendar or a division of the calendar into four three-month periods. Using this approach, seasons are conventionally defined as shown in Table 5.4.

Table 5.4: Conventional definitions of seasons.

	Winter	Spring	Summer	Fall
Astronomical definition	Winter solstice to spring equinox (on or about 22 December to on or about 21 March)	Spring equinox to summer solstice (on or about 21 March to on or about 21 June)	Summer solstice to autumnal equinox (on or about 21 June to on or about 22 September)	Autumnal equinox to winter solstice (on or about 22 September to on or about 22 December)
Calendar definition	December, January, February	March, April, May	June, July, August	September, October, November

Unfortunately, these definitions are arbitrary and independent of geostrophic latitude, and thus, are not very informative concerning actual meteorological seasons. An early, cold frontal passage in New England in early September, for example, is obviously indicative of colder season weather, yet using the astronomical definition of season in Table 5.4, one would presume it is still summer.

With this method we hypothesize that meteorological seasons at a site could be defined with respect to geographic location relative to the polar front. The synoptic classification scheme presented previously was used to specify broad meteorological features. Conditions poleward of the front are assumed to be characteristic of the winter season, and in contrast, locations equatorward of the front are experiencing the summer season-type characteristics.

Figures 5.5a and b present examples of weather maps in July and December where cold and warm fronts on the polar front are indicated. Note that the polar front tends to be more poleward in the summer. Five major synoptic categories are defined using synoptic surface analyses that have the general characteristics summarized in Tables 5.1 to 5.3. Category 4, the region corresponding to an equatorward bulge in the polar high with sinking air through the lower and midtroposphere is a winter characteristic air mass which is beginning the process of mixing with the warmer air at the lower latitudes. Of course this is the mechanism by which the general circulation of the earth seeks (but does not reach) a thermal equilibrium. Category 5 is associated with the western periphery of a subtropical ridge. The subtropical

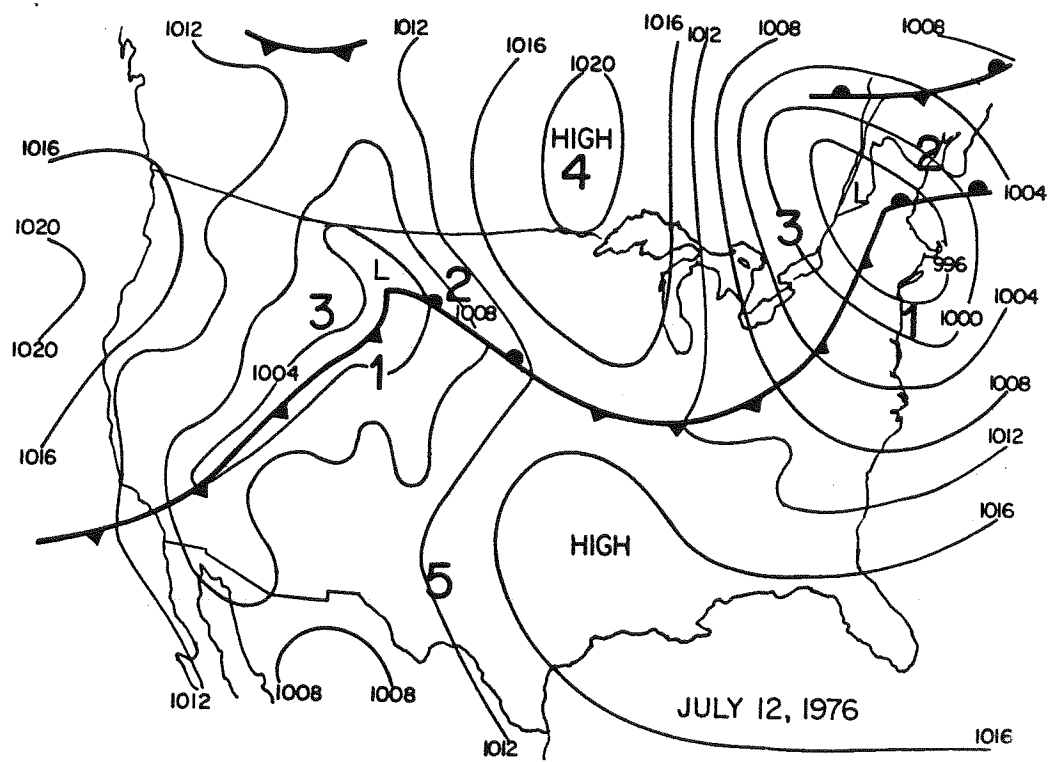


Figure 5.5: (a). Synoptic classification scheme illustrating a typical summer pattern.

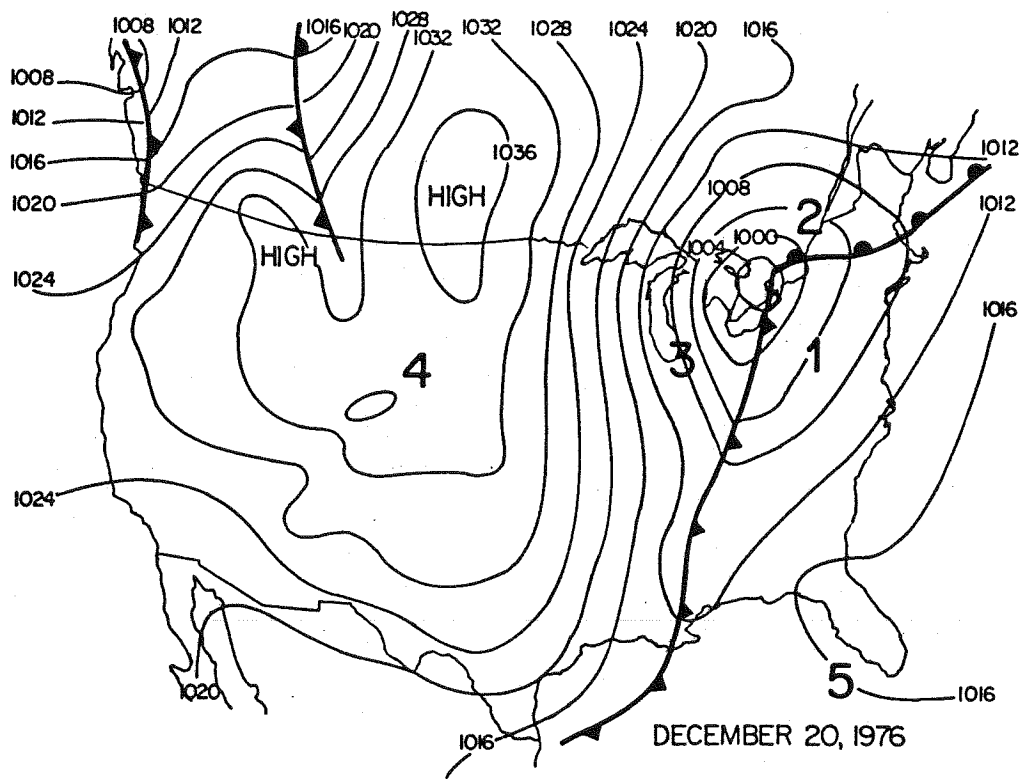


Figure 5.5: (b). Synoptic classification scheme illustrating a typical winter pattern.

ridge results from the descending portion of the Hadley Cell. Since, in general, over the United States high pressure regions (i.e., where the surface isobars are anticyclonic) cover larger areas than low pressure circulations (i.e., where the surface isobars are cyclonic), it is expected that Categories 4 and 5 situations geographically should be more common than Categories 1, 2, and 3. Category 4 is most common poleward of the polar front; Category 5 is most common for tens of degrees of latitude equatorward of the front.

Using upper-air synoptic analyses (e.g., 700 mb for temperature advection; 500 mb for vorticity advection), the synoptic classification could be refined further. Figure 5.5c illustrates how the categories could be further classified using typical locations of cold and warm advection, and positive and negative vorticity advection. In the absence of conveniently available upper-air data, however, the surface map alone can be used effectively in a synoptic climatological analysis.

The classification of surface weather maps can be performed subjectively. In the studies listed in the next two paragraphs, the maps were analyzed once a day although more frequent evaluations are straightforward. In order to estimate the reproducibility of the categorization technique, at least two, and occasionally three individuals independently classify a sample set of weather maps for the area and time period of interest. In the eastern United States, there is agreement about 90 percent of the time. Disagreements occur either because the pattern is ill-defined or a location is in transition between categories and there is ambiguity as to which classification to place a location. In the mountainous western United States, because of the requirement to reduce pressure from terrain height to sea level using an arbitrary specification of temperature lapse rate, the degree of agreement between analysts reduces to about 80 percent. In several of the analyses (e.g., Yu and Pielke 1986), an undefined category was identified for the situations in which it was not straightforward to identify a synoptic class.

As mentioned above, several investigations have used this synoptic categorization to analyze local climatology. In Yu and Pielke (1986), for example, the frequency and duration of these synoptic classes for a five-year period between October and May in southern Utah were determined as part of an air quality study. Pielke et al. (1986) used these synoptic categories and subclasses related to surface synoptic geostrophic wind speed and direction within each category to estimate worst case air pollution dispersion situations over southern Florida. Garstang et al. (1980) and Lindsey (1980), where this synoptic classification procedure was first introduced, determined the daily frequency of the different synoptic categories for a 10-year period along the Atlantic and Gulf coasts of the United States. Lindsey and Glantz (1984, 1986) used this approach to characterize local meteorology at nuclear facilities.

Figures 5.6 through 5.14 from Garstang et al. (1980) and Lindsey (1980) illustrate the 10-year average variation of the five synoptic categories during the year for several geographic locations. The data was produced for 52 stations from a 10-year record of twice daily observations with 9 representative sites presented in these figures. The data was smoothed using a 25-day running average.

An obvious result of this type of analysis is that it is straightforward to interpret seasons in terms of frequency of time that a location is poleward and equatorward of the polar front. Categories 2, 3, and 4 occur poleward and Categories 1 and 5 are situated on the warm side of the front. Therefore, meteorological seasons can be defined as:

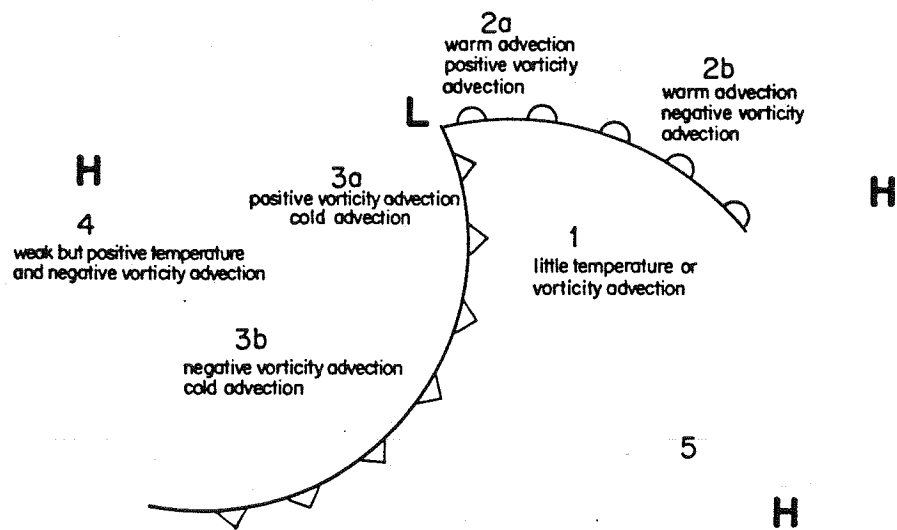


Figure 5.5: (c). Schematic as to how temperature and vorticity advection patterns could be used to refine synoptic classification scheme.

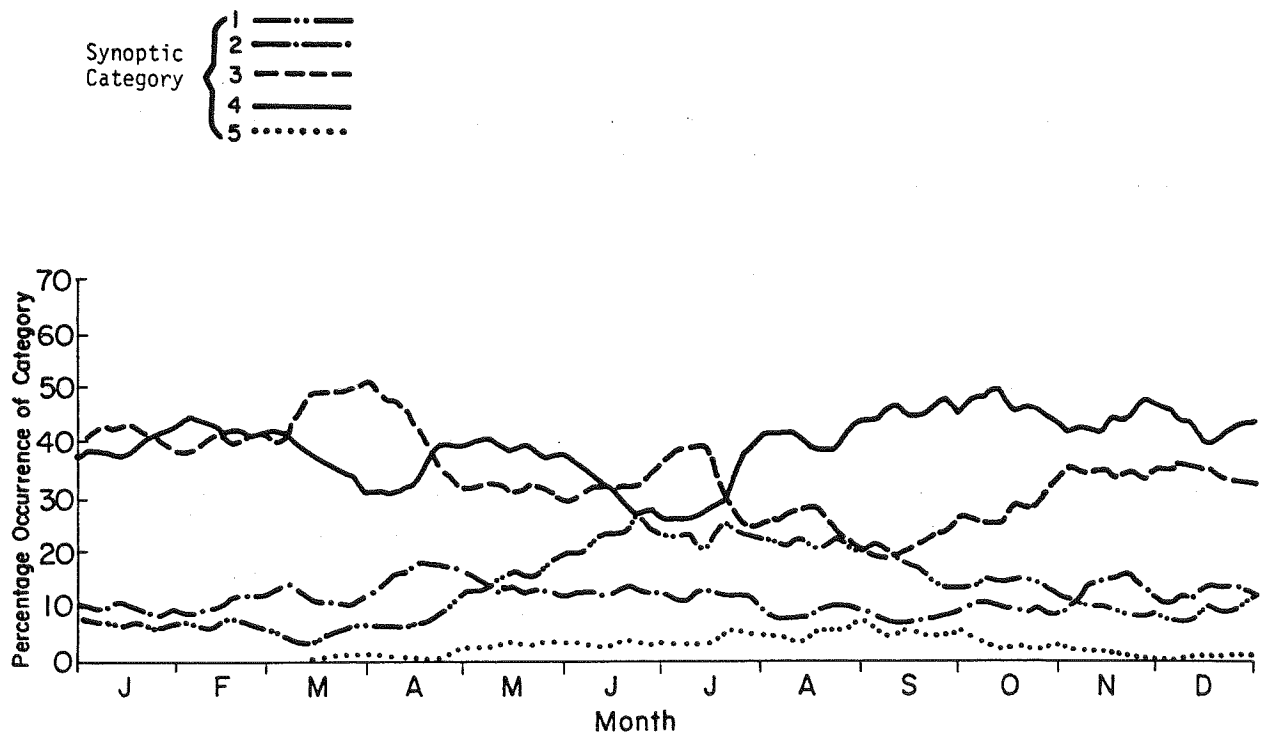


Figure 5.6: 25-day weighted average frequency distributions of synoptic categories for Portland, Maine stations: 1 January 1955 – 31 December 1964, from Garstang et al. (1980), and Lindsey (1980).

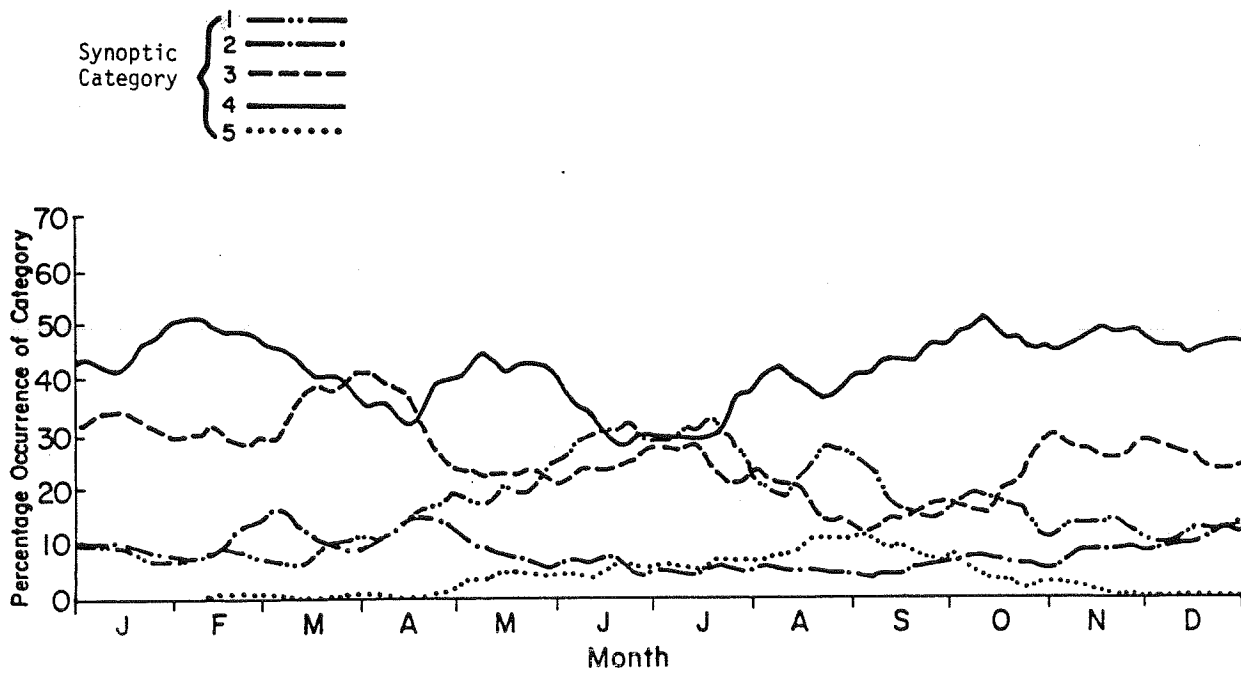


Figure 5.7: 25-day weighted average frequency distributions of synoptic categories for New York City, New York stations: 1 January 1955 – 31 December 1964, from Garstang et al. (1980), and Lindsey (1980).



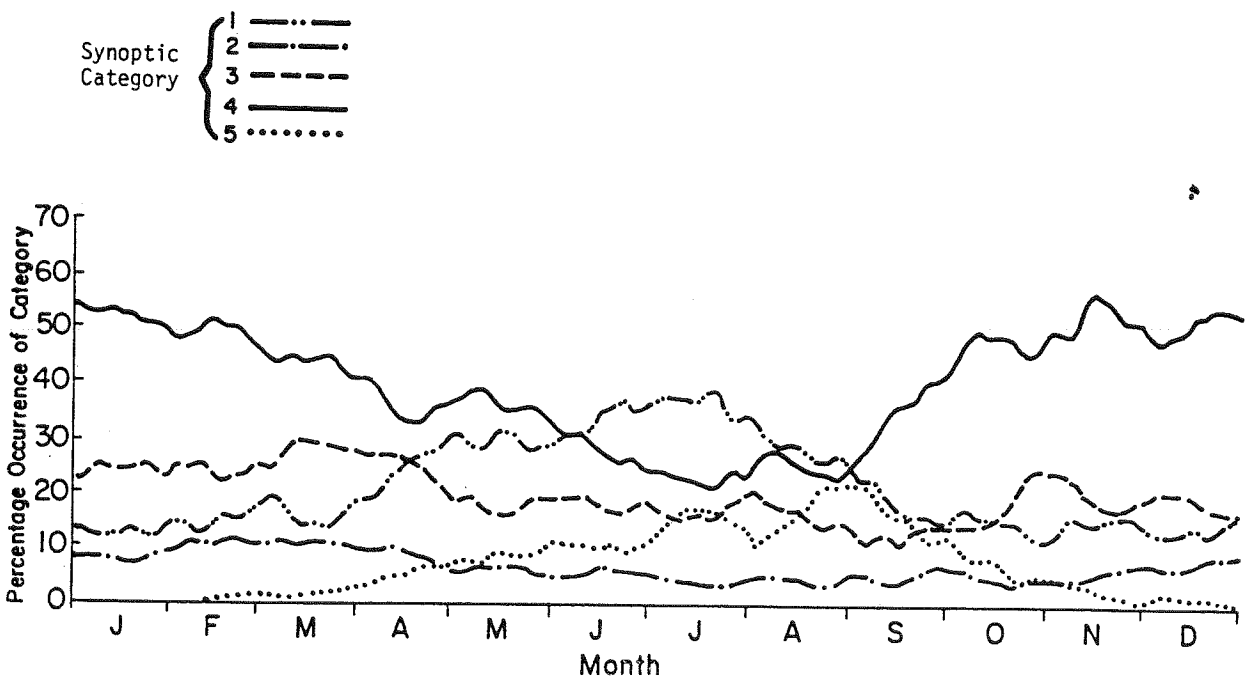


Figure 5.8: 25-day weighted average frequency distributions of synoptic categories for Hampton, Virginia stations: 1 January 1955 – 31 December 1964, from Garstang et al. (1980), and Lindsey (1980).

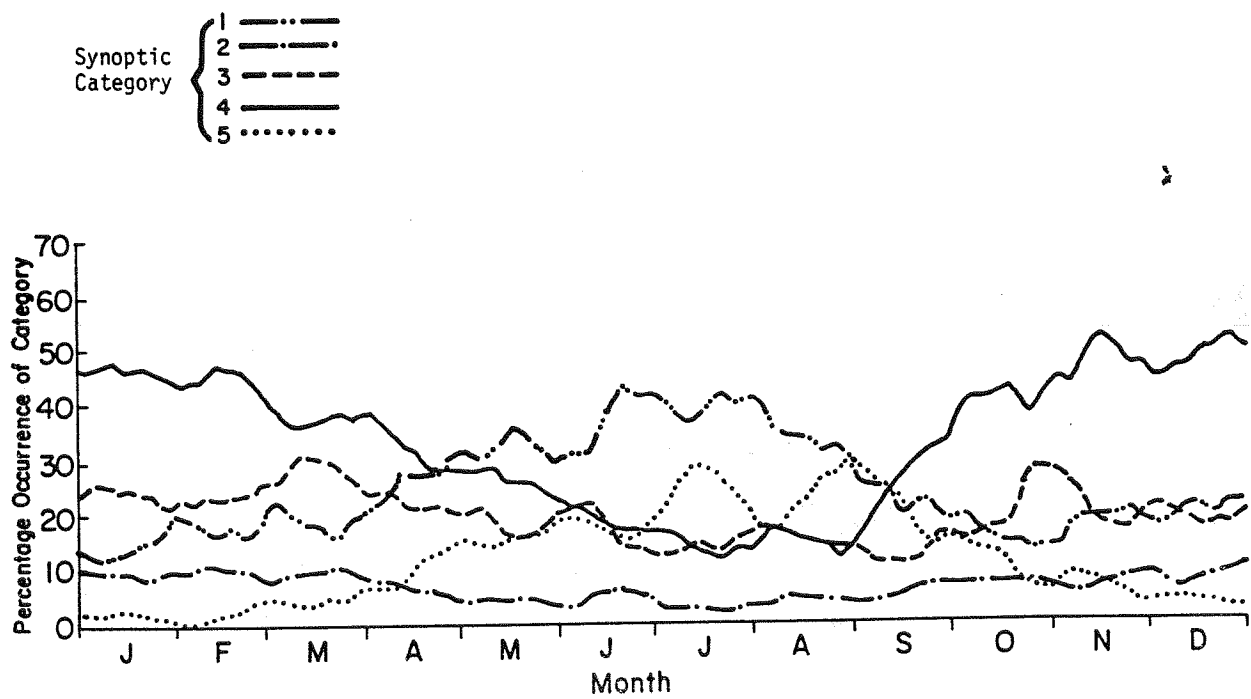


Figure 5.9: 25-day weighted average frequency distributions of synoptic categories for Cape Hatteras, North Carolina stations: 1 January 1955 – 31 December 1964, from Garstang et al. (1980), and Lindsey (1980).

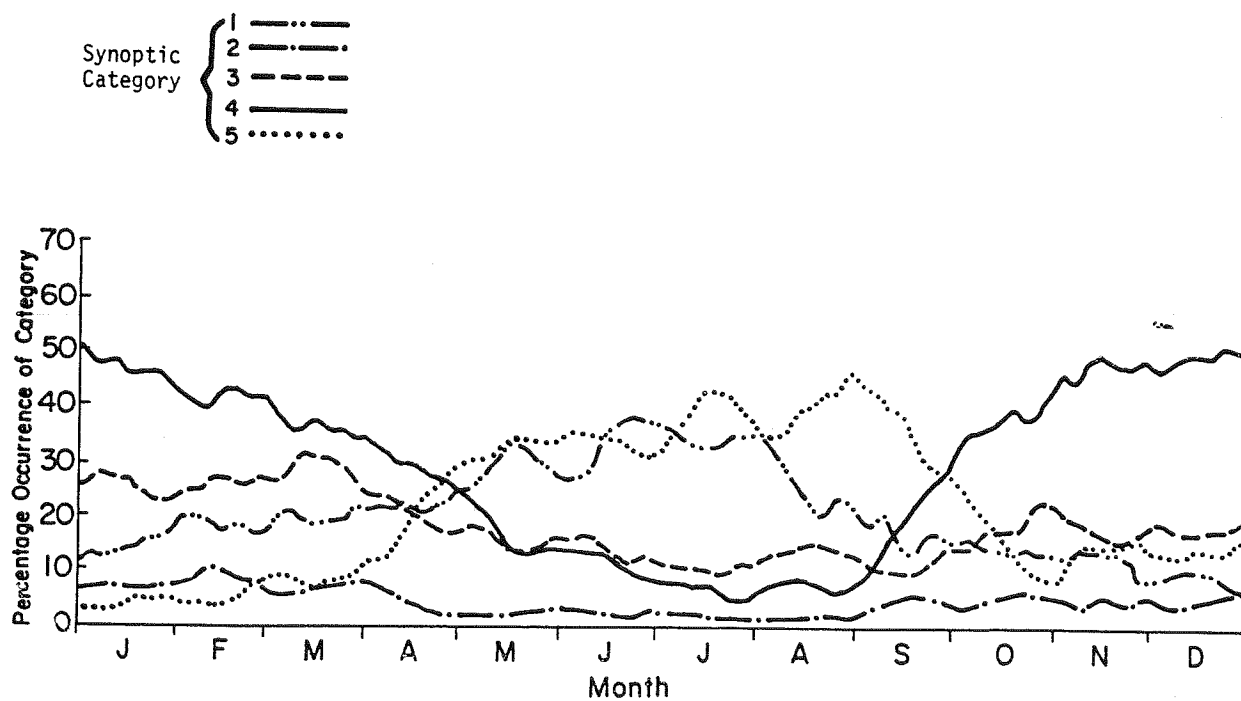


Figure 5.10: 25-day weighted average frequency distributions of synoptic categories for Charleston, South Carolina stations: 1 January 1955 – 31 December 1964, from Garstang et al. (1980), and Lindsey (1980).

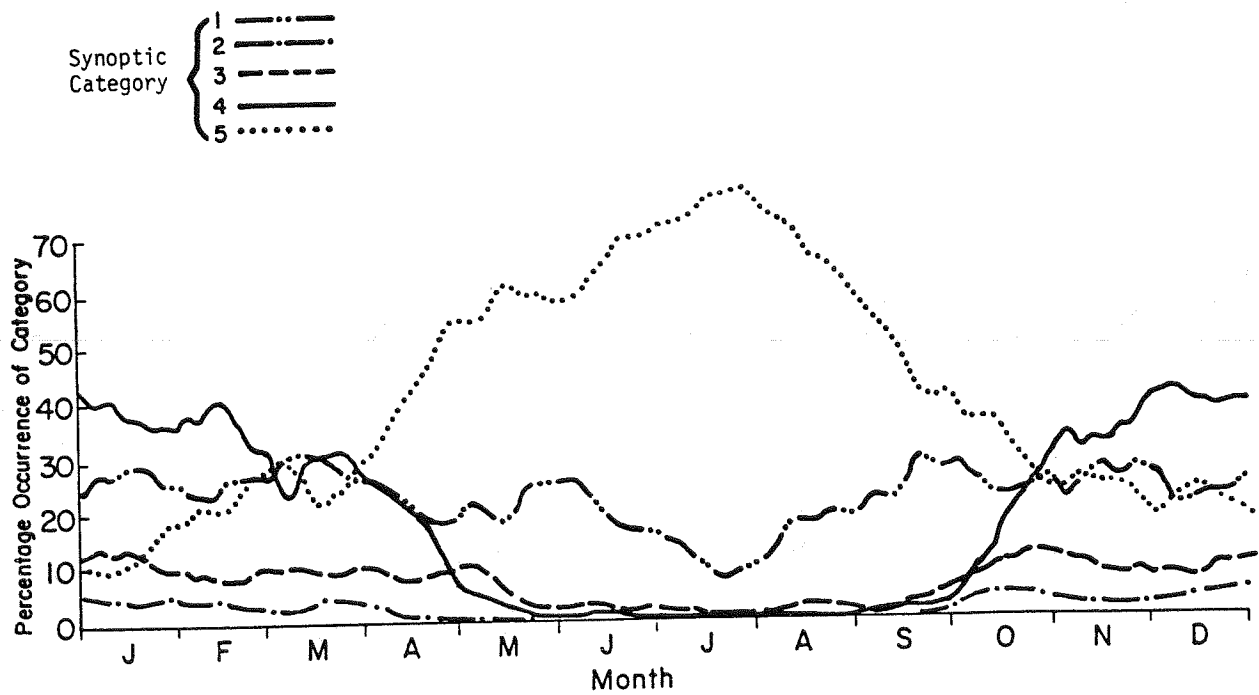


Figure 5.11: 25-day weighted average frequency distributions of synoptic categories for Miami, Florida stations: 1 January 1955 – 31 December 1964, from Garstang et al. (1980), and Lindsey (1980).

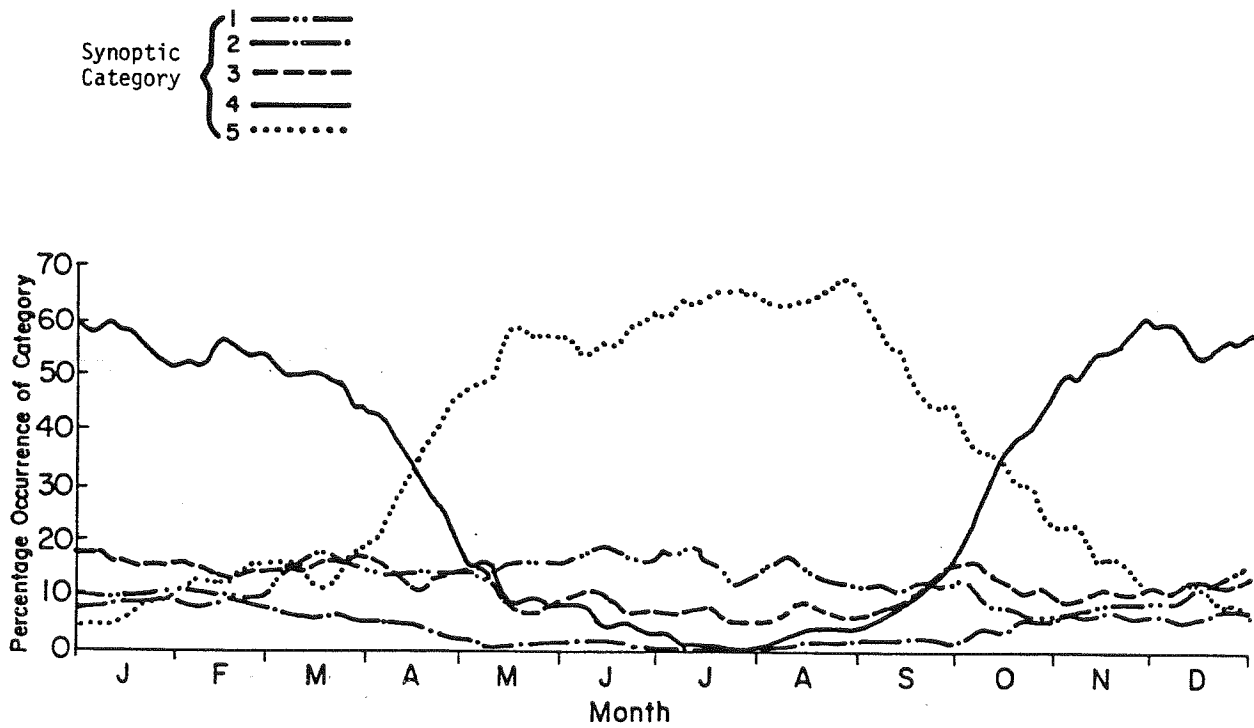


Figure 5.12: 25-day weighted average frequency distributions of synoptic categories for Mobile, Alabama stations: 1 January 1955 – 31 December 1964, from Garstang et al. (1980), and Lindsey (1980).

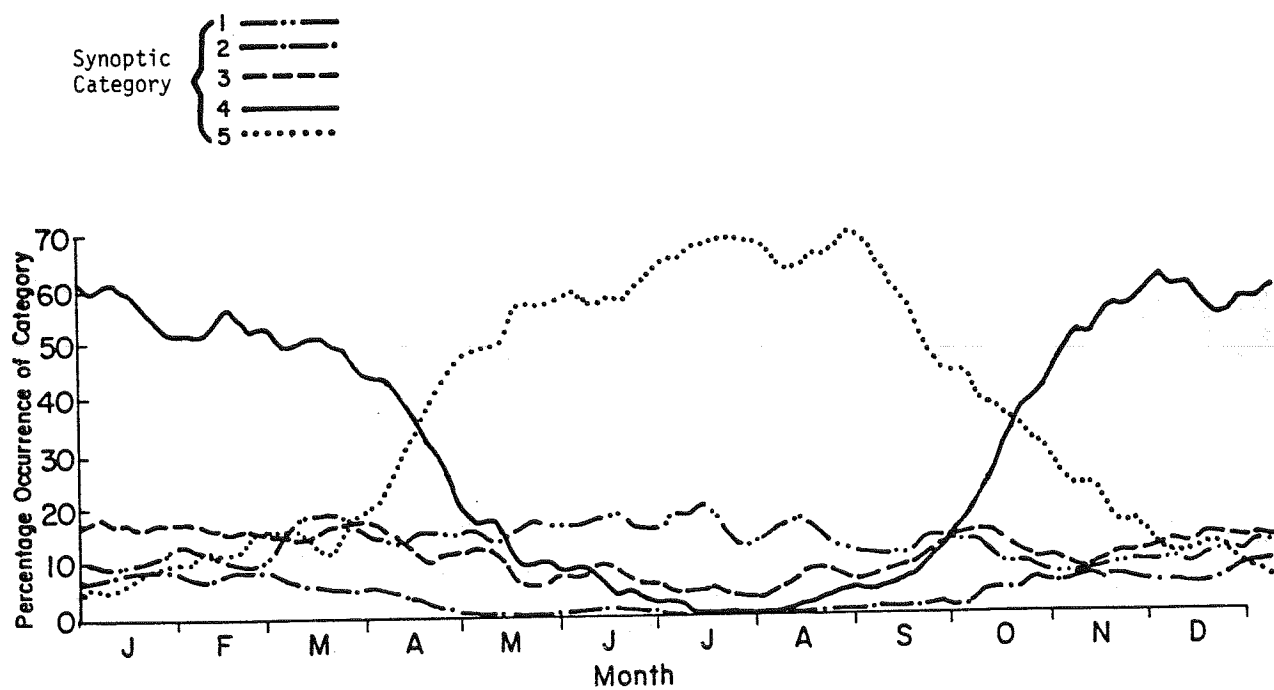


Figure 5.13: 25-day weighted average frequency distributions of synoptic categories for New Orleans, Louisiana stations: 1 January 1955 – 31 December 1964, from Garstang et al. (1980), and Lindsey (1980).

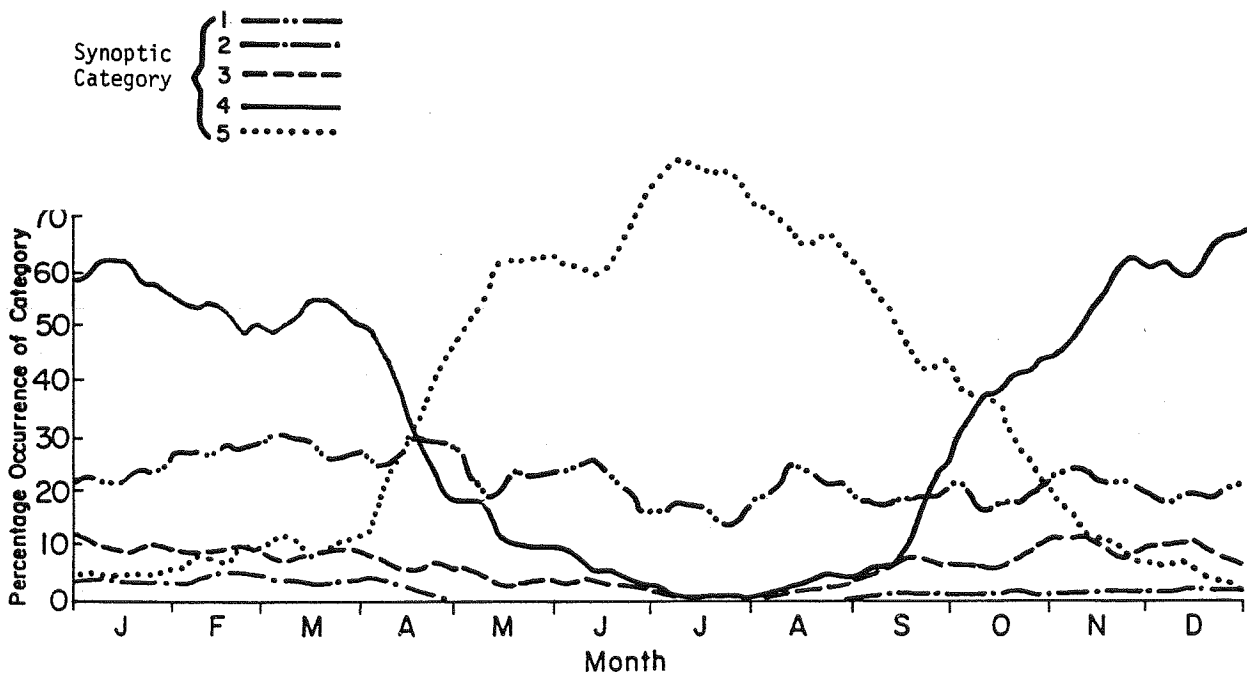


Figure 5.14: 25-day weighted average frequency distributions of synoptic categories for Brownsville, Texas stations: 1 January 1955 – 31 December 1964, from Garstang et al. (1980), and Lindsey (1980).

- winter: highest frequency of Category 2, 3, and 4 occurrences,
- summer: highest frequency of Category 1 and 5 occurrences,

with fall and spring being the transition to the more constant frequencies found during the winter (cold) and summer (warm) seasons.

To quantify this definition, the following procedure, originally reported in Lindsay (1980) and Garstang et al. (1980) was used. The cumulative changes in frequency of occurrence of Categories 2, 3, and 4, defined as  $\Delta S$ , were calculated and plotted, as shown in Figs. 5.15 through 5.23.  $\Delta S$  for day  $n$  is defined as:

$$\Delta S_n = \Delta S_{n-1} + (C2_n - C2_{n-1}) + (C3_n - C3_{n-1}) + (C4_n - C4_{n-1}) \quad (5.1)$$

where  $CN_n$  is the 25-day weighted average of the frequency of occurrence of category  $N$  on day  $n$  and,

$$\Delta S_0 = 0.$$

The slope of the  $\Delta S$  plots or  $\Delta^2 S$  plots, was used to provide a quantitative definition of seasons for any station as follows:  $\Delta^2 S$  is measured across 91 days to eliminate short-term fluctuations. Thus,  $\Delta^2 S$  for day  $n$  is:

$$\Delta^2 S_n = \Delta S_{n-45} - \Delta S_{n+45}; \quad n = 1, \dots, 365 \quad (5.2)$$

(Since  $\Delta S$  is based on 10 years of data,  $\Delta^2 S$  can be taken across the end of the calendar year.) When  $\Delta^2 S$  has been calculated for each day of the calendar year, a positive cut-off value,  $\beta$ , is selected, and the value of  $\Delta^2 S$  for each day is compared with  $\beta$ . 1 January is defined as winter; as long as the value of  $\Delta^2 S$  remains greater than or equal to  $-\beta$ , each succeeding day is classified as winter. When  $\Delta^2 S < -\beta$ , then the first day of spring is defined. As long as this condition is met, each succeeding day is classed as spring. Similarly, the condition for summer is  $|\Delta^2 S| \leq \beta$ , and for fall is  $\Delta^2 S > \beta$ . Thus,

$$\text{winter : } \quad \Delta^2 S \geq -\beta$$

$$\text{spring : } \quad \Delta^2 S < -\beta$$

$$\text{summer : } \quad |\Delta^2 S| \leq \beta$$

$$\text{fall : } \quad \Delta^2 S > \beta$$

A problem arises in defining the last days of spring and fall because in many cases  $\Delta^2 S$  changes from spring to summer and then back to spring conditions again, and similarly for fall-winter-fall. This problem is met by defining the first day of summer as the *last* time  $\Delta^2 S$  changes from spring to summer conditions and the first day of winter as the *last* time  $\Delta^2 S$  changes from fall to winter conditions.

Since the  $\Delta S$  plots show a great variation in range (maximum  $\Delta S$  - minimum  $\Delta S$ ), the cut-off value was made a function of the range of  $\Delta S$  for each station. A Fortran program was



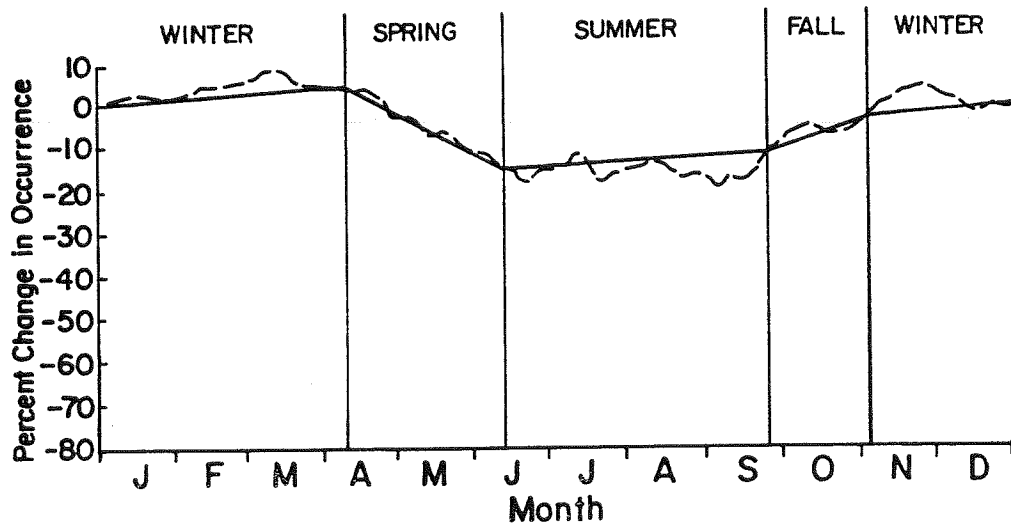


Figure 5.15: Changes in frequency of synoptic categories 2, 3, and 4 for Portland, Maine – 1955-1964 using Fig. 5.6.

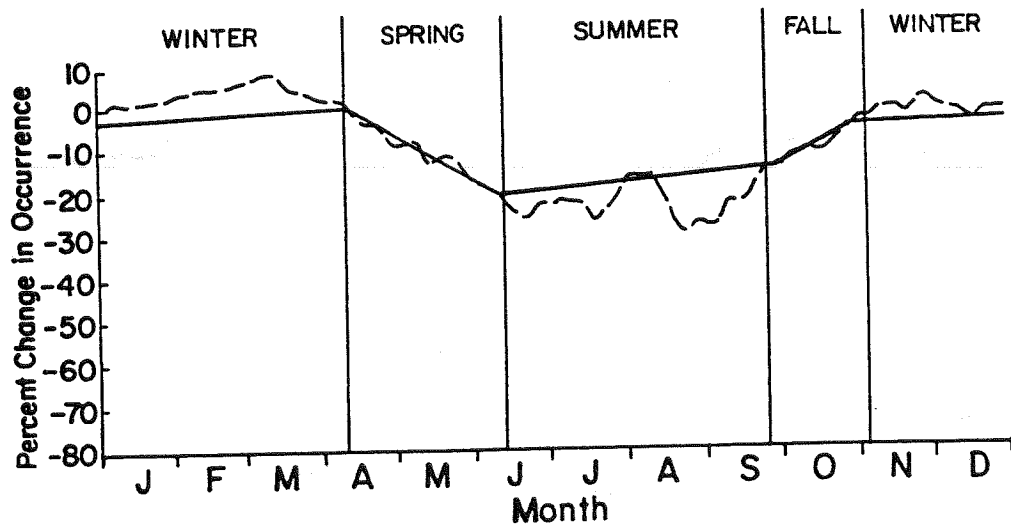


Figure 5.16: Changes in frequency of synoptic categories 2, 3, and 4 for New York City, New York – 1955-1964 using Fig. 5.7.

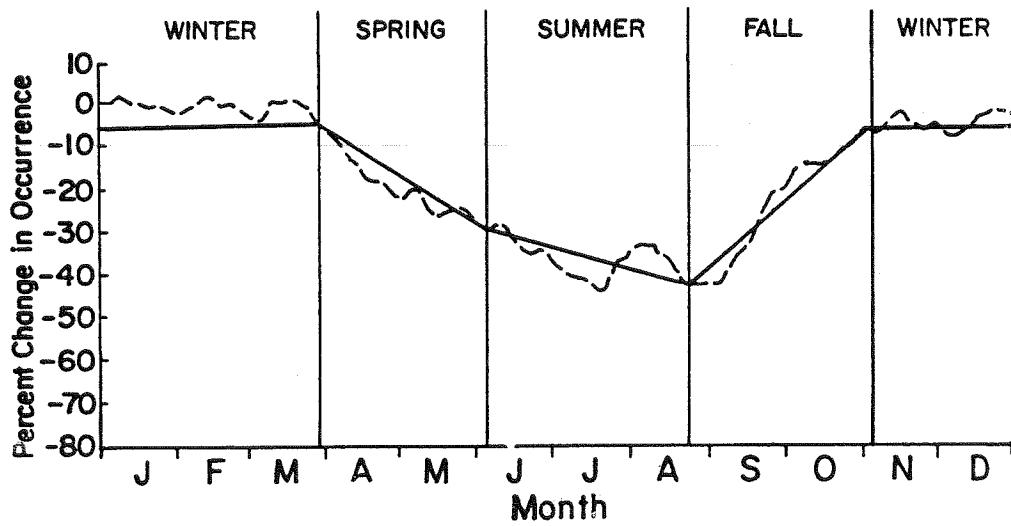


Figure 5.17: Changes in frequency of synoptic categories 2, 3, and 4 for Hampton, Virginia – 1955-1964 using Fig. 5.8.

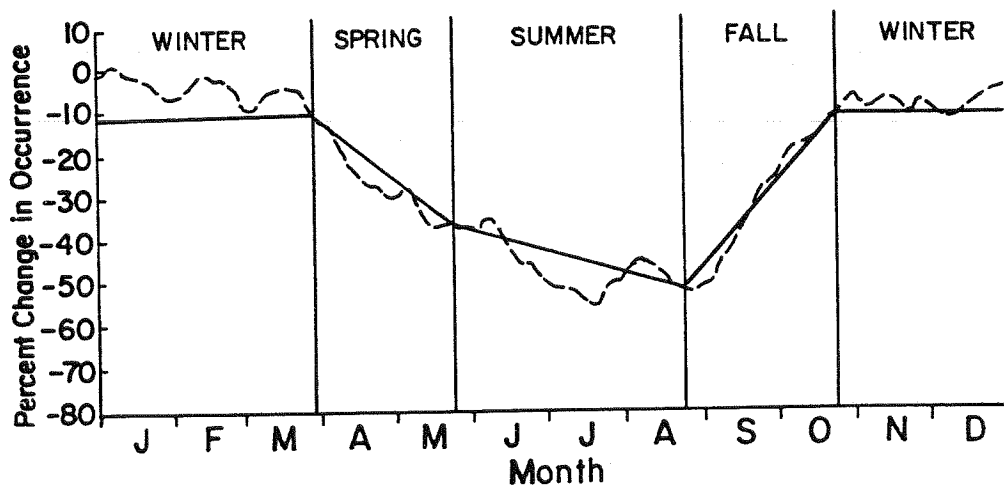


Figure 5.18: Changes in frequency of synoptic categories 2, 3, and 4 for Cape Hatteras, North Carolina – 1955-1964 using Fig. 5.9.

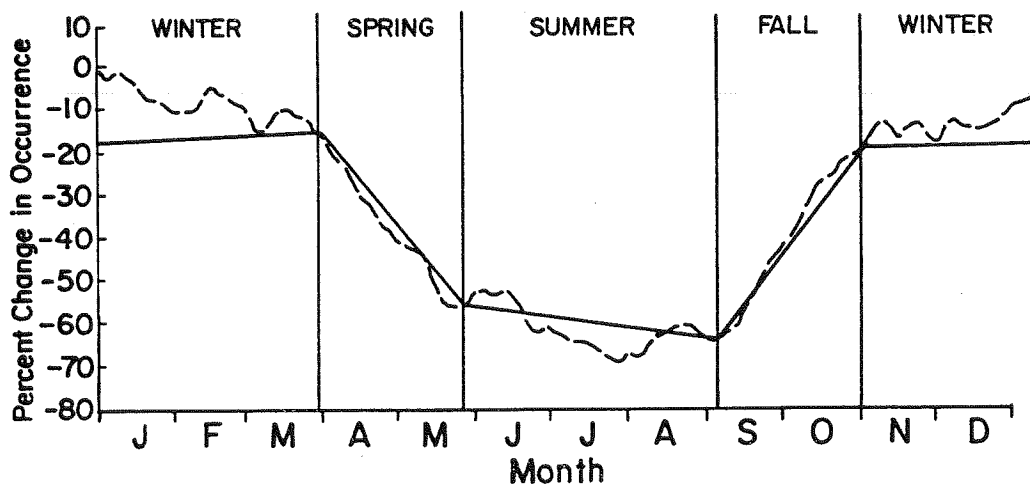


Figure 5.19: Changes in frequency of synoptic categories 2, 3, and 4 for Charleston, South Carolina – 1955-1964 using Fig. 5.10.

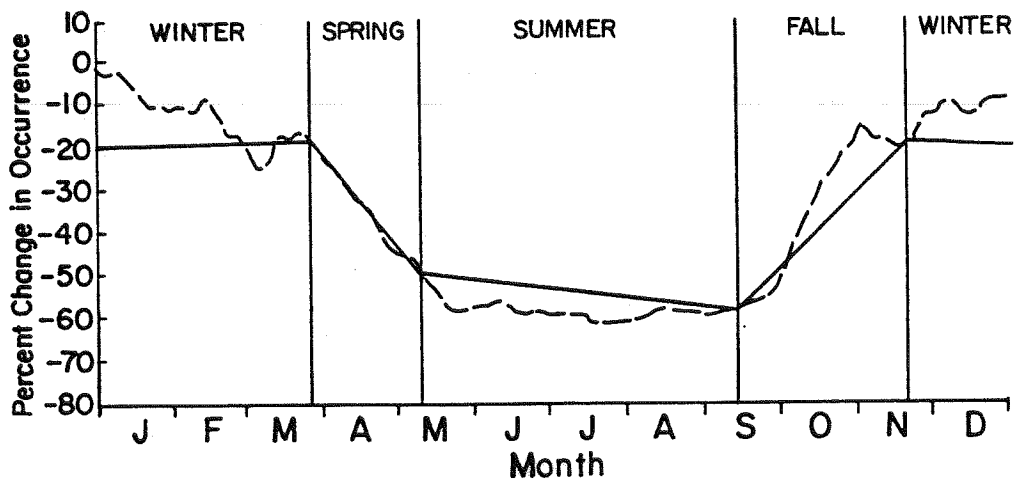


Figure 5.20: Changes in frequency of synoptic categories 2, 3, and 4 for Miami, Florida – 1955-1964 using Fig. 5.11.

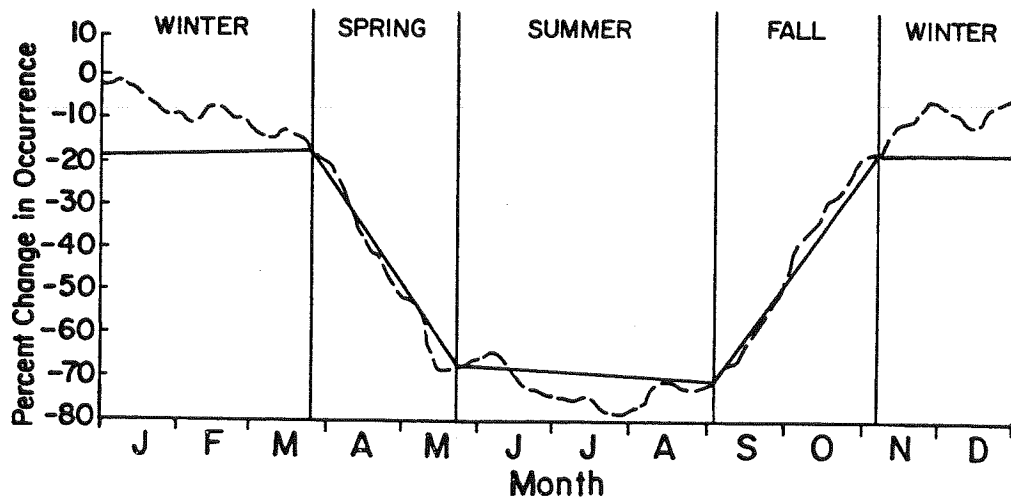


Figure 5.21: Changes in frequency of synoptic categories 2, 3, and 4 for Mobile, Alabama – 1955-1964 using Fig. 5.12.

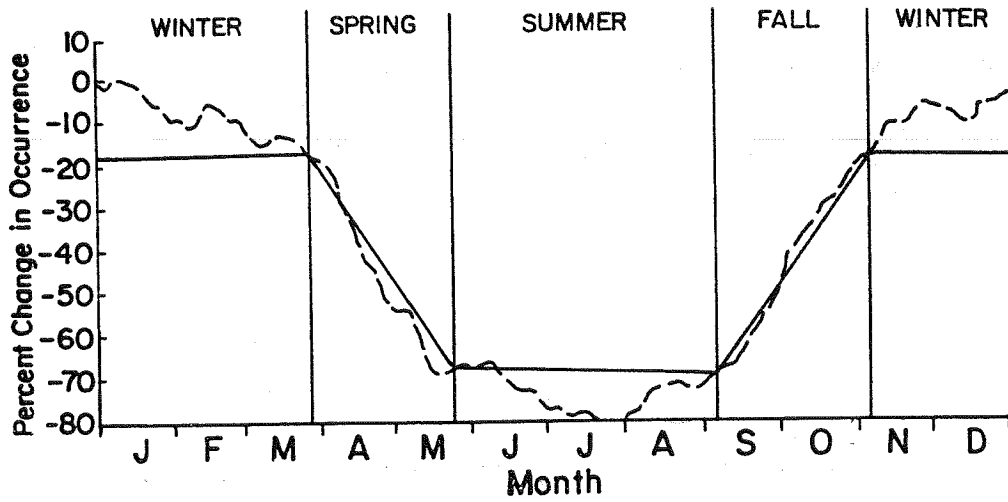


Figure 5.22: Changes in frequency of synoptic categories 2, 3, and 4 for New Orleans, Louisiana – 1955-1964 using Fig. 5.13.



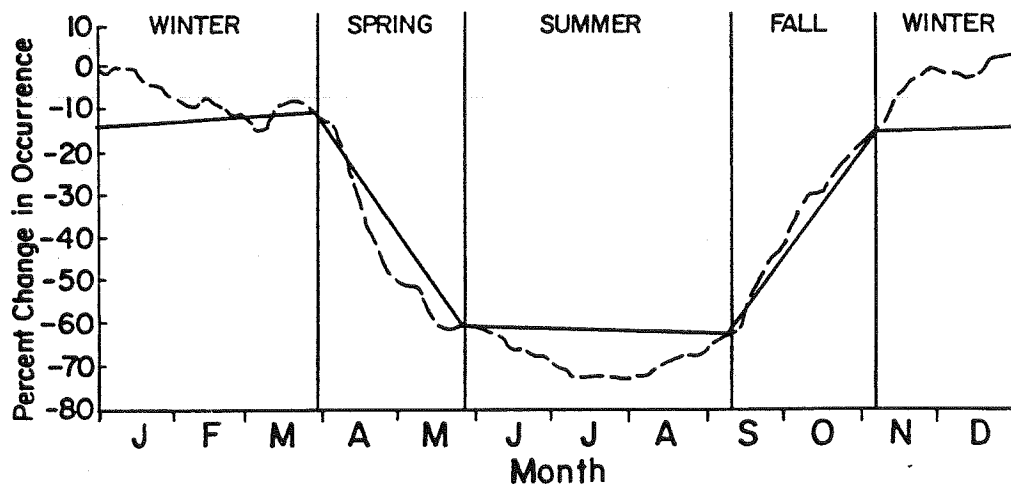


Figure 5.23: Changes in frequency of synoptic categories 2, 3, and 4 for Brownsville, Texas - 1955-1964 using Fig. 5.14.

used to calculate seasons for each representative station using seven cut-off values between  $0.4 \times \text{range}$  and  $0.7 \times \text{range}$ . Each of these seasons were drawn on the 25-day average synoptic frequency and  $\Delta S$  plots, and the best one (shown on Figs. 5.15 through 5.23) was selected for each station. The criteria of selection were as follows.

On the  $\Delta S$  plots lines were drawn connecting the intersections of the  $\Delta S$  line with the seasonal demarcations. These connecting lines should be as flat as possible for winter and summer, and as steep as possible for spring and fall. On the 25-day average synoptic frequency plots, spring and fall should include most or all of the rapid changes in frequency of individual categories from their summer to winter levels.

When all of the best fitting seasonal plots were compared, it was discovered that the coefficient by which the ranges were multiplied to get the best fits is itself an approximate inverse function of latitude,  $\varphi$ . That is, if each range is multiplied by  $(90^\circ - \varphi) \times 0.0105$ , the cut-off obtained is close to the selected best fit. All of the seasons displayed in Figs. 5.15 through 5.23 and in Table 5.5 are based on cut-offs determined by this formula. The ranges, latitudes, cut-offs, and seasonal dates for each of the selected stations are shown in Table 5.5.

In going from the most northerly to the most southerly station, one might expect spring and summer to begin earlier, and fall and winter to begin later. Although there is a clear progression to earlier summers between Portland and Miami, the first days of summer for Mobile, New Orleans, and Brownsville are not consistent with this trend. Furthermore, none of the other seasonal starts show consistent trends with latitude. For example, fall begins earlier at Hatteras than over New England. This is because the seasons are defined as periods of comparatively constant synoptic conditions (winter and summer) or of transition (spring and fall). They are not selected according to meteorological measurements such as temperature, or length of growing season (although there should be some correlation) so that winter in Brownsville does not indicate the same conditions as found for winter in Portland, but rather the period when the poleward front tends to move to its most equatorward position.

Thus, Brownsville winters are dominated by cold core highs that move southward in the wake of polar front lows that have moved eastward north of that site. Portland's winter weather is dominated by a progression of extratropical lows that generally move to its south and east resulting in the frequent change from Categories 2 to 3 to 4, and back to 2.

The analysis also suggests that the latitudinal movement of the front is not a steady, smooth progression but occurs as rapid and substantial changes in average position. This result should not be too surprising since after the spring equinox the northern latitudes of the United States can warm rapidly because of long daylight, thereby reducing or eliminating the horizontal temperature gradient which is required to support the polar front within the contiguous United States. Therefore, the polar front reestablishes itself further north. In the fall the rapid cooling in northern latitudes of the United States permits a strong polar front to develop with vigorous extratropical storm development. These storms advect cold air (and therefore, the polar front) southward over the country in their wake bringing a relatively rapid transition to fall even in the southern latitudes.

This evaluation suggests that on the average, winter lasts from late October or early November to late March or early April over the Atlantic and Gulf of Mexico coastal regions

Table 5.5: Determination of seasons.

Station	Range	Latitude	Cut-off	First day of			
				Spring	Summer	Fall	Winter
Portland, Maine	27.67	43.65	13.56	4/11	6/14	9/26	11/5
New York City, New York	37.76	40.65	19.64	4/13	6/10	9/30	10/30
Hampton, Virginia	45.76	37.08	25.63	3/30	6/6	8/24	11/4
Hatteras, North Carolina	57.33	35.27	32.68	3/31	5/27	8/26	10/26
Charleston, South Carolina	68.34	32.78	41.00	3/29	5/23	8/31	10/26
Miami, Florida	61.22	25.80	41.02	3/30	5/13	9/16	11/23
Mobile, Alabama	78.77	30.68	48.84	3/28	5/25	9/5	11/8
New Orleans, Louisiana	80.91	29.95	50.97	3/29	5/26	9/7	11/7
Brownsville, Texas	75.03	25.92	50.27	3/31	5/27	9/11	11/7

of the United States. Summer is from late May to early June until late August or late September.

Whether this type of analysis has utility elsewhere in the midlatitudes still needs to be examined, however, the term "midlatitudes" itself is often used by meteorologists subjectively to describe regions which are equatorward on average with respect to the polar front in the summer, but frequently in its vicinity during the colder season. Over Europe, similar definitions should hold with northern Europe having less frequent incursions of polar air during the warmer season, and southern Europe being predominantly influenced by the subtropical ridge well south of the polar front, during the summer.

These notes discuss the application of a synoptic classification scheme to define frequency of occurrence of major weather features as related to the polar front, and to use the frequency of times a location is poleward of the front to meteorologically define seasons. An example of the use of this technique is presented using 10 years of data from the Atlantic and Gulf coasts of the United States. While the frequency of the specific types of major synoptic weather features vary with latitude, the meteorological definitions of season are comparatively invariant with latitude (differing by no more than a month) for this geographic area. Using a meteorological definition, the average winter occurs from late October or early November to late March or early April. Summer is from late May to early June until late August or late September.

The application of synoptic climatological categories within geographic regions also permits more economical analyses of available climate data. In the original study (e.g., Garstang et al. 1980) from which this material was derived, 52 stations along the Atlantic and Gulf Coasts were available for analysis. By using the climatological categorization, however, relatively homogeneous climate regions could be defined so that only one representative site within each region needed to be analyzed. Thus, the 52 stations could be represented by the nine sites listed in Figs. 5.6 through 5.15.

The analysis presented here suggests that public awareness on a day-to-day basis could be enhanced by knowledge of their relation to the polar front. In the astronomical summer, for example, the period a short time after the passage of a cold front is referred to as "fall" weather, as individuals perceive the transition to an air mass of polar origin. Similarly, in the astronomical "winter", the period after a warm frontal passage is referred to as "spring" weather (particularly if the sun shines). Thus, in a meteorological sense, on a day-by-day basis, a region can transit from meteorological winter (interpreted as "fall" conditions) back to meteorological summer (interpreted as "spring" conditions). When the transitions between meteorological winter and summer become infrequent or occur with a more-or-less constant frequency, one of the two main meteorological seasons (i.e., winter or summer) has arrived. When the frequencies are changing substantially with time, the time of year corresponds to one of the transit seasons (i.e., fall or spring).

Changes in climatic conditions do not occur as just a gradual change in temperature or in the amount of precipitation but rather in the frequency with which a given region is subjected to the dominant synoptic systems, such as defined in these notes. The net result of the aggregation of synoptic systems yields climate. If the aggregation changes, climate changes.

## 5.3 Colorado Climate

The National Weather Service portions Colorado into 17 zones as illustrated in Fig. 5.24. The reason, of course, is that each of these zones either has unique terrain characteristics which markedly influence local weather, and/or cover an area which is small enough that the synoptic-scale influences are assumed to be reasonably uniform over the area.

In this section, examples of local weather patterns for Zone 11 (the Front Range) are presented. An adequate discussion of the entire state would require a book in itself. Zone 11 was chosen: (1) because the most extensive meteorological studies in the state have been made for this area; and (2) the Department of Atmospheric Science at CSU is located in Zone 11 and interest among students is almost always highest regarding local weather.

### 5.3.1 Summer Weather

The generally expected surface flow pattern in Zone 11 on a synoptically undisturbed day is illustrated in Fig. 5.25, reproduced from Toth and Johnson (1985).

Forecasting of the maximum temperature on synoptically undisturbed summer days can be performed effectively using the value of the convective temperature. Once this value is exceeded, the convective condensation level will have been reached and cumulus clouds will begin to develop. Particularly if they have significant vertical development, most of the energy from the sun is used to generate clouds rather than raise the temperature of the layer. Also, clouds shade the ground reducing the surface heating.

A rule of thumb is that if the sky is hazy, the thermodynamic stratification is rather stable and the vertical growth of any cumulus clouds which can develop will be slow. Thus, surface temperatures will be higher. In contrast, if the sky is blue the atmosphere is less stable, the cumulus clouds grow rapidly, and hence the depth of mixing will be higher and the increase of surface temperature will slow or stop.

The minimum temperatures at night under synoptically undisturbed days can be predicted using the dewpoint temperature as the lower value. Although dew formation will permit cooling below that value, the rate of decrease of temperature usually slows once dew occurs. In addition, if dewpoint is close to the temperature at sunset, cooling through a deep enough layer may permit fog to develop.

In Zone 11, a dewpoint depression of less than about 10°C would indicate the strong possibility of fog, particularly in low-lying areas. Such low-lying areas permit the accumulation of cooler air – Greeley is a preferred low-level location for the cooler morning temperatures. In contrast, areas along slopes have higher minimum temperatures than either the ridges or valleys because the cooler air flowing downhill keeps the atmosphere more mixed.

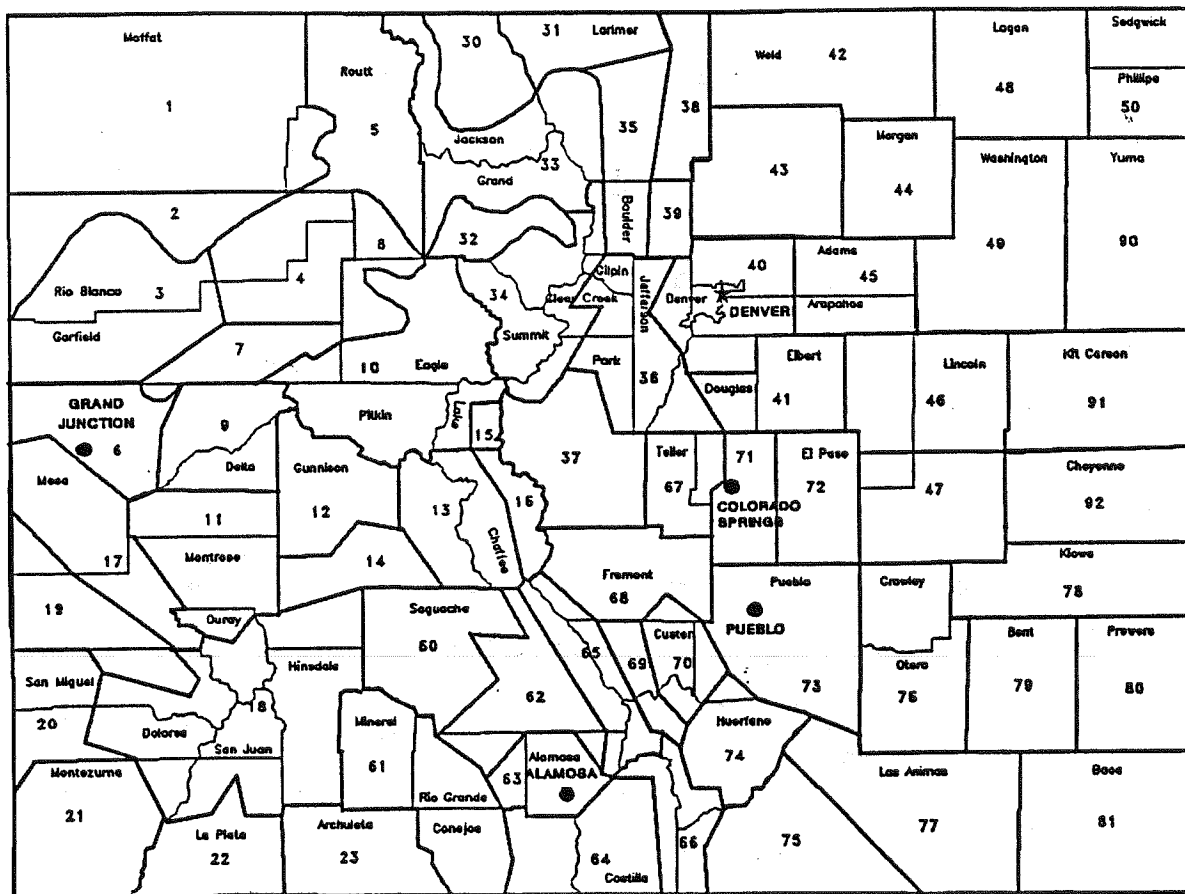
### 5.3.2 Winter Weather

The temperature attained after precipitation begins from stratiform clouds will tend to approach the wet bulb temperature. If this temperature is below freezing, even if the actual temperature before precipitation begins is above freezing, the temperature will fall rapidly below 0°C and ice can form quickly. This occurrence often explains why roads ice over quickly in Colorado when precipitation commences since during the winter the wet bulb temperature is usually below freezing.

# COLORADO

## ZONE FORECAST BOUNDARIES

CO Zones 1-23, 30-50, 60-81 and 90-92 prepared by WSFO Denver, CO  
 CO Zone numbers 24-29, 51-59 and 82-89 reserved for future use.



★ WEATHER SERVICE FORECAST OFFICE  
 ● WEATHER SERVICE OFFICE

NATIONAL WEATHER SERVICE  
 CENTRAL REGION

*Effective October 1, 1993*

Figure 5.24: National Weather Service. Zone Forecast Boundaries.

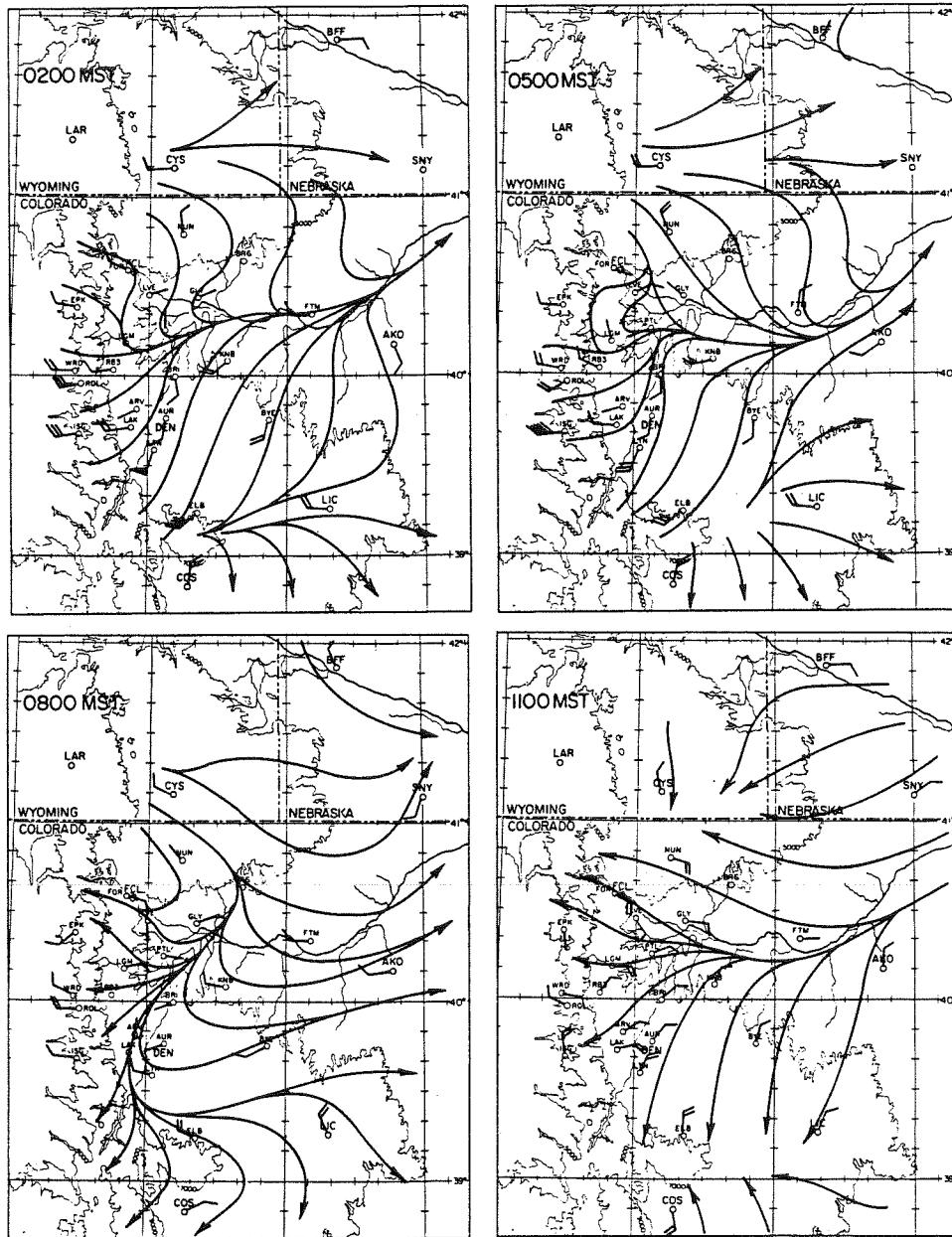


Figure 5.25: Surface streamline analyses for July 1981 (a) 0200 MST; (b) 0500 MST; (c) 0800 MST; (d) 1100 MST; (e) 1400 MST; (f) 1700 MST; (g) 2000 MST; and (h) 2300 MST. Plotted winds are in meters per second (one full barb =  $1 \text{ m s}^{-1}$ ).

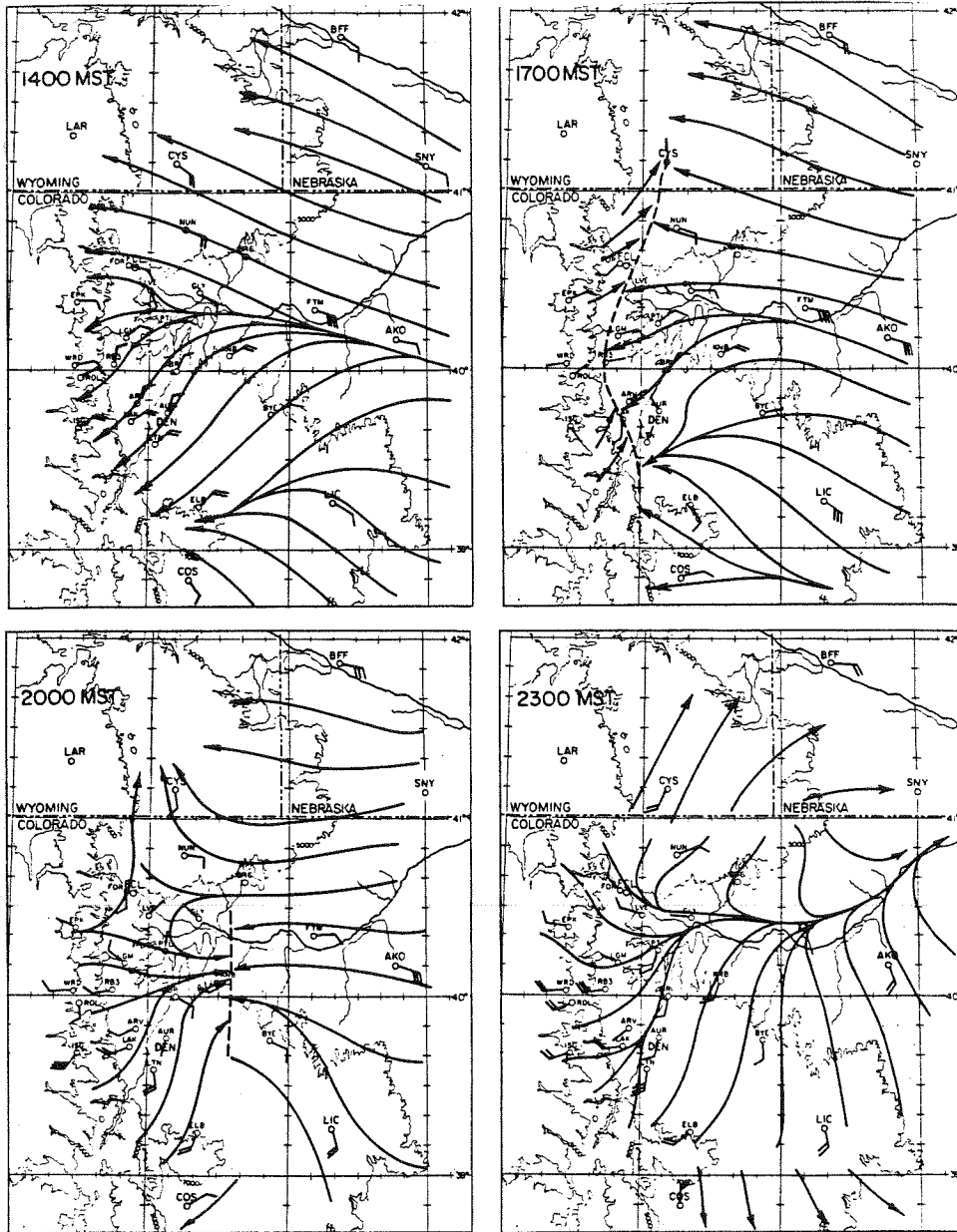


Figure 5.25: Continued.

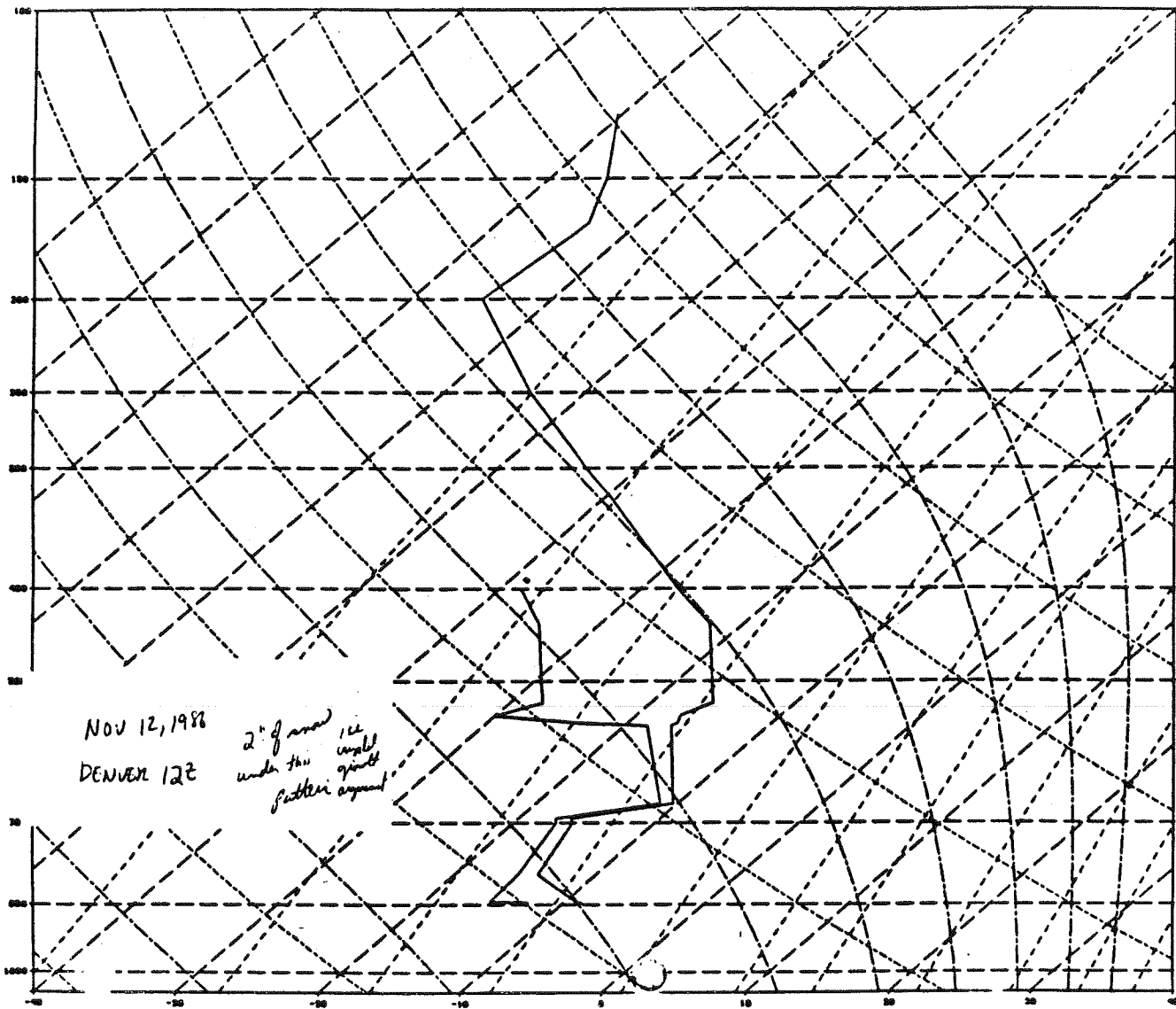


Snowfall rate depends on both the magnitude of ascent and the cloud physics properties of the clouds. Jiusto and Weickmann (1973) presented a discussion of the seeder-feeder concept in which ice crystals falling from a mid- or upper-tropospheric cloud (the seeder cloud) provides the embryo on which supercooled water present in a lower tropospheric cloud (the feeder cloud) grows. When one of these clouds is absent, the precipitation efficiency for the same ascent rate is reduced.

In addition, the greatest rate of snow crystal growth in the lower cloud (if the temperature, of course, is less than  $0^{\circ}\text{C}$ ) will occur when the difference in the saturation pressure between ice and supercooled liquid water is the largest (at about  $-16^{\circ}\text{C}$  where rapid dendritic crystal growth can occur).

Figure 5.26 illustrates an atmospheric sounding in which a 2" snowfall in Ft. Collins occurred. This event occurred even without a seeder cloud because the cloud layer had a deep layer near  $-10^{\circ}\text{C}$ .

061112/1200 73400 DEN 0000 7011 K108 0461  
35 -12 -30 310



--- SF FFF FAE FF E F F E F

Figure 5.26: An example of an atmospheric sounding in which a 2" snowfall occurred in Fort Collins, Colorado.

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## 7. Appendices

**Appendix A – Radiosonde and upper wind reports**

Symbolic form for Rawinsonde Code for use at pressures higher than 100 mb. Code forms are the same at lower pressures but data processing indicators TTCC, TTDD, PPDD, etc. are used.

*MANDATORY* TTAA YGGI<sub>d</sub> II111 99P<sub>o</sub>P<sub>o</sub>P<sub>o</sub> T<sub>o</sub>T<sub>o</sub>T<sub>o</sub>D<sub>o</sub>D<sub>o</sub> d<sub>o</sub>d<sub>o</sub>f<sub>o</sub>f<sub>o</sub>f<sub>o</sub> 00hhh TTT<sub>a</sub> DD dffff  
 85hhh TTT<sub>a</sub> DD dffff 70... 50... 40... 30... 25... 20... 15... 10...  
 88P<sub>t</sub>P<sub>t</sub>P<sub>t</sub> T<sub>t</sub>T<sub>t</sub>T<sub>t</sub>D<sub>t</sub>D<sub>t</sub> d<sub>t</sub>d<sub>t</sub>f<sub>t</sub>f<sub>t</sub>f<sub>t</sub> 77(or 66) P<sub>m</sub>P<sub>m</sub>P<sub>m</sub> d<sub>m</sub>d<sub>m</sub>f<sub>m</sub>f<sub>m</sub>f<sub>m</sub> φ

This format is used for the mandatory levels.

*SIGNIFICANT*

TTBB YGG/ II111 00P<sub>o</sub>P<sub>o</sub>P<sub>o</sub> T<sub>o</sub>T<sub>o</sub>T<sub>o</sub>D<sub>o</sub>D<sub>o</sub> 11PPP TT<sub>a</sub> DD 22PPP TTT<sub>a</sub> DD  
 33... 44... 55... 66... 77... 88... 99... 11... 22... φ

Continues to 100 mb; mandatory levels are included, but treated the same as significant levels. Also, TTBB is used for the beginning of the UX reports, but the format is that of the TTAA section. If you can read the rest of the code, you'll be able to read the UX messages.

*SIGNIFICANT WIND*

PPBB YGGa<sub>4</sub> 9t<sub>n</sub>u<sub>1</sub>u<sub>2</sub>u<sub>3</sub> d<sub>1</sub>d<sub>1</sub>f<sub>1</sub>f<sub>1</sub>f<sub>1</sub> d<sub>2</sub>d<sub>2</sub>f<sub>2</sub>f<sub>2</sub>f<sub>2</sub> d<sub>3</sub>d<sub>3</sub>f<sub>3</sub>f<sub>3</sub>f<sub>3</sub> 9t<sub>n</sub>u<sub>1</sub>u<sub>2</sub>u<sub>3</sub>

... .. φ In addition, abbreviated PPAA winds using the same basic code are included in UC messages for mandatory levels.

General Subscripts:

- o surface data
- t tropopause data
- m maximum wind level

Explanation of symbols:

- YY gives the day of observation. Subtract 50 from the number to get the day of the month.
- GG the time of observation to the nearest whole hour.
- I<sub>d</sub> coded indicator of the last standard isobaric surface for which the wind group is included in TTAA (usually used in practice).
- II block number.
- iii station number.
- 99 when it appears in TTAA indicates that surface data follows.
- PPP pressure in mbs.



- TT when printed within a message section, indicates temperature in degrees Celsius.
- hhh height of a pressure surface; given in meters (with thousands digit dropped) up to 500 mb, and in decameters beyond.
- T<sub>a</sub> the approximate tenths value of the temperature and the sign of the temperature. It is decoded as follows:

<u>Code figure</u>	<u>Sign of temp.</u>	<u>Tenths value of temp.</u>
0	+	0.0 or 0.1
1	-	0.0 or 0.1
2	+	0.2 or 0.3
3	-	0.2 or 0.3
4	+	0.4 or 0.5
5	-	0.4 or 0.5
6	+	0.6 or 0.7
7	-	0.6 or 0.7
8	+	0.8 or 0.9
9	-	0.8 or 0.9

For example:  $-17.6^{\circ}\text{C}$  is coded as 177 for TTT<sub>a</sub>.

- DD Depression of the dew point temperature.  
 Note: When the depression is  $5^{\circ}\text{C}$  or less, the units and tenths figures are reported. When the depression is more than  $5^{\circ}\text{C}$ , the tens and units digits are reported.

Examples: 01  $\rightarrow$   $0.1^{\circ}\text{C}$   
 32  $\rightarrow$   $3.2^{\circ}\text{C}$   
 50  $\rightarrow$   $5.0^{\circ}\text{C}$  to  $5.4^{\circ}\text{C}$  inclusive  
 51 to 55 are not used  
 56  $\rightarrow$   $6^{\circ}\text{C}$  ( $56 - 50 = 6$ )  
 71  $\rightarrow$   $21^{\circ}\text{C}$  ( $71 - 50 = 21$ )

- dd tens and hundreds of degrees of wind direction.

- fff wind velocity in knots or in knots plus 500.  
 Note: If 500 is added to fff, add  $5^{\circ}$  to the wind direction in dd.

e.g. 1) code 29662  $\rightarrow$  wind speed of 162 kt at  $295^{\circ}$   
 2) code 29162  $\rightarrow$  wind speed of 162 kt at  $290^{\circ}$

00, 85, in TTAA section, refers to mandatory pressure levels 1000 mb,  
70,...10 850 mb, 700 mb, ... 100 mb.

88 in TTAA section, indicates tropopause data follows.

77 (or  
66) indicates level of maximum wind velocity.

77999 indicates maximum wind level not observed.

$\phi$  message separation signal; indicates end of a section.

00 in TTBB section indicates surface data follows.

11, 22, in TTBB section numbers the significant levels successively;  
... 99, note that 00 is not used here after the surface report.  
11,...

$a_4$  coded indicator for type of wind measuring equipment (not usually important).

9 when it leads a coded set in the Wind Group, indicates beginning of wind data.

$t_n$  tens digit for tens of thousands of feet.  
e.g. 0 + 1000 to 9000 feet  
2 + 20,000 to 29,000 feet

$u_1$  units digit of thousands of feet for the first dffff group following.

$u_2$  and  $u_3$  similar to  $u_1$ , but for second and third dffff groups following, respectively.

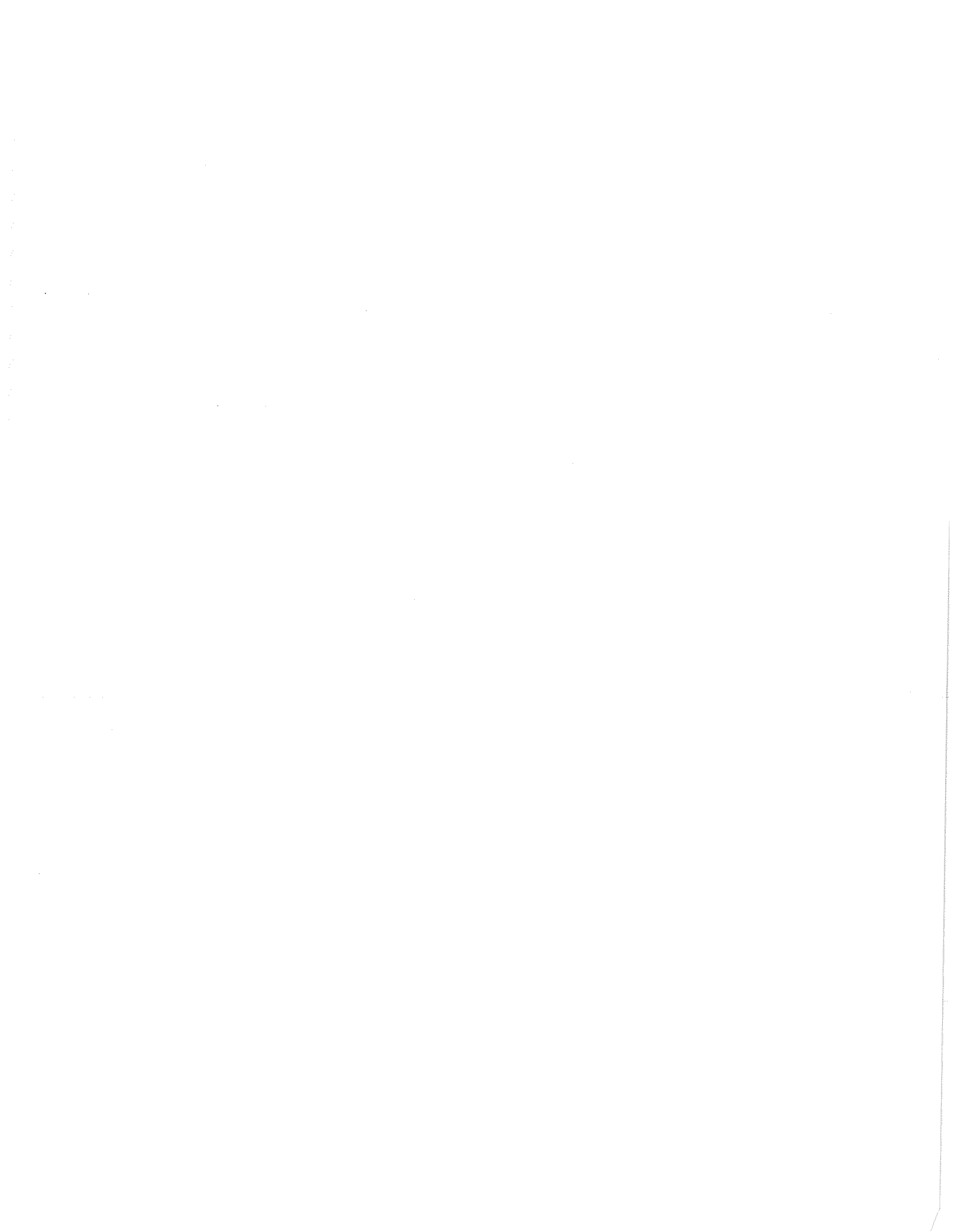
Example: 91468 23050 24560 25070 gives winds from 230 at 50 kt, 245 at 60 kt and 250 at 70 kt for 14,000, 16,000, and 18,000 feet respectively.

## Notes:

- 1) Significant levels are determined by changes from linearity in the lapse rate of temperature and relative humidity.
- 2) The solidus, or slash, is used to indicate a missing element. In the case of dew point temperature this means that the air is too dry for accurate measurement of humidity. This phenomenon is called motorboating. When used in the place of a wind level indicator, the appropriate corresponding data groups are omitted.
- 3) For mandatory levels occurring below the ground, only heights are computed and sent. Solidi are transmitted for other groups. If the 1000 mb surface is below sea level, 500 is added to the value to indicate the negative.

- 4) Wind reports are given in M L heights. Therefore, certain stations will send, say, the 6000 ft wind as their first level above the ground.
- 5) SUPER is inserted to highlight superadiabatic layers.

The accompanying map shows the North American Radiosond stations.



**Appendix B – Example of RAOB report**

DENRAOB

\*\*\*\*\*

DRA2:[FAA604]333.DAT;369

72469 TTAA 67121 72469 99839 03242 20004 00132 // // //  
 85503 // // // 70099 03263 29511 50573 15563 26024 40738  
 25580 25032 30940 417// 25034 25061 523// 25042 20203 563//  
 25547 15386 579// 24550 10635 649// 26040 88217 573// 25547  
 77999 51515 10164 00005 10194 // // // 25005=

\*\*\*\*\*

DRA2:[FAA604]333.DAT;350

72469 TTAA 67001 72469 99839 16067 13008 00138 // // //  
 85503 // // // 70106 01257 19506 50572 15759 27036 40736  
 29961 27030 30934 445// 25534 25055 495// 29535 20201 515//  
 30048 15385 571// 27537 10636 643// 27029 88260 497// 29033  
 77999 51515 10164 00004 10194 // // // 15011=

\*\*\*\*\*

DRA2:[FAA604]333.DAT;331

72469 TTAA 66121 72469 99841 00044 16004 00159 // // //  
 85521 // // // 70096 01160 20512 50569 18764 27032 40732  
 27758 27044 30933 439// 25546 25052 537// 25049 20193 585//  
 25549 15374 575// 28042 10630 595// 27028 88219 601// 25050  
 77999 51515 10164 00005 10194 // // // 17008=

\*\*\*\*\*

DRA2:[FAA604]328.DAT;223

72469 TTBB 67121 72469 00839 03242 11831 05850 22817 07259  
 33733 06065 44388 07565 53570 09339 66500 15363 77488 14980  
 88400 25580 99315 39163 11238 553// 22217 573// 33162 553//  
 44105 669// 55100 649//=  
 PPBB 67120 72469 90067 20004 22007 24003 9089/ 20501 31505  
 91024 30010 27511 26522 916// 26022 9205/ 25522 25032 9305/  
 25033 25043 942// 25556 9503/ 26045 26040=  
 MISSING  
 MISSING

\*\*\*\*\*

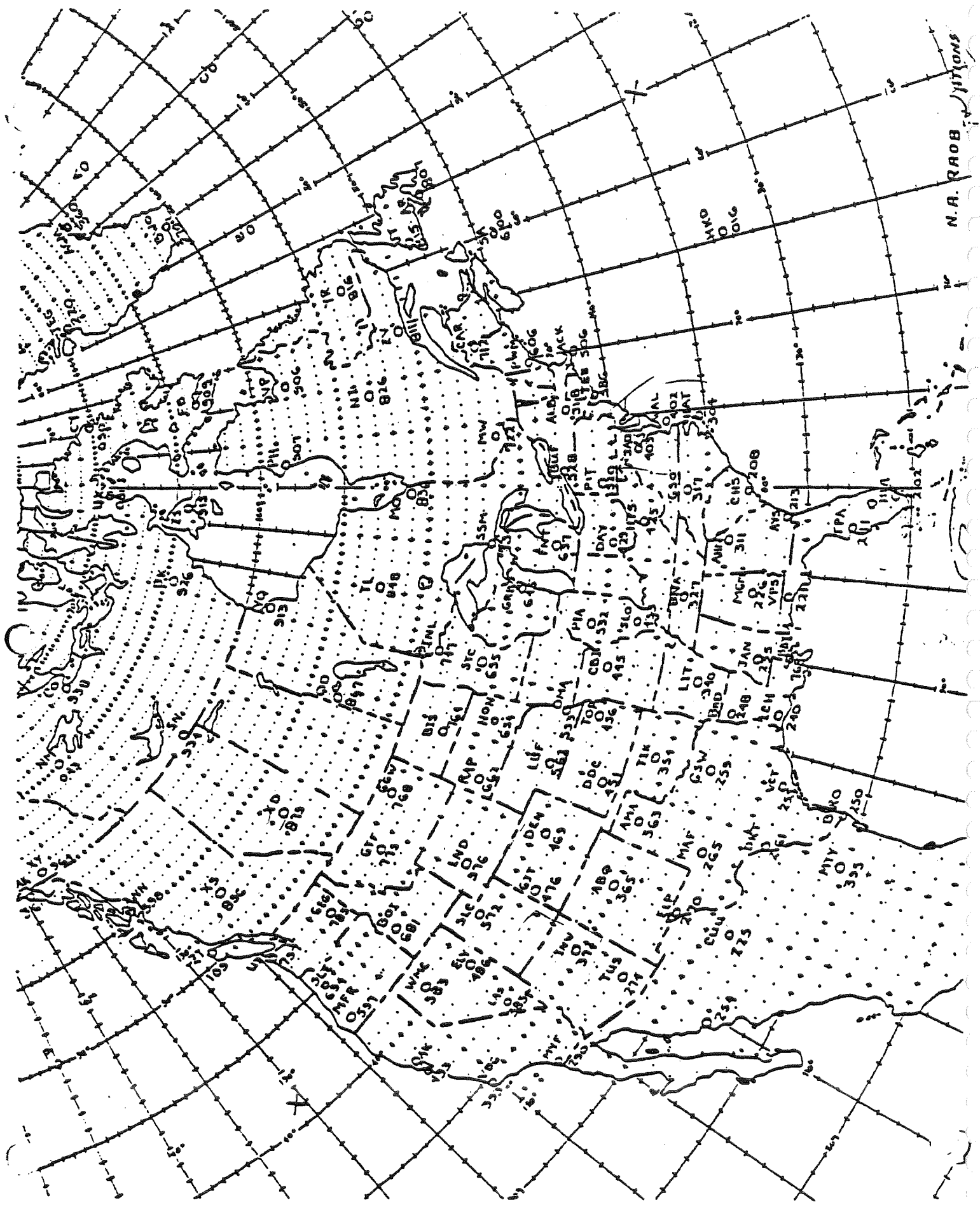
DRA2:[FAA604]328.DAT;215

72469 TTBB 6700/ 72469 00839 16067 11700 01257 22694 00861  
 33549 13556 44520 14150 53500 15759 66475 18956 77442 23557  
 88422 26163 99400 29961 11371 34539 22353 36560 33330 39961  
 44260 497// 55214 499// 66150 571// 77136 617// 88106 645//  
 99100 643//=  
 PPBB  
 ^Y

*mandator*

*Signature*

*Signature*







**Appendix C – Daily weather maps**

# "DAILY WEATHER MAPS"

## WEEKLY SERIES

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 U.S. DEPARTMENT OF COMMERCE  
 ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION  
 Environmental Data Service

### EXPLANATION OF THE WEATHER MAP

The charts in this publication are a continuation of the principal charts of the Weather Bureau publication, Daily Weather Map. They include the Surface Weather Map, the 500-Millibar Chart, the Highest and Lowest Temperatures Chart, and the Daily Precipitation Chart. All of the charts for one day are arranged on a single page of this publication. They are copied from operational weather maps prepared by the National Meteorological Center, Weather Bureau. The symbols used on the Surface Weather Map and the 500-Millibar Chart are the same as those used previously in Daily Weather Map. (The seven maps for a week are issued in a single booklet mailed to subscribers by Superintendent of Documents, G. P. O., Washington, D. C. 20402.)

The Surface Weather Map presents station data and the analysis for 7:00 a.m./e.s.t. The tracks of well-defined

low pressure areas are indicated by chains of arrows; the locations of these centers at times 6, 12, and 18 hours preceding map time are indicated by small black squares enclosing white crosses. Areas of precipitation are indicated by shading. The weather reports that are printed here are only a fraction of those that are included in the operational weather maps, and on which the analyses are based. Occasional apparent discrepancies between the printed station data and the analyses result from those station reports that cannot be included in the published maps because of lack of space.

The 500-Millibar Chart presents the height contours and isotherms of the 500-millibar surface at 7:00 a.m./e.s.t. The height contours are shown as continuous lines, and are labeled in feet above sea level. The isotherms are shown as dashed lines, and are labeled in degrees Celsius. The arrows show

the wind direction and speed at the 500-millibar level.

The Highest and Lowest Temperatures Chart presents the maximum and minimum values for the 24-hour period ending at 1:00 a.m./e.s.t. The names of the reporting points can be obtained from the Surface Weather Map. The maximum temperature is plotted above the station location, and the minimum temperature is plotted below this point.

The Precipitation Areas and Amounts Chart indicates by means of shading the areas that had precipitation during the 24 hours ending at 1:00 a.m. Amounts in inches to the nearest hundredth of an inch are for the same period. Incomplete totals are underlined. "T" indicates a trace of precipitation. Dashed lines show the depth of snow on the ground in inches as of 7:00 a.m. of the previous day.

Weather maps showing the development and movement of weather systems are among the principal tools used by the weather forecaster. Of the several types of maps used, some portray conditions near the surface of the earth, while others depict conditions at various heights in the atmosphere. Some cover the entire Northern Hemisphere, while others cover only local areas as required for special purposes. The maps used for daily forecasting by the Weather Bureau are similar in many respects to the printed Daily Weather Map. At Weather Bureau offices, maps showing conditions at the earth's surface are drawn four times daily. Maps of upper level temperature, pressure, and humidity are prepared twice each day. A more detailed explanation of weather forecasting from synoptic charts appears in the pamphlet "Weather Forecasting," U. S. Department of Commerce, Weather Bureau, 1952, and is for sale by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C.

#### PRINCIPAL SURFACE WEATHER MAP

To prepare the surface map and present the information quickly and pictorially, two actions are necessary: (1) Weather observers at many places must go to their posts at regular times each day to observe the weather and send the information by wire or radio to the offices where the maps are drawn; and (2) the information must be quickly transcribed to the maps. In order that the necessary speed and economy of space and transmission time may be realized, codes have been devised for sending the information and for plotting it on the maps.

#### CODES AND MAP PLOTTING

A great deal of information is contained in a brief coded weather message. If each item were named and described in plain language, a very lengthy message would be required; and it would be confusing to read and difficult to transfer to a map. Use of a code permits the message to be condensed to a few five-figure numeral groups, each figure of which has a meaning depending on its position in the message. Persons trained in the use of the code can read the message as easily as plain language.

The location of the reporting station is printed on the map as a small circle (the station circle). A definite arrangement of the data around the station circle, called the station model, is used (see block 1). When the report is plotted in these fixed positions around the station circle on the weather map, many of the code figures are transcribed exactly as sent. Entries in the station model which are not made in code figures or actual values found in the message are usually in the form of symbols which graphically represent the element concerned. In some cases, certain of the data may or may not be reported by the observer, depending on local weather conditions. Precipitation and clouds are examples. In such cases the absence of an entry on the map is interpreted as non-occurrence or non-observance of the phenomena. The letter "M" is entered where data are normally observed but not received by teletypewriter.

Both the code and the station model are based on international agreements. Through such standardized use of numerals and symbols, a meteorologist of one country can use the weather reports and weather maps of another country even though he does not understand the language. Weather codes are, in effect, an international language making possible complete interchange and use of worldwide weather reports so essential in present-day activities.

The international code form for surface reports used by the Weather Bureau beginning January 1, 1955, is shown in abridged form in block 1 together with a corresponding sample message. Also included are the symbolic station model used on the printed map, a sample station model entered from the sample message, and an explanation of the symbols with remarks on map entries in block 2.

Many of the elements in the plotting model are entered in values which can be interpreted directly. However, some require reference to code tables. These tables are given in the numbered blocks 3 through 11 to the right of the station model and explanation of symbols and map entries. Those who wish a more complete explanation of the code are referred to the Manual for Synoptic Code (WBAN) which is for sale by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D.C. Specify "Federal Meteorological Handbook No. 2, Synoptic Code" (Latest Edition).

#### FRONTS AND AIR MASSES

The boundary between two different air masses is called a "front." Important changes in weather, temperature, wind direction, and clouds, often occur with the passage of a front. Half circles and/or triangular symbols are placed on the lines representing fronts to indicate the kind of front. The side on which the symbols are placed indicates the direction of frontal movement. The boundary of relatively cold air of polar origin advancing into an area occupied by warmer air, often of tropical origin, is called a "cold front." The boundary of relatively warm air advancing into an area occupied by colder air is called a "warm front." The line along which a cold front has overtaken a warm front at the ground is called an "occluded front." A boundary between two air masses, which shows at the time of observation little tendency to advance into either the warm or cold areas, is called a "stationary front." Air mass boundaries are known as "surface fronts" when they intersect the ground, and as "upper air fronts" when they do not. Surface fronts are drawn in solid black, fronts aloft are drawn in outline only.

Front symbols are given below:

▲▲▲▲ Cold front (surface)      ◐◐◐◐ Stationary front (surface)  
 ▲▲▲▲ Warm front (surface)      ◐◐◐◐ Warm front (aloft)  
 ▲▲▲▲ Occluded front (surface)      ▲▲▲▲ Cold front (aloft)

front which is disappearing or is weak and decreasing in intensity is called "Frontolysis."

A front which is forming is labeled "Frontogenesis."

A "squal line" is a line of thunder storms or squalls usually accompanied by heavy showers and shifting winds, and is indicated as

The paths followed by individual disturbances are called storm tracks and are shown as  $\rightarrow \rightarrow$ . The symbols  $\square$  indicate past positions of the low pressure center at 6-hour intervals.

"HIGH" (H) and "LOW" (L) indicate the centers of high and low barometric pressure.

Solid lines are isobars and connect points of equal sea level barometric pressure. The spacing and orientation of these lines on weather maps are an indication of speed and direction of wind flow. In general, wind direction is parallel to these lines with low pressure to the left of observer looking downwind. Speed is directly proportional to the closeness of the lines (termed pressure gradient). Isobars are labeled in the metric unit, millibars, and may be converted to inches of mercury by use of the scale in block 12.

Isotherms are lines connecting points of equal temperature. Two isotherms are drawn on the large surface weather map when applicable. The freezing or 32° F. isotherm is drawn as a dashed line (---), the 0° F. isotherm is drawn as a dash-dot (-.-.-) line.

Masses of air are classified to indicate their origin and basic characteristics. For example, the letter P (Polar) denotes relatively cold air from northern regions, and the letter T (Tropical) denotes relatively warm air from southern regions. Letters placed before P and T indicate air of maritime characteristics (m) or continental characteristics (c). Letters placed after P and T show that the air mass is colder (h) or warmer (w) than the surface over which it is moving. A plus sign (+) between two air mass symbols indicates mixed air masses, and an arrow  $\rightarrow$  between two symbols indicates a transitional air mass changing from one type to the other. Two air mass symbols, one above the other and separated by a line, indicate one air mass aloft and another at lower levels. Air mass symbols are formed by combinations of the following letters:

m = Maritime; c = Continental; A = Arctic; P = Polar, T = Tropical; E = Equatorial; S = Superior (a warm, dry air mass having its origin aloft);

h = colder, and w = warmer than the surface over which the air mass is moving.

Where precipitation is occurring at the time of observation are

## EXPLANATION OF SYMBOLS AND MAP ENTRIES

Symbols in order as they appear in the message	Explanation of symbols and decode of example above	Remarks on coding and plotting
iii	Station number 405 - Washington	Usually printed on manuscript maps below station circle. Omitted on Daily Weather Map in favor of printed station names.
N	Total amount of cloud 8 = completely covered	Observed in tenths of cloud cover and coded in Oktas (eighths) according to code table in block 1. Plotted in symbols shown in same table.
dd	True direction from which wind is blowing 32 = 320° - NW	Coded in tens of degrees and plotted as the shaft of an arrow extending from the station circle toward the direction from which the wind is blowing.
ff	Wind speed in knots 20 = 20 knots	Coded in knots (nautical miles per hour) and plotted as feathers and half-feathers representing 10 and 5 knots, respectively, on the shaft of the wind direction arrow. See block 1.
VV	Visibility in miles and fractions 12 = 12/16 or 3/4 miles	Decoded and plotted in miles and fractions up to 3 1/8 miles. Visibilities above 3 1/8 miles but less than 10 miles are plotted to the nearest whole mile. Values higher than 10 miles are omitted from the map.
W	Present weather 71 = continuous slight snow	Coded in figures taken from the "ww" table (block 1) and plotted in the corresponding symbols same block. Entries for code figures 00, 01, 02, and 03 are omitted from this map.
W	Past weather 6 = rain	Coded in figures taken from the "ww" table (block 1) and plotted in the corresponding symbols same block. No entry made for code figures 0, 1, or 2.

## SYMBOLIC FORM OF MESSAGE

iii Nddff VVww PPPTT NChCC TTppp 7RRRS

Note: This Abridged Code Shows Only Data Normally Plotted on Printed Maps

## SAMPLE CODED MESSAGE

405 83220 12716 24731 67292 30228 74542

SYMBOLIC STATION MODEL	SAMPLE PLOTTED REPORT

ppp	Barometric Pressure (in millibars) reduced to sea-level 247 = 1024.7 mb.	Coded and plotted in tens, units, and tenths of millibars. The initial 9 or 10 and the decimal point are omitted. See block 12.
TT	Current air temperature 31 = 31° F.	Coded and plotted in actual value in whole degrees F. See block 11.
N <sub>h</sub>	Fraction of sky covered by low or middle cloud 8 = 7 or 8 tenths	Observed and coded in tenths of cloud cover. Plotted on map as code figure in message. See block 7.
C <sub>L</sub>	Cloud type 7 = Fractostratus and/or Fractocumulus of bad weather (acid)	Predominating clouds of types in C <sub>L</sub> table (block 1) are coded from that table and plotted in corresponding symbols.
h	Height of base of cloud 2 = 300 to 599 feet	Observed in feet and coded and plotted as code figures according to code table in block 3.
C <sub>M</sub>	Cloud type 9 = Altostratus of chaotic sky	See C <sub>M</sub> table in block 1.
C <sub>H</sub>	Cloud type 2 = Dense cirrus in patches	See C <sub>H</sub> table in block 1.
T <sub>d</sub> T <sub>d</sub>	Temperature of dewpoint 30 = 30° F.	Coded and plotted in actual value in whole degrees F.
g	Characteristic of barograph trace 2 = rising steadily or unsteadily	Coded according to table in block 10 and plotted in corresponding symbols.
PP	Pressure change in 3 hours preceding observation 28 = 2.8 millibars	Coded and plotted in units and tenths of millibars.
7	Indicator figure	Not plotted.
RR	Amount of precipitation 45 = 0.45 inches	Coded and plotted in inches to the nearest hundredth of an inch.
R <sub>t</sub>	Time precipitation began or ended 4 = 3 to 4 hours ago	Coded and plotted in figures from table in block 1.
8	Depth of snow on ground	Not plotted.

CLOUD ABBREVIATION	CL	DESCRIPTION <small>(Abridged from WMO Code)</small>	CM	DESCRIPTION <small>(Abridged from WMO Code)</small>	CH	DESCRIPTION <small>(Abridged from WMO Code)</small>
St or Fs-Stratus or Fractostratus	1	Cu of fair weather, little vertical development and seemingly flattened	1	Thin As (most of cloud layer semi-transparent)	1	Filaments of Ci, or "mare's tails," scattered and not increasing
Ci-Cirrus	2	Cu of considerable development, generally towering, with or without other Cu or Sc bases at same level	2	Thick As, greater part sufficiently dense to hide sun (or moon), or Ns	2	Dense Ci in patches or twisted sheaves, usually not increasing, sometimes like remains of Cb; or towers or tufts
Cs-Cirrostratus	3	Cb with tops lacking clear-cut outlines, but distinctly not cirriform or anvill-shaped, with or without Ce, Sc, or St	3	Thin Ac, mostly semi-transparent; cloud elements not changing much and at a single level	3	Dense Ci, often anvill-shaped, derived from or associated with Cb
Cc-Cirrocumulus	4	Sc formed by spreading out of Cu; Cu often present also	4	Thin Ac in patches; cloud elements continually changing and/or occurring at more than one level	4	Ci, often hook-shaped, gradually spreading over the sky and usually thickening as a whole
Ac-Alto cumulus	5	Sc not formed by spreading out of Cu	5	Thin Ac in bands or in a layer gradually spreading over sky and usually thickening as a whole	5	Ci and Cs, often in converging bands, or Cs alone; generally overspreading and growing denser; the continuous layer not reaching 45° altitude
As-Altostratus	6	St or Fs or both, but no Fs of bad weather	6	Ac formed by the spreading out of Cu	6	Ci and Cs, of en in converging bands, or Cs alone; generally overspreading and growing denser; the continuous layer exceeding 45° altitude
Sc-Stratocumulus	7	Fs and/or Fs of bad weather (acu@)	7	Double-layered Ac, or a thick layer of Ac, not increasing; or Ac with As and/or Ns	7	Veil of Cs covering the entire sky
Ns-Nimbostratus	8	Cu and Sc (not formed by spreading out of Cu) with bases at different levels	8	Ac in the form of Cu-shaped tufts or Ac with turrets	8	Cs not increasing and not covering entire sky
Cu or Fc-Cumulus or Fractocumulus	9	Cb having a clearly fibrous (cirriform) top, often anvill-shaped, with or without Cu, Sc, St, or scud	9	Ac of a chaotic sky, usually at different levels; patches of dense Ci are usually present also	9	Cc alone or Cc with some Ci or Cs, but the Cc being the main cirriform cloud
Cb-Cumulonimbus						

Rt	TIME OF PRECIPITATION	h	HEIGHT IN FEET (Rounded Off)	HEIGHT IN METERS (Approximate)	N	SKY COVERAGE (Total Amount)	Nh	SKY COVERAGE (Low And/Or Middle Clouds)
0	No Precipitation	0	0 - 149	0 - 49	0	No clouds	0	No clouds
1	Less than 1 hour ago	1	150 - 299	50 - 99	1	Less than one-tenth or one-tenth	1	Less than one-tenth or one-tenth
2	1 to 2 hours ago	2	300 - 599	100 - 199	2	Two-tenths or three-tenths	2	Two-tenths or three-tenths
3	2 to 3 hours ago	3	600 - 999	200 - 299	3	Four-tenths	3	Four-tenths
4	3 to 4 hours ago	4	1,000 - 1,999	300 - 599	4	Five-tenths	4	Five-tenths
5	4 to 5 hours ago	5	2,000 - 3,999	600 - 999	5	Six-tenths	5	Six-tenths
6	5 to 6 hours ago	6	3,500 - 4,999	1,000 - 1,499	6	Seven-tenths or eight-tenths	6	Seven-tenths or eight-tenths
7	6 to 12 hours ago	7	5,000 - 6,499	1,500 - 1,999	7	Nine-tenths or overcast with openings	7	Nine-tenths or overcast with openings
8	More than 12 hours ago	8	6,500 - 7,999	2,000 - 2,499	8	Completely overcast	8	Completely overcast
9	Unknown	9	At or above 8,000, or no clouds	At or above 2,500, or no clouds	9	Sky obscured	9	Sky obscured

Symbol VV=Horizontal Visibility

Code Figure	Statute Mile	Code Figure	Statute Mile	Code Figure	Statute Mile
00	under 1/8	65	9 1/4	83	28 1/2
01	1/8 to 1/4	66	10	84	31 1/2
02	1/4 to 3/8	67	10 1/2	85	34 1/2
03	3/8 to 1/2	68	11 1/4	86	37 1/2
04	1/2 to 5/8	69	11 1/2	87	40 1/2
05	5/8 to 3/4	70	12 1/4	88	43 1/2
06	3/4 to 7/8	71	13 1/4	89	over 43 1/2
07	7/8 to 1	72	13 1/2	90	under 1/2
08	1 to 1 1/8	73	14 1/4	91	1/2
09	1 1/8 to 1 1/4	74	15 1/4	92	3/4
10	1 1/4 to 1 1/2	75	16 1/4	93	1
11	1 1/2 to 1 3/4	76	17 1/4	94	1 1/4
12	1 3/4 to 2	77	18 1/4	95	1 1/2
13	2 to 2 1/4	78	19 1/4	96	2
14	2 1/4 to 2 1/2	79	20 1/4	97	2 1/2
15	2 1/2 to 2 3/4	80	21 1/4	98	3
16	2 3/4 to 3	81	22 1/4	99	3 1/2
17	3 to 3 1/4	82	25	100	more

NOTE: (1) The values given are discrete values (i.e., not ranges). If the observed visibility is between two of the reportable distances as given in the table, the code figure of the lower reportable distance shall be reported. (2) Only the code figures 00-99 shall be used in reports from fixed stations. (3) In reporting visibility at sea the device 99-99 shall be used.

WW PRESENT WEATHER (Descriptions Abridged from W. M. O. Code)

00	Cloud development NOT observed or NOT observed during past hour	0	Clear sky on the whole unchanged during past hour	1	Clouds generally clearing or becoming less developed during past hour	2	State of sky on the whole unchanged during past hour	3	Clouds generally forming or developing during past hour	4	Visibility reduced by smoke	5	Base	6	Widespread dust in suspension in the air, NOT raised by wind, at time of observation	7	Dust or sand raised by wind, at time of observation	8	Well developed dust devil(s) within past hour	9	Dust storm or sand storm within sight of or at station during past hour
10	Light fog	1	Shore or less confinement shallow fog at station, NOT deeper than 6 feet on land	2	More or less confinement shallow fog at station, NOT deeper than 6 feet on land	3	State of sky on the whole unchanged during past hour	4	Clouds generally forming or developing during past hour	5	Base	6	Widespread dust in suspension in the air, NOT raised by wind, at time of observation	7	Dust or sand raised by wind, at time of observation	8	Well developed dust devil(s) within past hour	9	Dust storm or sand storm within sight of or at station during past hour		
20	Rain NOT falling as shower during past hour, but NOT at time of observation	1	Shore or less confinement shallow fog at station, NOT deeper than 6 feet on land	2	More or less confinement shallow fog at station, NOT deeper than 6 feet on land	3	State of sky on the whole unchanged during past hour	4	Clouds generally forming or developing during past hour	5	Base	6	Widespread dust in suspension in the air, NOT raised by wind, at time of observation	7	Dust or sand raised by wind, at time of observation	8	Well developed dust devil(s) within past hour	9	Dust storm or sand storm within sight of or at station during past hour		
30	Slight or moderate dust storm or sand storm, has decreased during past hour	1	Shore or less confinement shallow fog at station, NOT deeper than 6 feet on land	2	More or less confinement shallow fog at station, NOT deeper than 6 feet on land	3	State of sky on the whole unchanged during past hour	4	Clouds generally forming or developing during past hour	5	Base	6	Widespread dust in suspension in the air, NOT raised by wind, at time of observation	7	Dust or sand raised by wind, at time of observation	8	Well developed dust devil(s) within past hour	9	Dust storm or sand storm within sight of or at station during past hour		
40	Fog at distance at time of observation, but NOT at station during past hour	1	Shore or less confinement shallow fog at station, NOT deeper than 6 feet on land	2	More or less confinement shallow fog at station, NOT deeper than 6 feet on land	3	State of sky on the whole unchanged during past hour	4	Clouds generally forming or developing during past hour	5	Base	6	Widespread dust in suspension in the air, NOT raised by wind, at time of observation	7	Dust or sand raised by wind, at time of observation	8	Well developed dust devil(s) within past hour	9	Dust storm or sand storm within sight of or at station during past hour		
50	Intermittent drizzle (NOT freezing) slight at time of observation	1	Shore or less confinement shallow fog at station, NOT deeper than 6 feet on land	2	More or less confinement shallow fog at station, NOT deeper than 6 feet on land	3	State of sky on the whole unchanged during past hour	4	Clouds generally forming or developing during past hour	5	Base	6	Widespread dust in suspension in the air, NOT raised by wind, at time of observation	7	Dust or sand raised by wind, at time of observation	8	Well developed dust devil(s) within past hour	9	Dust storm or sand storm within sight of or at station during past hour		
60	Intermittent rain (NOT freezing) slight at time of observation	1	Shore or less confinement shallow fog at station, NOT deeper than 6 feet on land	2	More or less confinement shallow fog at station, NOT deeper than 6 feet on land	3	State of sky on the whole unchanged during past hour	4	Clouds generally forming or developing during past hour	5	Base	6	Widespread dust in suspension in the air, NOT raised by wind, at time of observation	7	Dust or sand raised by wind, at time of observation	8	Well developed dust devil(s) within past hour	9	Dust storm or sand storm within sight of or at station during past hour		
70	Intermittent fall of snow flakes, slight at time of observation	1	Shore or less confinement shallow fog at station, NOT deeper than 6 feet on land	2	More or less confinement shallow fog at station, NOT deeper than 6 feet on land	3	State of sky on the whole unchanged during past hour	4	Clouds generally forming or developing during past hour	5	Base	6	Widespread dust in suspension in the air, NOT raised by wind, at time of observation	7	Dust or sand raised by wind, at time of observation	8	Well developed dust devil(s) within past hour	9	Dust storm or sand storm within sight of or at station during past hour		
80	Slight rain shower(s)	1	Shore or less confinement shallow fog at station, NOT deeper than 6 feet on land	2	More or less confinement shallow fog at station, NOT deeper than 6 feet on land	3	State of sky on the whole unchanged during past hour	4	Clouds generally forming or developing during past hour	5	Base	6	Widespread dust in suspension in the air, NOT raised by wind, at time of observation	7	Dust or sand raised by wind, at time of observation	8	Well developed dust devil(s) within past hour	9	Dust storm or sand storm within sight of or at station during past hour		
90	Moderate or heavy shower(s) of hail with or without rain, or moderate or heavy shower(s) associated with thunder	1	Shore or less confinement shallow fog at station, NOT deeper than 6 feet on land	2	More or less confinement shallow fog at station, NOT deeper than 6 feet on land	3	State of sky on the whole unchanged during past hour	4	Clouds generally forming or developing during past hour	5	Base	6	Widespread dust in suspension in the air, NOT raised by wind, at time of observation	7	Dust or sand raised by wind, at time of observation	8	Well developed dust devil(s) within past hour	9	Dust storm or sand storm within sight of or at station during past hour		

ff	(MILES) (Statute) Per Hour	<b>9</b> KNOTS
☉	Calm	Calm
—	1 - 2	1 - 2
┆	3 - 8	3 - 7
┆┆	9 - 14	8 - 12
┆┆┆	15 - 20	13 - 17
┆┆┆┆	21 - 25	18 - 22
┆┆┆┆┆	26 - 31	23 - 27
┆┆┆┆┆┆	32 - 37	28 - 32
┆┆┆┆┆┆┆	38 - 43	33 - 37
┆┆┆┆┆┆┆┆	44 - 49	38 - 42
┆┆┆┆┆┆┆┆┆	50 - 54	43 - 47
┆┆┆┆┆┆┆┆┆┆	55 - 60	48 - 52
┆┆┆┆┆┆┆┆┆┆┆	61 - 66	53 - 57
┆┆┆┆┆┆┆┆┆┆┆┆	67 - 71	58 - 62
┆┆┆┆┆┆┆┆┆┆┆┆┆	72 - 77	63 - 67
┆┆┆┆┆┆┆┆┆┆┆┆┆┆	78 - 83	68 - 72
┆┆┆┆┆┆┆┆┆┆┆┆┆┆┆	84 - 89	73 - 77
┆┆┆┆┆┆┆┆┆┆┆┆┆┆┆┆	119 - 123	103 - 107

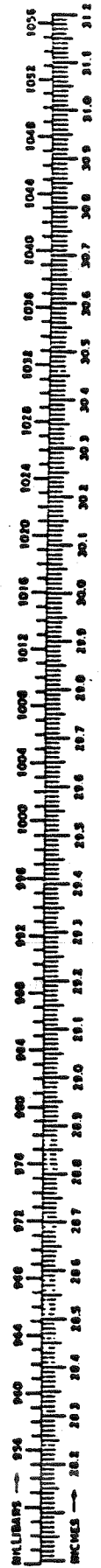
Code Number	d	BAROMETRIC TENDENCY <b>10</b>
0	↗	Rising, then falling
1	↗	Rising, then steady; or rising, then rising more slowly
2	↗	Rising steadily, or unsteadily
3	✓	Falling or steady, then rising; or rising, then rising more quickly
4	—	Steady, same as 3 hours ago
5	↘	Falling, then rising, same or lower than 3 hours ago
6	↘	Falling, then steady; or falling, then falling more slowly
7	↘	Falling steadily, or unsteadily
8	↘	Steady or rising, then falling; or falling, then falling more quickly

} Barometer now higher than 3 hours ago

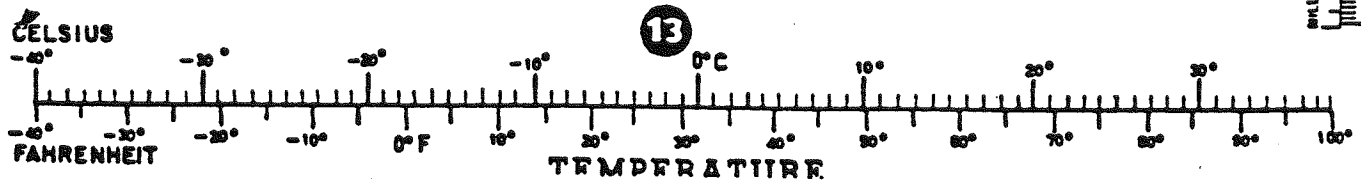
} Barometer now lower than 3 hours ago

Code Number	W	PAST WEATHER <b>11</b>
0		Clear or few clouds
1		Partly cloudy (scattered) or variable sky
2		Cloudy (broken) or overcast
3	☉+	Sandstorm or dust-storm, or drifting or blowing snow
4	≡	Fog, or smoke, or thick dust haze
5	⋮	Drizzle
6	•	Rain
7	*	Snow, or rain and snow mixed, or ice pellets (sleet)
8	▽	Shower(s)
9	⊚	Thunderstorm, with or without precipitation

} Not Plotted



PRESSURE



LOCATION IDENTIFIER (TO RE)	SKY AND CEILING	VISIBILITY WEATHER AND OBSTRUCTION TO VISION	SEA-LEVEL PRESSURE	TEMPERATURE AND DEW POINT	WIND	ALTIMETER SETTING	RUNWAY VISUAL RANGE	CODED PIREPS
MKC	150M250	1R-K	132	/58/56	/1807	/993/	R04LVR20V40	/UA05-

**SKY AND CEILING**  
 Sky cover symbols are in ascending order. Figures preceding symbols are heights in hundreds of feet above station. Sky cover symbols are:  
 ○ Clear: Less than 0.1 sky cover.  
 ⊕ Scattered: 0.1 to 0.5 sky cover.  
 ⊖ Broken: 0.5 to 2.9 sky cover.  
 ⊕ Overcast: More than 0.9 sky cover.  
 - Thin (When prefixed to the above symbols.)  
 -X Partial obscuration: 0.1 to less than 1.0 sky hidden by precipitation or obstruction to vision (bases at surface).  
 X Obscuration: 1.0 sky hidden by precipitation or obstruction to vision (bases at surface).  
 Letter preceding height of layer identifies ceiling layer and indicates how ceiling height was obtained. Thus:  
 A Aircraft      R Radar  
 B Balloon      W Indefinite  
 (ceiling, pilot, V immediately or radiosonde balloon)  
 E Estimated height  
 M Measured      indicates a variable ceiling.

**VISIBILITY**  
 Reported in statute miles and fractions. (V=Variable) The symbol - indicates visibility greater than that being reported.  
**WEATHER AND OBSTRUCTION TO VISION SYMBOLS**  
 A Mist      IC Ice crystals      S Snow  
 BD Blowing dust      IP Ice fog      SS Snow grains  
 BS Blowing sand      IP Ice pellets      SP Snow pellets  
 BN Blowing snow      IPW Ice pellet showers      SW Snow showers  
 D Dust      K Smoke      T Thunderstorms  
 F Fog      L Drizzle      T- Severe thunderstorm  
 GF Ground fog      R Rain      ZL Freezing drizzle  
 M Haze      RW Rain showers      ZR Freezing rain  
 Precipitation intensities are indicated thus:  
 - Very Light; - Light; (no sign) Moderate; + Heavy  
**WIND**  
 Direction in tens of degrees from true north, speed in knots. 0000 indicates calm. G indicates gusty. Peak speed of gusts follows G or Q when gusts or squall are reported. The contraction WSHT followed by GMT time group in remarks indicates windshift and its time of occurrence. (Knots X 1.15=statute mi/hr.)  
**EXAMPLES:** 3627=360 Degrees, 27 knots;  
 3627G40=360 Degrees, 27 knots Peak speed in gusts 40 knots.  
**ALTIMETER SETTING**  
 The first figure of the actual altimeter setting is always omitted from the report.

**RUNWAY VISUAL RANGE (RVR)**  
 RVR is reported from some stations. Extreme values during minutes prior to observation are given in hundreds of feet. Runway identification precedes RVR report.  
**CODED PIREPS**  
 Pilot reports of clouds not visible from ground are coded with ASL height data preceding and/or following sky cover symbol to indicate cloud bases and/or tops, respectively. UA precedes all PIREPS.  
**DECODED REPORT**  
 Kansas City: Record observation, 1500 feet scattered clouds, measured ceiling 2500 feet overcast, visibility 1 mile, light rain, smoke, sea-level pressure 1013.2 millibars, temperature 58°F, dewpoint 56°F, wind 180°, 7 knots, altimeter setting 29.93 inches. Runway 04 left, visual range 2000 feet variable to 4000 feet. Pilot reports top of overcast 5500 feet.  
**\*TYPE OF REPORT**  
 The omission of type-of-report data identifies a scheduled record observation for the hour specified in the sequence heading. An out-of-sequence, special observation is identified by the letters "SP" following station identification and a hour clock time group, e.g., "PIT SP 0715 -XM:⊕". A special report indicates a significant change in one or more elements.

U.S. DEPARTMENT OF COMMERCE - NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION - NATIONAL WEATHER SERVICE - REVISED 1974

AVIATION WEATHER FORECASTS . . . . .

**TERMINAL FORECASTS** contain information for specific airports on expected ceiling, cloud heights, cloud amounts, visibility, weather and obstructions to vision and surface wind. They are issued 2 times/day and are valid for 24 hours. The last six hours of each forecast are covered by a categorical statement indicating whether VFR, MVFR or IFR conditions are expected. Terminal forecasts will be written in the following form:  
**CEILING:** Identified by the letter "C"  
**CLOUD HEIGHTS:** In hundreds of feet above the station (ground)  
**CLOUD LAYERS:** Stated in ascending order of height  
**VISIBILITY:** In statute miles but omitted if over 6 miles  
**WEATHER AND OBSTRUCTION TO VISION:** Standard weather and obstruction to vision symbols are used  
**SURFACE WIND:** In tens of degrees and knots; omitted when less than 10  
**EXAMPLE OF TERMINAL FORECAST**  
 DCA 222323-DCA Forecast 22nd day of month-valid time 23Z-23Z. ceiling 8 hundred feet sky obscured, visibility 1 mile in light snow showers.  
 12Z C500 3312G22-At 12Z becoming ceiling 5000 feet broken, surface wind 330 degrees 12 knots Gusts to 22.  
 17Z MVFR BCMG VFR AFT 21Z-Last 6 hours of FT at 17Z marginal VFR conditions becoming VFR after 21Z.  
**AREA FORECASTS** are 18-hour aviation forecasts plus a 12-hour categorical outlook prepared 2 times/day giving general descriptions of cloud cover, weather and frontal conditions for an area the size of several states. Heights of cloud tops, and icing are referenced ABOVE SEA LEVEL (ASL); ceiling heights, ABOVE GROUND LEVEL (AGL); bases of cloud layers are ASL unless indicated. Each SIGMET or AIRMET affecting an FA area will also serve to amend the Area Forecast.

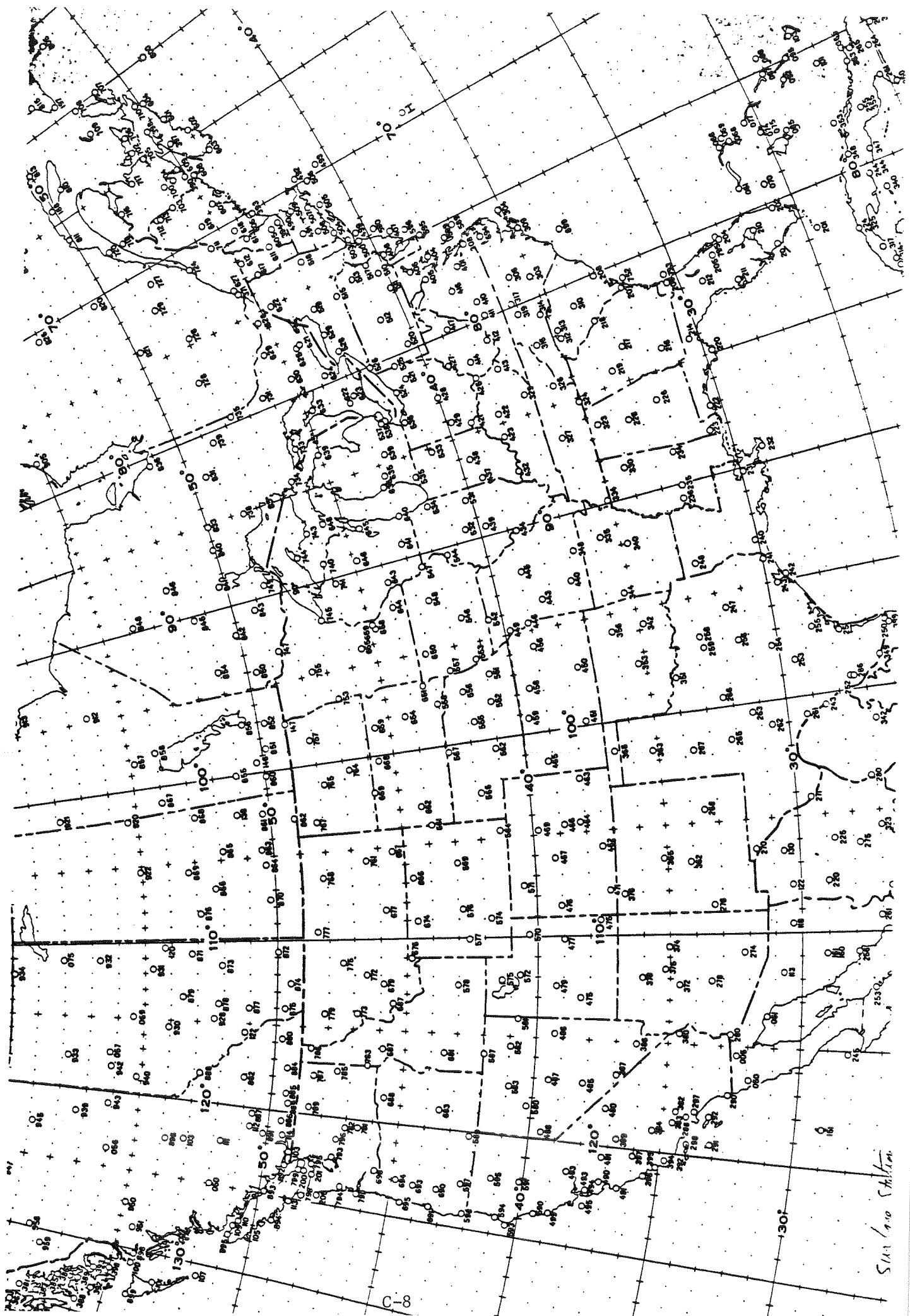
**SIGMET or AIRMET** messages warn airmen in flight of potentially hazardous weather such as squall lines, thunderstorms, fog, icing, and turbulence. SIGMET concerns severe and extreme conditions of importance to all aircraft. AIRMET concerns less severe conditions which may be hazardous to some aircraft or to relatively inexperienced pilots. Both are broadcast by FAA on NAVD voice channels.  
**WINDS AND TEMPERATURES ALOFT (FD) FORECASTS** are 12-hour forecasts of wind direction (nearest 10° true N) and speed (knots) for selected flight levels. Temperatures aloft (°C) are included for all but the 3000-foot level.  
**EXAMPLES OF WINDS AND TEMPERATURES ALOFT (FD) FORECASTS:**  
 FD WBC 121745  
 BASED ON 121200Z DATA  
 VALID 130000Z FOR USE 1800-0300Z. TEMPS NEG ABV 24000  

FT	3000	6000	9000	12000	18000	24000	30000	34000	39000
BOS	3127	3425-07	3420-11	3421-16	3516-27	3512-38	311649	292451	283451
JFK	3026	3327-08	3324-12	3322-16	3120-27	2923-38	284248	285150	285749

 At 6000 feet ASL over JFK wind from 330° at 27 knots and temperature minus 8°C  
**TWEB (CONTINUOUS TRANSCRIBED WEATHER BROADCAST)**- Individual route forecasts covering a 25 nautical mile zone either side of a course line for the route. By requesting a specific route number, detailed en route weather for an 18-hour period plus a synopsis can be obtained.  
**PILOTS . . .** report in-flight weather to nearest FSS. The latest surface weather reports are available by phone at the nearest pilot weather briefing office by calling at H+10.

U.S. DEPARTMENT OF COMMERCE - NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION - NATIONAL WEATHER SERVICE - REVISED 1974

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402. Price 25¢; \$2.50 per hundred. Stock Number 0318-00054  
 \* GPO : 1974 O - 532-884



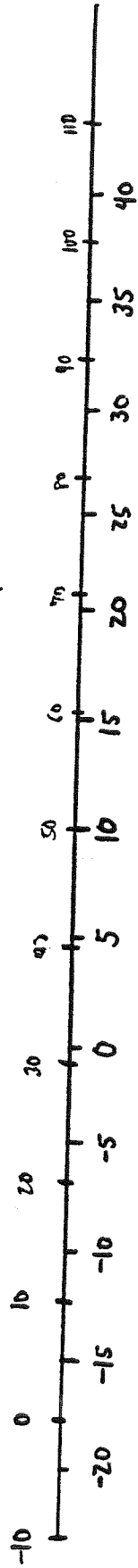
5111/910 Station



**Appendix D – Fahrenheit/Celsius conversion**

$$^{\circ}\text{C} = \frac{(^{\circ}\text{F} - 32) \times 5}{9}$$
$$^{\circ}\text{F} = \frac{9}{5}^{\circ}\text{C} + 32$$

°F



D-2

°C

*Celsius - Fahrenheit*

## Appendix E – Lab Exercises



Fall 1987

**Exercise # 1**  
**AT 540**

Reference Material (Can be obtained from Dallas, Room 221)

1. Lecture notes. Required
2. CASL manual. Required
3. "The use of the Skew T, Log P Diagram in Analysis and Forecasting." Air Weather Service. pgs. 1-1 to 3-2. Recommended

Exercise

1. Using GMPACK, plot the Denver sounding for today, 12z (0500 MST) on the CRT and make a hard copy on the laser printer. Write up the computer commands you used to make this plot.
2. Print out radiosonde transmission for Denver for 12z today using the FAA604 file. List in tabular form and hard plot on a thermodynamic chart.

Fall 1987

Lab Exercise # 2  
AT 540

Recommended "The Use of the Skew T, Log P Diagram in Analysis and Forecasting."  
Air Weather Service. pgs. 4-1 to 4-19;

Required Lecture notes.

Assignment

1. Using the sounding plotted in Lab Exercise #1, compute:

- (a) mixing ration -  $w$
- (b) saturation mixing ration -  $w_s$
- (c) relative humidity -  $R.H.$
- (d) vapor pressure -  $e$
- (e) saturation vapor pressure -  $e_s$
- (f) potential temperature -  $\theta$
- (g) wet bulb temperature -  $T_w$
- (h) wet-bulb potential temperature -  $\theta_w$
- (i) equivalent temperature -  $T_E$
- (j) equivalent potential temperature -  $\theta_E$
- (k) virtual temperature -  $T_v$
- (l) tropopause

at 1000 mb, 900 mb, 800 mb, 700 mb, 600 mb, 500 mb, 400 mb, 300 mb, 200 mb and 100 mb (except for the tropopause)

2. Compute from surface values, or other values as necessary.

- (a) convection condensation level -  $CCL$
- (b) convection temperature -  $T_c$
- (c) lifting condensation level -  $LCL$
- (d) mixing condensation level -  $MCL$
- (e) level of free convection -  $LFC$
- (f) equilibrium level -  $EL$
- (g) heights and pressure depth of layers of positive buoyancy -  $p_i, p_{i+1}, \Delta p$
- (h) K index -  $KI$
- (i) Lifted Index -  $LI$

Fall 1987

**Lab Exercise # 3**  
**AT 540**

Recommended Facsimile Products. National Weather Service, pgs. 6-39 to 6-55.

Required Lecture notes, Chapter 3.

Assignment

1. Using the FAA 604 sounding that you obtained for the Lab Exercise #1
  - (a) obtain the reported 700 mb, 500 mb, 300 mb and 200 mb heights
  - (b) use the temperatures in the sounding information to calculate the 500 mb, 300 mb and 200 mb heights assuming that the 700 mb height is known. Compare with heights given in the sounding.
2. Use the appropriate station model and plot on a blank sheet of paper the surface, 700 mb, 500 mb, 300 mb and 200 mb observation for Denver for the sounding time used in #1.
3. Use GMPAK to plot the 700 mb, 500 mb and 200 mb fields over the United States
  - (a) contour by hand the
    - i. heights (60 m intervals)
    - ii. temperature (5°C intervals)
    - iii. dew point temperature (5°C intervals)
  - (b) use graphical subtraction to obtain the 700 mb - 500 mb thickness at 60 m intervals.
  - (c) use GMPAK to plot the 700 mb - 500 mb thickness and compare with (b).
4. On your 700 mb analyses, color in red areas of temperature advection greater than 1°/hour; color in blue areas of temperature advection less than -1°/hour.
5. Draw the 500 mb and 700 mb winds in a vector format. Superimpose the winds and calculate the wind shear between these two layers. Contour the wind shear by drawing lines parallel to the wind shear vectors. Compare this result with the thickness calculation performed in #3(b). For Denver and Seattle, compute the thickness gradient from this analysis and from the thickness analysis in #3.

You will need tracing paper to perform these analyses.

Fall 1987

**Lab Exercise # 4**  
**AT 540**

Required Lecture Notes (Chapter 5)

Assignment

1. Obtain from GMPACK in hard copy, surface observations over the contiguous U.S. Any time period is okay.
2. Analyze the
  - (a) isobaric field at 4 mb intervals
  - (b) temperature field at 10°C intervals
  - (c) dew point temperature field at 10°C intervals
  - (d) frontal locations (justify on a separate sheet of paper).
3. Calculate the geostrophic and gradient winds at Denver. Compare with the observed surface and 700 mb winds.
4. Use the surface field to infer what the vorticity and temperature advection patterns and diabatic heating terms are at Washington, D.C.
5. Label synoptic categories on your surface map (use tracing paper if you wish).



Fall 1987

Lab Exercise # 5

AT 540

Recommended Cahir, J.J. *et al.*, 1976: New tools for forecasters: real-time cross sections produced in field. *BAMS*, 1426-1433.

Required Lecture notes (Chapter 3).

Assignment

Obtain sounding analyses for the cross section given in class which are

- (a) parallel to the general flow
- (b) perpendicular to the general flow

Using the stations along each cross section, your thermodynamic diagrams and tracing paper:

- plot and contour  $\theta$  and  $\theta_E$  at  $5^\circ\text{C}$  intervals for each cross section. Use separate sheets for  $\theta$  and  $\theta_E$ .
- calculate and contour relative humidity in intervals of 10%, 30%, 50%, 70%, and 90%. Shade in green, values of relative humidity greater than 70%.
- use your  $\theta$  analysis where R.H.  $< 70\%$ , and your  $\theta_E$  analysis where R.H.  $\geq 70\%$  to compute trajectory lines on a separate sheet of tracing paper.
- superimpose the observed winds on your analysis and evaluate vertical velocity at those locations using the adiabatic method. Contour in red, areas of vertical motion greater than  $1 \text{ cm s}^{-1}$  and in blue areas less than  $-1 \text{ cm s}^{-1}$ .

Fall 1987

**Lab Exercise # 6**  
**AT 540**

Readings (on reserve)

1. Recommended Brandli, N.W., 1976: Satellite Meteorology. AWS-TR-76-264.
2. Recommended Anderson, R.K., *et al.*, 1974: Application of meteorological satellite data in analysis and forecasting. ESSA Technical Report NESC 51.
3. Recommended Mesoscale Cloud Interpretation from NOAA-2 High Resolution Visible and Infrared Imagery. Eastern U.S., January 29, 1973.
4. Recommended Tropical Cyclone Intensity Analysis using Satellite Data. NOAA Technical Report NESDIS 11, 1984.
5. Recommended A Technique for the Analysis and Forecasting of Tropical Cyclone Intensities from Satellite Pictures. V.F. Dvorak. NOAA Technical Memorandum NESS 45.

Assignment

Select

1. a hemispheric image
2. a western U.S. sector

of your choice and interpret the major cloud and clear air features in terms of our discussion of weather patterns in class. Write up your discussion and attach relevant synoptic analyses.

Fall 1987

Lab Exercise # 7  
AT 540  
NWP Models and MOS

Readings

1. Facsimile Products, pgs. 1-1 to 1-7, 2-1 to 2-24, and 8-43 to 8-75.
2. Anthes, R.A., 1983: Regional models of the atmosphere in middle latitudes (Review). *Mon. Wea. Rev.*, 1306-1335.
3. Guaraldi, J. and L.F. Bosart, 1985: An assessment of the skill of the NMC 6-10 temperature and precipitation outlook. *Bull. Amer. Meteor. Soc.*, **66**, 831-839.
4. Glahn, H.R., 1985: Yes, precipitation forecasts have improved. *Bull. Amer. Meteor. Soc.*, **66**, 820-830.
5. Klein, W.H., 1982: Statistical weather forecasting on different time scales. *Bull. Amer. Meteor. Soc.*, 170-177.
6. Bosart, L.F., 1981: A preliminary assessment of the state of the art of thunderstorm probability forecasting. *Bull. Amer. Meteor. Soc.*, **62**, 790-792.
7. Charba, J.P. and W.H. Klein, 1980: Skill in precipitation forecasting in the National Weather Service. *Bull. Amer. Meteor. Soc.*, **61**, 1546-1555.
8. Policy Statement of the American Meteorological Society on Weather Forecasting. *Bull. Amer. Meteor. Soc.*, 1385-1387.

Assignment

1. Using GMPACK, obtain the surface, 700 mb, and 500 mb analyses for a specific time period. Contour the surface map for isobars at 4 mb intervals and insert fronts. Contour the 700 mb and 500 mb analyses at 30 m and 60 m intervals, respectively.
2. Obtain the LFM or NGM 12 hour, 24 hour, 36 hour, and 48 hour forecasts corresponding to the time analyzed in #1 for the surface, 700 mb, and 500 mb levels. Discuss the degree of agreement between the predictions and your analyses.
3. Obtain the spectral 72 hour 500 mb simulation corresponding to the corresponding time in your analysis. Discuss the degree of agreement between the predictions and your analysis.

Fall 1987

**Lab Exercise # 8**  
**AT 540**  
**Mesoscale**

Readings

1. Pielke, R.A., 1984: *Mesoscale Meteorological Modelling*, pgs. 455-508.
2. Browning, K.A., 1982: *Nowcasting*, pgs. 149-166 and 207-221.

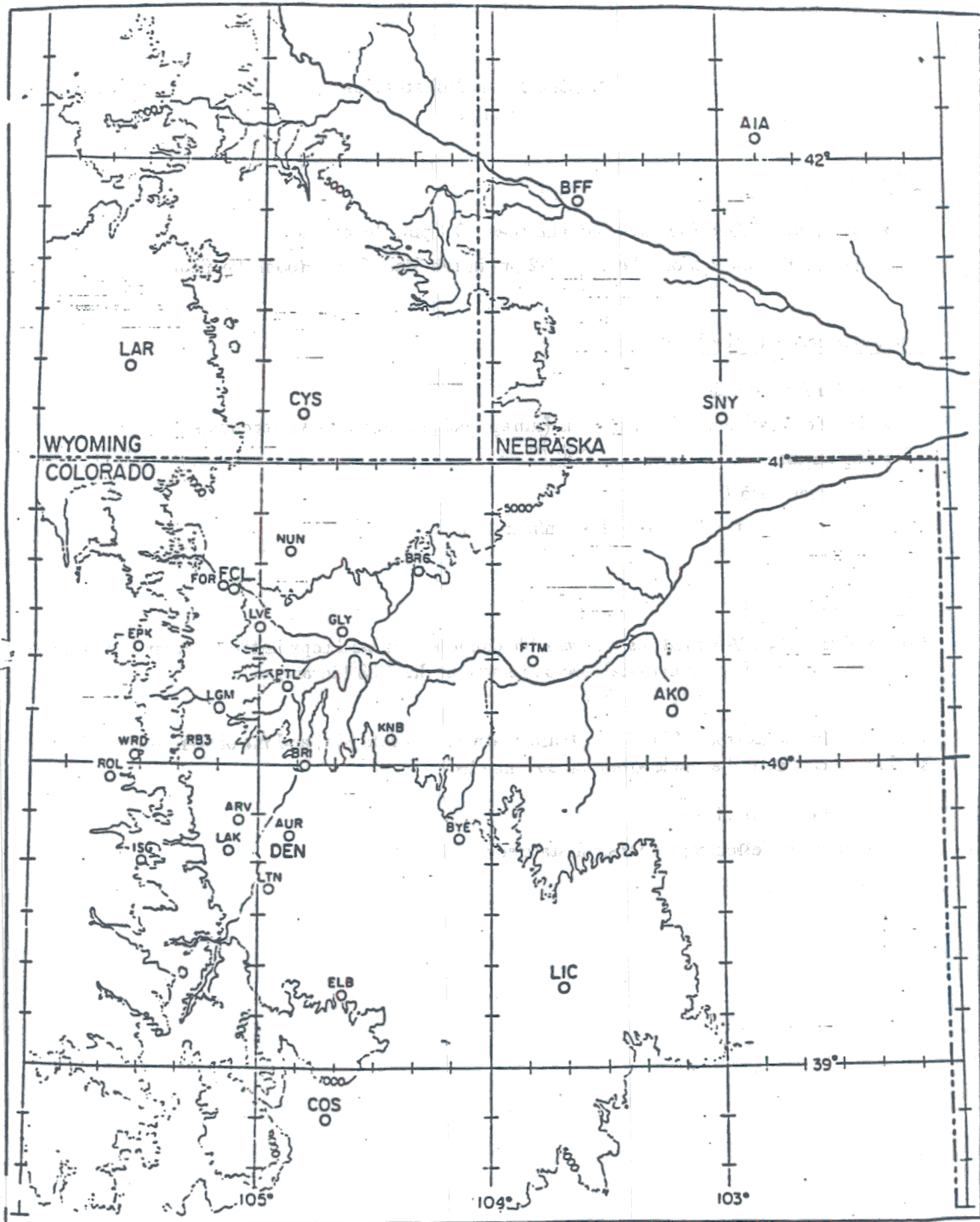
Assignment

1. Using the terminal, plot and analyze the fields of  $T$ ,  $T_D$ ,  $\theta$ , and  $\vec{V}$  from the PROFS data for two separate time periods. (Discuss the patterns in relation to the synoptic atmospheric structure.) Outline areas of terrain-forced ascent and descent (a figure with the PROFS network and an example of PROFS output are attached).
2. Obtain the Grand Junction (GTJ) Sounding for a situation with westerly 700 mb flow. Lift the GTJ sounding to 2.7 km above GTJ. Assume that the entire sounding lifts uniformly. Then descend the sounding assuming:
  - (a) 0% rainout
  - (b) 20% rainout
  - (c) 50% rainout
  - (d) 100% rainout



and compare with the Denver sounding (DEN). If the precipitation is dropped out uniformly over a 100 km distance, what would be the amount of precipitation at the surface per unit area?





**AT 540 Basic Information**  
Fall 1994

Office hours:

- Dr. Roger Pielke: Tuesdays and Thursdays, 3-4 pm, Room 220
- Pier Luigi Vidale: Mon, Wed, Fri, 1-2 pm in the Riehl Conf. Room, 1st floor.

Computer access in the Weather Lab:

- GEMPAK, Mosaic.
- Use the Weather Lab workstations (mirage, eclipse) or your own terminals.
- Log on as:  
    user : at540  
    passwd: p1er213 (keep this confidential)

Manuals, references:

Copies of the GEMPAK manuals are available online and as hard copy in the Weather Lab. Copies of the rest of the reference materials are on reserve in the ATS Library.

Please notify Dallas (room 221, [dallas@europa.atmos.colostate.edu](mailto:dallas@europa.atmos.colostate.edu)) and me of your e-mail address, so that we can have the whole group on our mail list.

TA: Pier Luigi Vidale  
e-mail: [vidale@entropy.atmos.colostate.edu](mailto:vidale@entropy.atmos.colostate.edu)  
phone: 1-8425

**Exercise #1**

**AT 540 WEATHER LAB**

Fall 1994

Reference Material (can be obtained from Dallas, Room 221)

1. Lecture notes – REQUIRED
2. GEMPAK manual – Located in Weather Lab
3. “The use of the Skew T, Log P Diagram in Analysis and Forecasting.” Air Weather Service, pgs. 1-1 to 3-2 – Recommended (on reserve in library).

Exercise

1. Decode the radiosonde transmission (attached) for Tampa Bay (TBW) for 12z (0500 MST) today (08/23/94). List in tabular form and hard plot on a thermodynamic chart (attached).
2. Use GEMPAK, after Steve Finley’s presentation, to plot the Tampa Bay (TBW) sounding for today (08/23/94) at 12z on the CRT and make a hard copy on the laser printer. Write up the computer commands you used to make this plot. The basic commands you need are SNLIST and SNPROF. Make abundant use of the HELP command in GEMPAK, save often and use gpend before you log out.



**Appendix F – Exams**



Fall 1983 AT 540

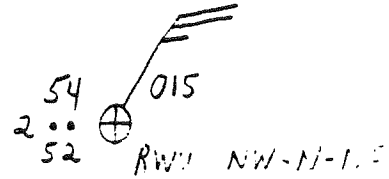
Mid Term Test - Part I

Open book

1. You have been given the 500 mb, 700 mb and surface data for 00Z on October 25, along with concurrent IR and visible satellite photographs. Perform the following analysis
  - a) plot the data for the three surfaces
  - b) analyze the following fields
    - i) 500 mb  
temperature at 5° C intervals; height at 30m intervals
    - ii) 700 mb  
temperature at 5° C intervals; height at 30 m intervals
    - iii) surface  
isobaric pattern at 4 mb intervals, front
  - c) compute
    - i) 500-700 mb thickness at 30 m intervals using whatever analysis procedure you wish. Superimpose velocity change vector on the analysis field and make sure it is consistent. If not, say why next to the wind vector which is different.
    - ii) 500 mb vorticity advection pattern; label significant areas of positive vorticity advection in red, negative areas in blue.
    - iii) 700 mb temperature advection pattern; label significant areas of warm advection in red, cold advection in blue.
    - iv) forced topographic ascent/descent using the surface analysis; label significant areas of forced upward motion in red; downward motion in blue
    - v) regions of significant diabatic heating/cooling. Label substantial deduced upward regions in red.
  - d) discuss each cloud area with respect to the four reasons for vertical motion listed above.

2. The mean height of the 500 mb surface over Fort Collins in July is \_\_\_\_\_
3. The mean height of the 500 mb surface over Fort Collins in January is \_\_\_\_\_
4. Below is a station model for a location in the central United States. Fill in the following question (include dimensions).

i) temperature \_\_\_\_\_  
 ii) dew point \_\_\_\_\_  
 iii) pressure \_\_\_\_\_  
 wind speed \_\_\_\_\_  
 wind direction \_\_\_\_\_  
 sky cover \_\_\_\_\_



comment (in plain english) \_\_\_\_\_

5. Indicate which of the following are correct expressions of the geostrophic wind relation (could be more than one)

- a)  $\mathbf{v}_g = \hat{k} \times \frac{1}{f\rho} \nabla_H p$
- b)  $\mathbf{v}_g = \hat{k} \times \frac{g}{f} \nabla_p z$
- c)  $\mathbf{v}_g = \hat{k} \times \frac{1}{f} \nabla_\theta (C_p T + gz)$
- d)  $\mathbf{v}_g = \hat{k} \times \frac{\rho}{p} \nabla_H f$

e) none of the above

6. Which of the following values of precipitable water are reasonable in an arctic high

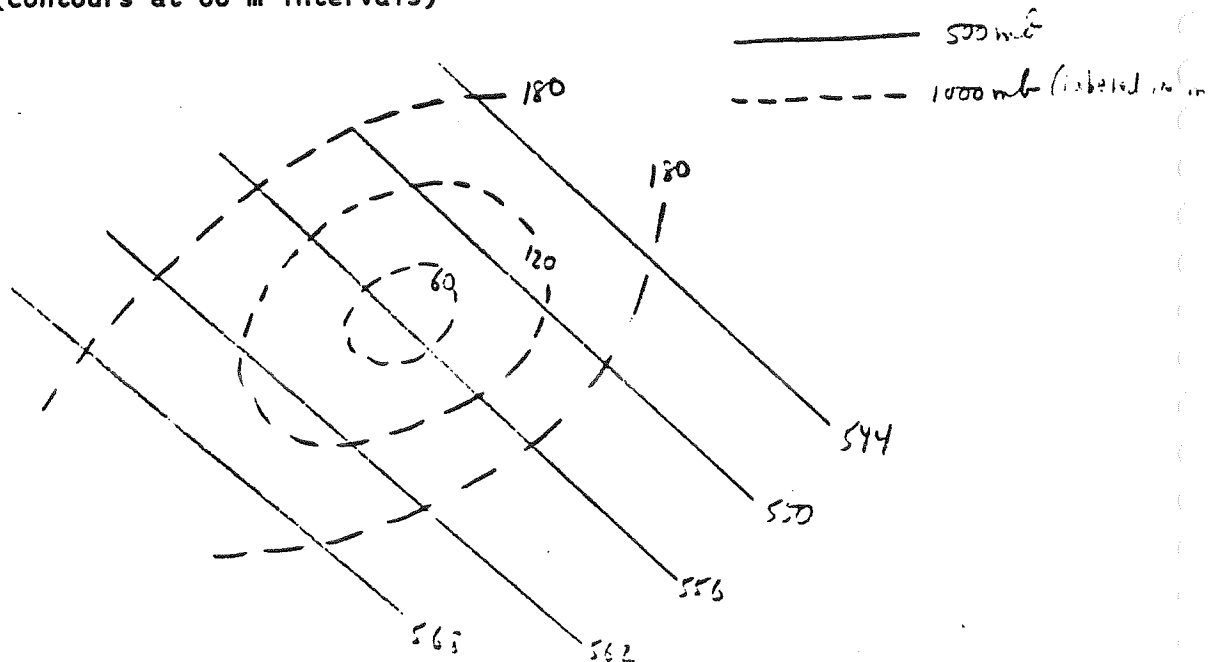
- a) 2.00 inches  
 b) 1.00 inches  
 c) .20 inches  
 d) .0001 inches  
 e) none of the above

*synoptic*

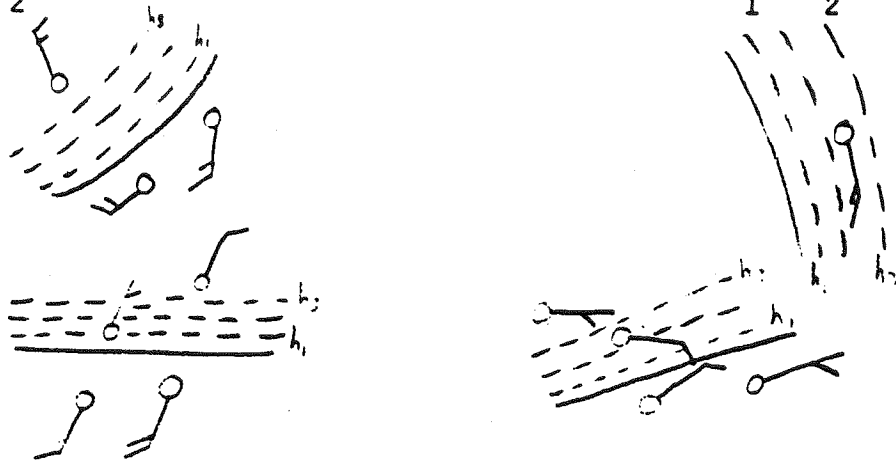
7. A necessary condition to define a front is

- a) the existence of a horizontal surface temperature gradient  
 b) the existence of a gradient of percent of cloud cover  
 c) the existence of a horizontal thickness gradient in the lower troposphere  
 d) the presence of precipitation  
 e) winds in the cold air normal to the front

8. Assume that the layer between 500 and 1000 mb is isothermal.  
 $R = .287 \times 10^7 \text{ ergs g}^{-1} \text{ K}^{-1}$  while  $g = 10^3 \text{ cms}^{-2}$  and  $\ln 2 = .69$ .  
 What is the thickness if the temperature of the layer is  $0^\circ\text{C}$   
 (1st column) and if the temperature of the layer is  $25^\circ\text{C}$  (2nd column)?
- |                      |                      |
|----------------------|----------------------|
| a) 4260 m            | a) 4172 m            |
| b) 4780 m            | b) 4830 m            |
| c) 5430 m            | c) 5420 m            |
| d) 5820 m            | d) 5928 m            |
| e) 6130 m            | e) 6520 m            |
| f) none of the above | f) none of the above |
9. Which of the following surface indications are useful in delineating a frontal location
- location of a pressure trof
  - a wind shift line
  - a horizontal dew point gradient
  - the pressure tendency
  - a horizontal temperature gradient
  - none of the above
10. The intensity of a front is most closely related to
- the horizontal dew point gradient
  - the intensity of the surface wind shift at frontal passage
  - the vertical shear of the horizontal wind
  - the magnitude of the pressure
  - the strength of surface winds in the cold air behind the front.
  - none of the above
11. Sketched below are the heights of a 1000 mb and a 500 mb pressure surface. Draw in and label in decameters the values of the thickness (contours at 60 m intervals)



12. Indicate by an arrow the direction towards which the front would be expected to move given the surface wind pattern indicated by the station model. Indicate the type of front. The values  $h_1, h_2, \dots$  are lines of constant thickness wher  $h_1 > h_2 > h_3$  etc.



13. The concept that winds backing with height implies cold advection and winds veering with height indicates warm advection was derived from
- the first law of thermodynamics
  - the hydrostatic equation and geostrophic wind relation
  - the gas law
  - the second law of thermodynamics
14. The radar analysis depicted as



indicates

- an area of thunderstorms and light rain showers with bases at 26000 feet moving west-southwest at 35 kts.
- an area of thunderstorms and light rain showers with tops at 26000 feet moving east-northeast at 35 kts.
- an area of light rain with between .6 to .9 coverage with individual cells moving east at 35 kts.
- an area of rain with the melting level at 26000 feet moving east-northeast and intensifying.

15. Which of the following cloud types is indicative of strong vertical mixing in the lower troposphere
- a) cirrus
  - b) cirrostratus
  - c) altocumulus
  - d) stratus
  - e) cumulonimbus
  - f) none of the above

Fall 1983 AT540

## Mid Term Test - Part II

16. What is the mean 200 mb wind over Fort Collins in  
 January \_\_\_\_\_  $\text{m s}^{-1}$   
 July \_\_\_\_\_  $\text{m s}^{-1}$ .
17. What is a representative height of  
 a) the polar tropopause \_\_\_\_\_ km  
 b) the tropical tropopause \_\_\_\_\_ km
18. What is the mathematical criteria for dynamic instability in straight line flow on the anticyclonic side of a jet stream?  
 \_\_\_\_\_
19. In Figure 10.17 of Palmen and Newton, delineate where the trajectories are cyclonic and where they are anticyclonic east of the 500 mb trof axis. You will have to xerox the Figure to show this, and attach Figure to the test.
20. What is a reasonable value in watts  $\text{m}^{-2}$  of heat gained as a cold outbreak traverses warm ocean water  
 \_\_\_\_\_ watts  $\text{m}^{-2}$
21. Give representative (i.e. realistic) values of the following quantities. You must provide the correct dimensional units.
- i) relative vorticity on the synoptic scale \_\_\_\_\_
  - ii) Coriolis parameter at  $40^\circ \text{N}$  \_\_\_\_\_
  - iii) 1000 - 500 mb thickness at  $30^\circ \text{N}$  in the summer \_\_\_\_\_
  - iv) 200 mb wind speed in the center of the jet stream \_\_\_\_\_
  - v) sea level maximum pressure associated with a cP high \_\_\_\_\_

Good luck on the test!

Bonus question (worth 3% on top of your grade)

Predict the 12 Noon temperature at Fort Collins on Monday.  
 If you are equal or are closer than my prediction, you earn a bonus of 3%. Your prediction must be made and given to me by 3:00 P.M. today.

prediction: \_\_\_\_\_



## Midterm

Fall 1984

AT 540  
(take-home; open book)

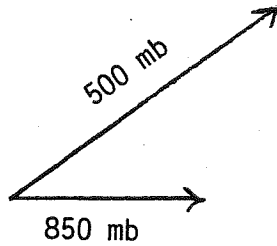
1. Give the heights in meters and temperature in  $^{\circ}\text{C}$  for the pressure surfaces listed below for Denver at 0500 MST today. Use the FAA604 circuit, if necessary

	height (m)	$T(^{\circ}\text{C})$
1000 mb	_____	_____
850 mb	_____	_____
700 mb	_____	_____
500 mb	_____	_____
300 mb	_____	_____
200 mb	_____	_____

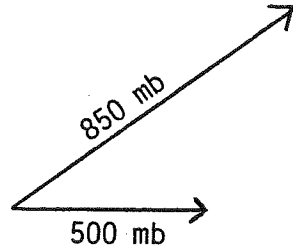
2. Determine the following thicknesses for Denver at the same time as in 1., and determine the layer mean temperature in  $^{\circ}\text{C}$ .

	Thickness (m)	$\bar{T}(^{\circ}\text{C})$
1000 mb - 850 mb	_____	_____
850 mb - 700 mb	_____	_____
700 mb - 500 mb	_____	_____
1000 mb - 500 mb	_____	_____

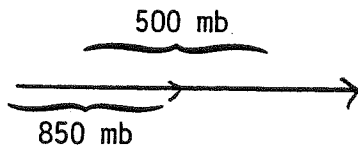
3. Given the 850 mb to 500 mb geostrophic wind changes drawn below, calculate the thickness gradient, and equivalent layer-mean temperature gradients. Draw the orientation of the lines of constant thickness. Indicate whether cold, neutral or warm advection is occurring and indicate the direction of the horizontal temperature gradient.



a)



b)



c)

- a)  $\frac{\nabla_p(\Delta z)}{\quad}$      $\frac{\nabla_p \bar{T}}{\quad}$
- b)
- c)

4. From today's 12z analyses and from tomorrow's LFM forecast, determine the following for Fort Collins. Give units

	<u>today</u>	<u>tomorrow</u>
i) absolute vorticity advection at 500 mb	_____	_____
ii) relative vorticity advection at 500 mb	_____	_____
iii) temperature advection at 500 mb	_____	_____
iv) sign and relative magnitude of diabatic effects at 500 mb	_____	_____
v) estimated vertical velocity at 500 mb	_____	_____

5) Give representative values for the following situations

1000-500 mb thickness

- i) average rain-snow line for Denver \_\_\_\_\_
- ii) average rain-snow line for New York City \_\_\_\_\_
- iii) maximum value normally expected in Denver in the summer \_\_\_\_\_
- iv) minimum value normally expected in Denver in the winter \_\_\_\_\_

500 mb temperature

- i) maximum value normally expected in Denver in the summer \_\_\_\_\_
- ii) minimum value normally expected in Denver in the winter \_\_\_\_\_

700 mb temperature

- i) maximum value normally expected in Denver in the summer \_\_\_\_\_
- ii) minimum value normally expected in Denver in the winter \_\_\_\_\_

- 6) Derive an expression relating 500 mb height to 1000-500 mb thickness.

### Forecast

Forecast the maximum and minimum temperature and precipitation total (melted) at the Fort Collins Weather Station for the following day. The forecasts must be to me no later than 5 P.M. each day of the week (except Saturday and Sunday). I will also forecast using the same guidelines. The forecast verification period is 7 A.M. to 7 A.M. (as at the weather station).

## AT 540 FINAL EXAM

Fall 1986

Open Book

1. Of the following, circle only the lapse rates (between 1000 mb to 900 mb and with a 1000 mb temperature of  $30^{\circ}\text{C}$ ) which are convectively neutral or unstable (5 pts.).

$$\frac{\partial \theta}{\partial z} = 1^{\circ}\text{C}/1\text{ km} \quad \frac{\partial \theta_w}{\partial z} = 1^{\circ}\text{C}/1\text{ km} \quad \frac{\partial T}{\partial z} = -1^{\circ}\text{C}/\text{km} \quad \frac{\partial \theta_E}{\partial z} = -1^{\circ}\text{C}/\text{km}$$

2. Circle the assumptions involved in deriving the adiabatic lapse rate (5 pts.).

hydrostatic relation                      ideal gas law  
 1st law of thermodynamics              equation of motion  
 conservation of mass

3. Circle all 500 mb temperatures which are reasonable for Denver between April 1 and October 1 (5 pts.).

$0^{\circ}\text{C}$      $-5^{\circ}\text{C}$      $-10^{\circ}\text{C}$      $-15^{\circ}\text{C}$      $-20^{\circ}\text{C}$      $-25^{\circ}\text{C}$   
 $-35^{\circ}\text{C}$      $-40^{\circ}\text{C}$      $-45^{\circ}\text{C}$      $-50^{\circ}\text{C}$      $-55^{\circ}\text{C}$      $-60^{\circ}\text{C}$

4. For a 500 - 1000 mb thickness of 5520 meters, calculate the mean temperature in  $^{\circ}\text{C}$ . If the surface temperature is  $10^{\circ}\text{C}$ , calculate a linear lapse rate consistent with this thickness, and the resultant 500 mb temperature. Show your work (10 pts.).

$$T = \quad \frac{\Delta T}{\Delta z} = \underline{\hspace{2cm}}^{\circ}\text{C}/\text{km} \quad T_{500\text{ mb}} = \quad \quad \quad ^{\circ}\text{C}$$

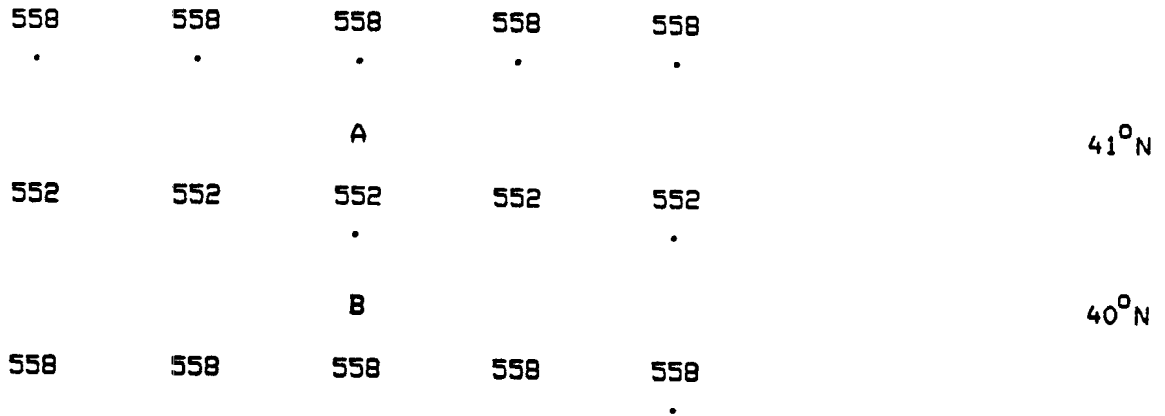
5. Calculate the virtual temperature for a temperature of  $35^{\circ}\text{E}$ , a dew point temperature of  $25^{\circ}\text{C}$  and a pressure of 1000 mb. Show your work (5 pts.).

$T_v$  \_\_\_\_\_  $^{\circ}\text{C}$

6. For an observed horizontal wind from  $235^{\circ}$  of  $50 \text{ ms}^{-1}$  at 500 mb, from  $305^{\circ}$  of  $10 \text{ ms}^{-1}$  at 850 mb, and a mean 850 mb - 500 mb thickness of 3020 m, calculate: (Assume a linear change of wind speed and direction with height. Show your work.) (15 pts.)

- i) vertical wind shear of the horizontal wind \_\_\_\_\_  $\text{ms}^{-1} \text{ km}^{-1}$
- ii) mean horizontal advection of temperature in the layer  
\_\_\_\_\_  $^{\circ}\text{C/hr}$
- iii) mean horizontal advection of the 850 mb - 500 mb thickness  
\_\_\_\_\_  $\text{m/hr}$

7. A portion of a gridded 500 mb height field in decameters is sketched below. Calculate the absolute and relative vorticity for points A and B. Show your work (10 pts).



8. If  $\partial\theta/\partial z = -1^\circ\text{C}/100\text{ m}$ , what is the velocity of a parcel at 1 km above the surface if it starts from rest at the surface and is given an initial upward push of  $1\text{ ms}^{-1}$ ? Assume a mean environmental temperature in the lowest 1 km of  $300^\circ\text{K}$ . Show your work (5 pts.).

\_\_\_\_\_  $\text{ms}^{-1}$

9. Calculate the gradient wind speed and direction if the geostrophic wind is  $30 \text{ ms}^{-1}$  from the west for

i) a low center with a radius of curvature of 500 km

$\text{ms}^{-1}$  from \_\_\_\_\_ °

ii) a high center with a radius of curvature of 500 km

\_\_\_\_\_  $\text{ms}^{-1}$  from \_\_\_\_\_ °

Show your work (7.5 pts.).



10. Listed below are observed weather conditions. Write them up using the synoptic radiosonde transmission code for the standard levels which are given (7.5 pts.).

<u>LEVEL</u>	<u>PRESSURE</u>	<u>TEMP</u> <u>°C</u>	<u>DEW POINT</u> <u>TEMP °C</u>	<u>WIND</u> <u>SPEED</u> (ms <sup>-1</sup> )	<u>DIRECTION</u>	<u>HEIGHT</u> (m)
Surface	1018 mb	- 2.3	- 2.4	2	NW	-
1000 mb	-	1.9	0.0	5	NNW	120
850 mb	-	- 1.1	- 5.6	10	W	1520
700 mb	-	-15.6	-28.6	12	S	3106
500 mb	-	-21.7	-31.5	25	SSE	5650
400 mb	-	-27.5	-36.5	30	NE	7180
300 mb	-	-44.0	M	35	NNE	9150
200 mb	-	-55.0	M	40	N	11700

11. For the previous (Question 10) data, calculate the mixing condensation level for a well mixed, mechanically forced boundary layer, whose top is at 850 mb. Show your work (2.5 pts.).

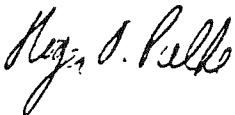
**BONUS**

Forecast the temperature at 1 pm MST tomorrow at the cities listed below. If you are equal or closer than my forecast, you will obtain +1% on your test score for each more accurate forecast.

BWI	HNL	MSP	PHX
MIA	DEN	BOS	
LAX	SEA	CHI	

Good luck on the test. I enjoyed having you in class and wish you success in your program.

Roger A. Pielke



## AT 540 FINAL EXAM

Fall 1986

Open Book

1. Of the following, circle only the lapse rates (between 1000 mb to 900 mb and with a 1000 mb temperature of  $30^{\circ}\text{C}$ ) which are convectively neutral or unstable (5 pts.).

$$\frac{\partial \theta}{\partial z} = 1^{\circ}\text{C}/1\text{ km} \quad \frac{\partial \theta_w}{\partial z} = 1^{\circ}\text{C}/1\text{ km} \quad \frac{\partial T}{\partial z} = -1^{\circ}\text{C}/\text{km} \quad \frac{\partial \theta_E}{\partial z} = -1^{\circ}\text{C}/\text{km}$$

2. Circle the assumptions involved in deriving the adiabatic lapse rate (5 pts.).

hydrostatic relation

ideal gas law

1st law of thermodynamics

equation of motion

conservation of mass

3. Circle all 500 mb temperatures which are reasonable for Denver between April 1 and October 1 (5 pts.).

$5^{\circ}\text{C}$      $0^{\circ}\text{C}$      $-5^{\circ}\text{C}$      $-10^{\circ}\text{C}$      $-15^{\circ}\text{C}$      $-20^{\circ}\text{C}$      $-25^{\circ}\text{C}$

$-30^{\circ}\text{C}$      $-35^{\circ}\text{C}$      $-40^{\circ}\text{C}$      $-45^{\circ}\text{C}$      $-50^{\circ}\text{C}$      $-55^{\circ}\text{C}$      $-60^{\circ}\text{C}$

4. For a 500 - 1000 mb thickness of 5520 meters, calculate the mean temperature in  $^{\circ}\text{C}$ . If the surface temperature is  $10^{\circ}\text{C}$ , calculate a linear lapse rate consistent with this thickness, and the resultant 500 mb temperature. Show your work (10 pts.).

$$T = \underline{\hspace{2cm}} \quad \frac{\Delta T}{\Delta z} = \underline{\hspace{2cm}}^{\circ}\text{C}/\text{km} \quad T_{500\text{ mb}} = \underline{\hspace{2cm}}^{\circ}\text{C}$$

5. Calculate the virtual temperature for a temperature of  $35^{\circ}\text{C}$ , a dew point temperature of  $25^{\circ}\text{C}$  and a pressure of 1000 mb. Show your work (5 pts.).

$T_v$  \_\_\_\_\_  $^{\circ}\text{C}$

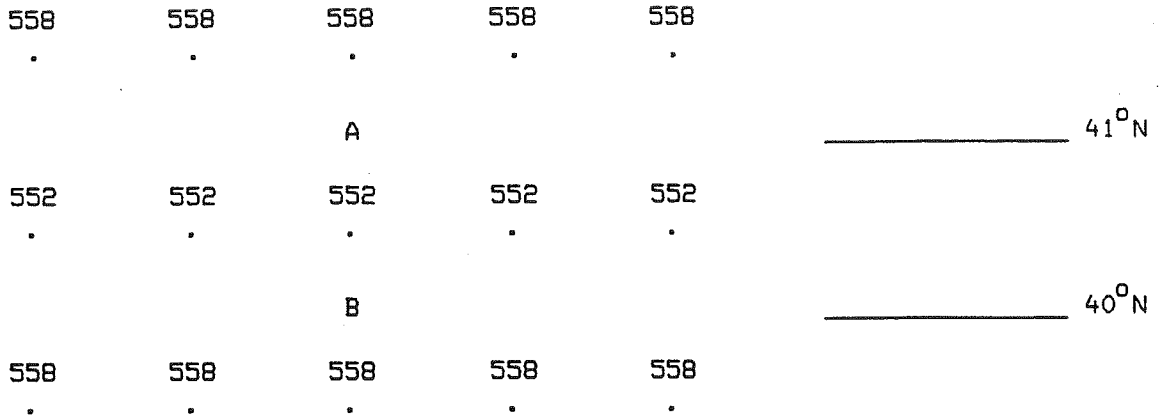
6. For an observed horizontal wind from  $235^{\circ}$  of  $50 \text{ ms}^{-1}$  at 500 mb, from  $305^{\circ}$  of  $10 \text{ ms}^{-1}$  at 850 mb, and a mean 850 mb - 500 mb thickness of 3020 m, calculate: (Assume a linear change of wind speed and direction with height. Show your work.) (15 pts.)

i) vertical wind shear of the horizontal wind \_\_\_\_\_  $\text{ms}^{-1} \text{ km}^{-1}$

ii) mean horizontal advection of temperature in the layer  
\_\_\_\_\_  $^{\circ}\text{C/hr}$

iii) mean horizontal advection of the 850 mb - 500 mb thickness  
\_\_\_\_\_  $\text{m/hr}$

7. A portion of a gridded 500 mb height field in decameters is sketched below. Calculate the absolute and relative vorticity for points A and B. Show your work (10 pts).



8. If  $\partial\theta/\partial z = -1^\circ\text{C}/100\text{ m}$ , what is the velocity of a parcel at 1 km above the surface if it starts from rest at the surface and is given an initial upward push of  $1\text{ ms}^{-1}$ ? Assume a mean environmental temperature in the lowest 1 km of  $300^\circ\text{K}$ . Show your work (5 pts.).

\_\_\_\_\_  $\text{ms}^{-1}$

9. Calculate the gradient wind speed and direction if the geostrophic wind is  $30 \text{ ms}^{-1}$  from the west for

i) a low center with a radius of curvature of 500 km

\_\_\_\_\_  $\text{ms}^{-1}$  from \_\_\_\_\_ °

ii) a high center with a radius of curvature of 500 km

\_\_\_\_\_  $\text{ms}^{-1}$  from \_\_\_\_\_ °

Show your work (7.5 pts.).

10. Listed below are observed weather conditions. Write them up using the synoptic radiosonde transmission code for the standard levels which are given (7.5 pts.).

<u>LEVEL</u>	<u>PRESSURE</u>	<u>TEMP</u> <u>°C</u>	<u>DEW POINT</u> <u>TEMP °C</u>	<u>WIND</u> <u>SPEED</u> (ms <sup>-1</sup> )	<u>DIRECTION</u>	<u>HEIGHT</u> (m)
Surface	1018 mb	- 2.3	- 2.4	2	NW	-
1000 mb	-	1.9	0.0	5	NNW	120
850 mb	-	- 1.1	- 5.6	10	W	1520
700 mb	-	-15.6	-28.6	12	S	3106
500 mb	-	-21.7	-31.5	25	SSE	5650
400 mb	-	-27.5	-36.5	30	NE	7180
300 mb	-	-44.0	M	35	NNE	9150
200 mb	-	-55.0	M	40	N	11700

11. For the previous (Question 10) data, calculate the mixing condensation level for a well mixed, mechanically forced boundary layer, whose top is at 850 mb. Show your work (2.5 pts.).

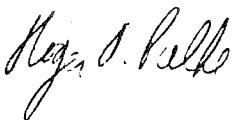
## BONUS

Forecast the temperature at 1 pm MST tomorrow at the cities listed below. If you are equal or closer than my forecast, you will obtain +1% on your test score for each more accurate forecast.

BWI	HNL	MSP	PHX
MIA	DEN	BOS	
LAX	SEA	CHI	

Good luck on the test. I enjoyed having you in class and wish you success in your program.

Roger A. Pielke





AT 540 FALL 1986

MIDTERM  
(Open book - open notes)

Using single station analysis, compute the following for the requested station. Using a transparency of your soundings and a work sheet, you are to make a 5-minute presentation of this information. Your clarity of presentation and completeness will contribute to your grade.

LCL

CCL

LFC

EL

Area and magnitude of positive buoyancy

Area and magnitude of negative buoyancy

$T_w$

MCL (assume a PBL height of 1 km)

Precipitable water

Lifted Index

K-index

1000 - 500mb thickness and mean temperature

1000 - 850mb thickness and mean temperature

850mb - 700mb thickness and mean temperature

1000 - 500mb thermal wind and mean temperature advection

1000 - 850mb thermal wind and mean temperature advection

850mb - 500mb thermal wind and mean temperature advection

**BONUS:** Forecast the temperature in Fort Collins 48 hours from now, as given on the digital read-out in the foyer and earn 3% on top of your midterm grade. Good Luck!

## AT 540 FINAL EXAM

FALL 1987

Open Book

1. Of the following, circle only the lapse rates (between 1000 mb to 900 mb and with a 1000 mb temperature of 30°C) which are convectively neutral or unstable (5 pts.).

$$\frac{\partial \theta}{\partial Z} = 2^{\circ}\text{C}/1 \text{ km} \quad \frac{\partial \theta_w}{\partial Z} = 2^{\circ}\text{C}/1 \text{ km} \quad \frac{\partial T}{\partial Z} = -2^{\circ}\text{C}/\text{km} \quad \frac{\partial \theta_E}{\partial Z} = -2^{\circ}\text{C}/\text{km}$$

2. Circle the assumptions involved in deriving the adiabatic lapse rate (5 pts.).

hydrostatic relation

ideal gas law

1st law of thermodynamics

equation of motion

conservation of mass

3. Circle all 500 mb temperatures which are reasonable for Denver between October 1 and April 1 (5 pts.).

15°C    10°C    5°C    0°C    -5°C    -10°C    -15°C    -20°C    -25°C

-30°C    -35°C    -40°C    -45°C    -50°C    -55°C    -60°C    -65°C    -70°C

4. For a 500-1000 mb thickness of 5700 meters, calculate the mean temperature in  $^{\circ}\text{C}$ . If the surface temperature is  $30^{\circ}\text{C}$ , calculate a linear lapse rate consistent with this thickness, and the resultant 500 mb temperature. Show your work (10 pts.).

$$T = \underline{\hspace{2cm}} = \underline{\hspace{2cm}}^{\circ}\text{C}/\text{km} \quad T_{500 \text{ mb}} = \underline{\hspace{2cm}}^{\circ}\text{C}$$

5. Calculate the virtual temperature for a temperature of  $40^{\circ}\text{C}$ , a dew point temperature of  $20^{\circ}\text{C}$  and a pressure of 900 mb. Show your work (5 pts.).

$$T_v \underline{\hspace{2cm}}^{\circ}\text{C}$$

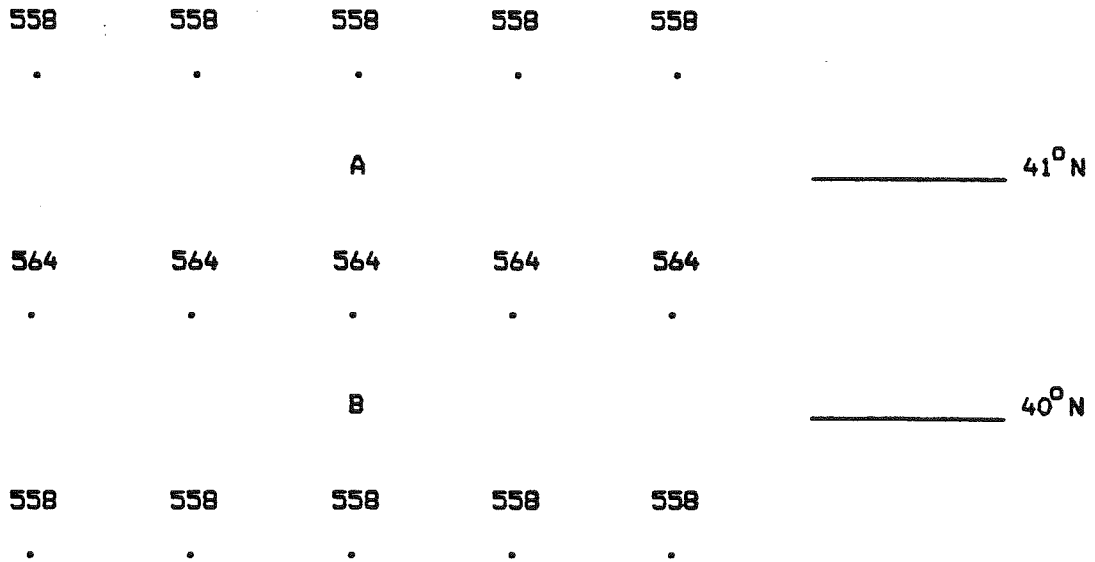
6. For an observed horizontal wind from  $180^\circ$  of  $70 \text{ ms}^{-1}$  at 500 mb, from  $90^\circ$  of  $20 \text{ ms}^{-1}$  at 850 mb, and a mean 850 - 500 mb thickness of 3140 m, calculate: (Assume a linear change of wind speed and direction with height. Show your work.) (15 pts.)

a) vertical wind shear of the horizontal wind \_\_\_\_\_  $\text{ms}^{-1} \text{ km}^{-1}$

b) mean horizontal advection of temperature in the layer  
\_\_\_\_\_  $^\circ\text{C/hr}$

c) mean horizontal advection of the 850 mb - 500 mb thickness  
\_\_\_\_\_  $^\circ\text{m/hr}$

7. A portion of a gridded 500 mb height field in decameters is sketched below. Calculate the absolute and relative vorticity for points A and B. Show your work (10 pts.) Assume a linear change of wind from points A to B.



8. Calculate the gradient wind speed and direction if the geostrophic wind is  $10 \text{ ms}^{-1}$  from the west for

a) a low center with a radius of curvature of 500 km

\_\_\_\_\_  $\text{ms}^{-1}$  from \_\_\_\_\_  $^{\circ}$

b) a high center with a radius of curvature of 500 km

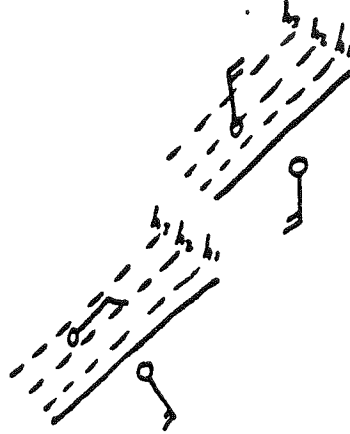
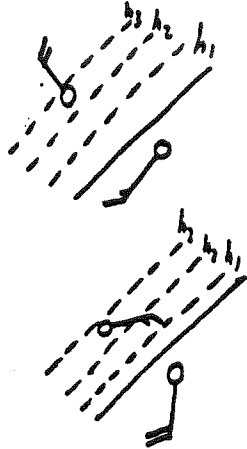
\_\_\_\_\_  $\text{ms}^{-1}$  from \_\_\_\_\_  $^{\circ}$

Show your work (7.5 pts.).

9. Listed below are observed weather conditions. Write them up using the synoptic radiosonde transmission code for the standard levels which are given (7.5 pts.).

<u>LEVEL</u>	<u>PRESSURE</u>	<u>TEMP</u> <u>°C</u>	<u>DEW POINT</u> <u>TEMP °C</u>	<u>WIND</u> <u>SPEED</u> <u>(ms<sup>-1</sup>)</u>	<u>DIRECTION</u>	<u>HEIGHT</u> <u>(m)</u>
Surface	1018 mb	- 2.3	-2.4	8	SW	-
1000 mb	-	6.9	0.0	13	SSW	120
850 mb	-	-11.1	-15.6	20	W	1520
700 mb	-	-16.6	-28.6	25	N	3106
500 mb	-	-30.0	-31.5	30	NNE	5650
400 mb	-	-27.5	-36.5	35	NE	7180
300 mb	-	-44.0	M	40	W	9150
200 mb	-	-55.0	M	50	WNW	11700

10. Given the observed surface winds and thickness gradient outlined below, indicate what type of front occurs and whether it is an 'active' or 'inactive' front. Use standard symbolism for frontal types (4 pts.).



11. List four meteorological parameters that are forecast by NMC using the method of model output statistics (MOS). (2 pts.)

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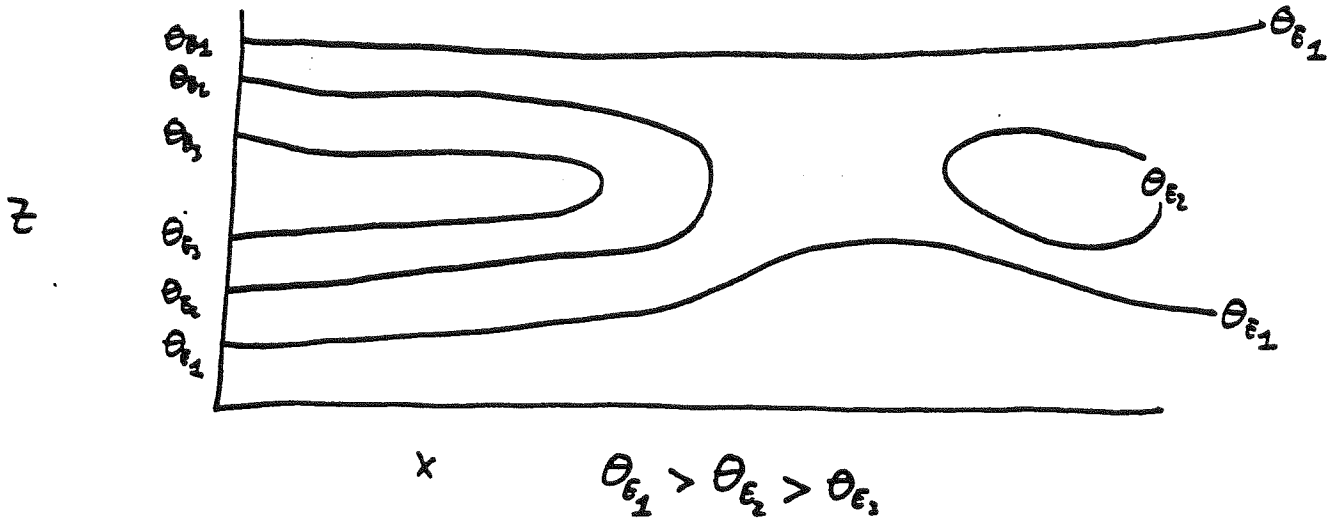
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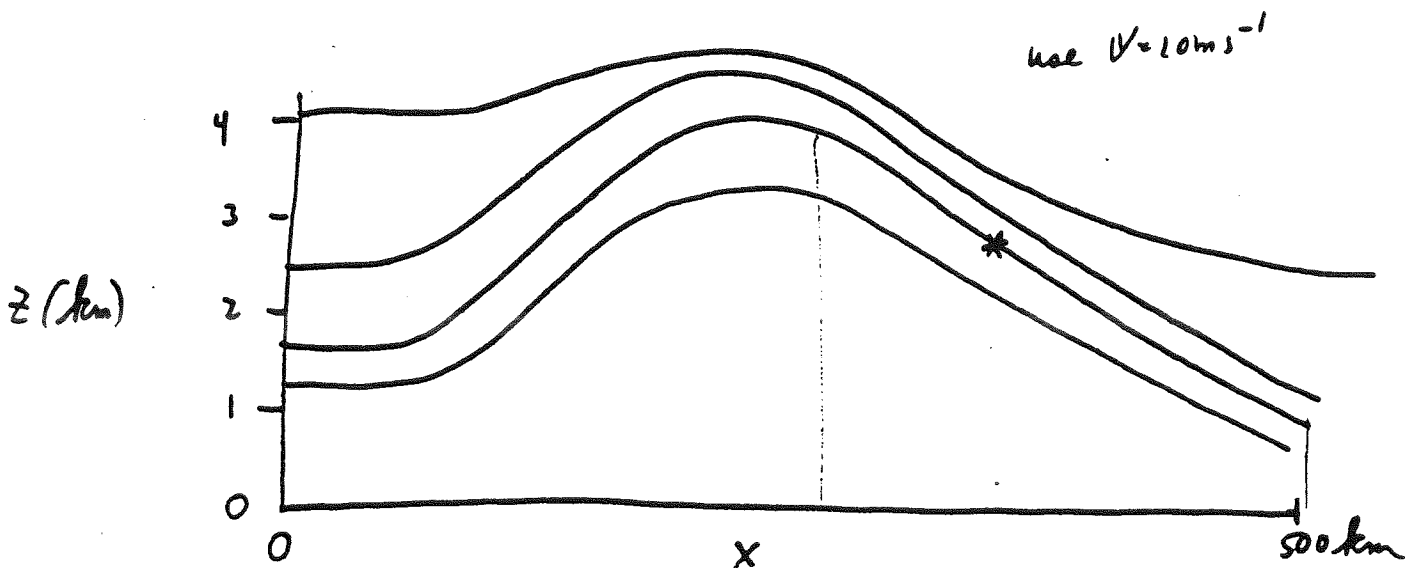


12. For the cross section of equivalent potential temperature sketched below, shade in red the regions of layer instability. (3 pts.)



13. For the cross section of potential temperature sketched below, estimate the magnitude and sign of vertical motion at point \*. Assume adiabatic motion and use a wind speed in the plane of the page of  $20 \text{ m s}^{-1}$ . Show calculations and formula used. (4 pts.)

\_\_\_\_\_  $\text{cm s}^{-1}$  \_\_\_\_\_ (formula used)



FALL 1987

**FINAL**

**AT 540 Re-Exam**

Open Book/Open Notes - Keep Analyses attached

1. Given the attached sounding, decode the following information.

<u>Mandatory Levels</u>	Wind Speed	Wind Direction	T(° C)	T <sub>d</sub> (° C)	Z (m)	p (mb)
Surface	_____	_____	_____	_____	_____	_____
1000 mb	_____	_____	_____	_____	_____	_____
850 mb	_____	_____	_____	_____	_____	_____
700 mb	_____	_____	_____	_____	_____	_____
500 mb	_____	_____	_____	_____	_____	_____
300 mb	_____	_____	_____	_____	_____	_____
200 mb	_____	_____	_____	_____	_____	_____

<u>Significant Levels</u> (Choose two)	T(° C)	T <sub>d</sub> (° C)
_____ (mb)	_____ ° C	_____ ° C
_____ (mb)	_____ ° C	_____ ° C

72407 TTAA 70122 72407 99015 03204 12012 00140 02809 12020  
85461 07215 21049 70046 00419 26050 50568 13743 // 40734  
25350 // 30937 403// 25570 25058 511// 26098 20200 621//  
26641 88999 66160 26700 462// 51515 10164 00008 10194 16034  
24553=

72407 TTBB 7012/ 72407 00015 03204 11898 02413 22842 07415  
33771 05219 44500 13743 55301 39956 66220 587// 77172 681//  
88159 683//=

PPBB 70120 72407 90012 12012 12528 15032 90346 16534 18542  
22551 90789 24054 25056 25556 9123/ 25551 26539 9268/ 25562  
24550 93057 25069 26105 26589 94023 27148 26648 26700=  
64700328

2. Given the attached plotted sounding, calculate the following information using surface values. Show work on a separate sheet.

*LCL* \_\_\_\_\_

*CCL* \_\_\_\_\_

*EL* a) using  $T_c$  \_\_\_\_\_

b) using observed  $T$  \_\_\_\_\_

$T_c$  \_\_\_\_\_

$T_w$  \_\_\_\_\_

$\theta$  \_\_\_\_\_

$\theta_w$  \_\_\_\_\_

$\theta_E$  \_\_\_\_\_

3. Given the attached 500 mb analysis, calculate the following at location A. Show work on a separate sheet.

geostrophic wind speed \_\_\_\_\_

geostrophic wind direction \_\_\_\_\_

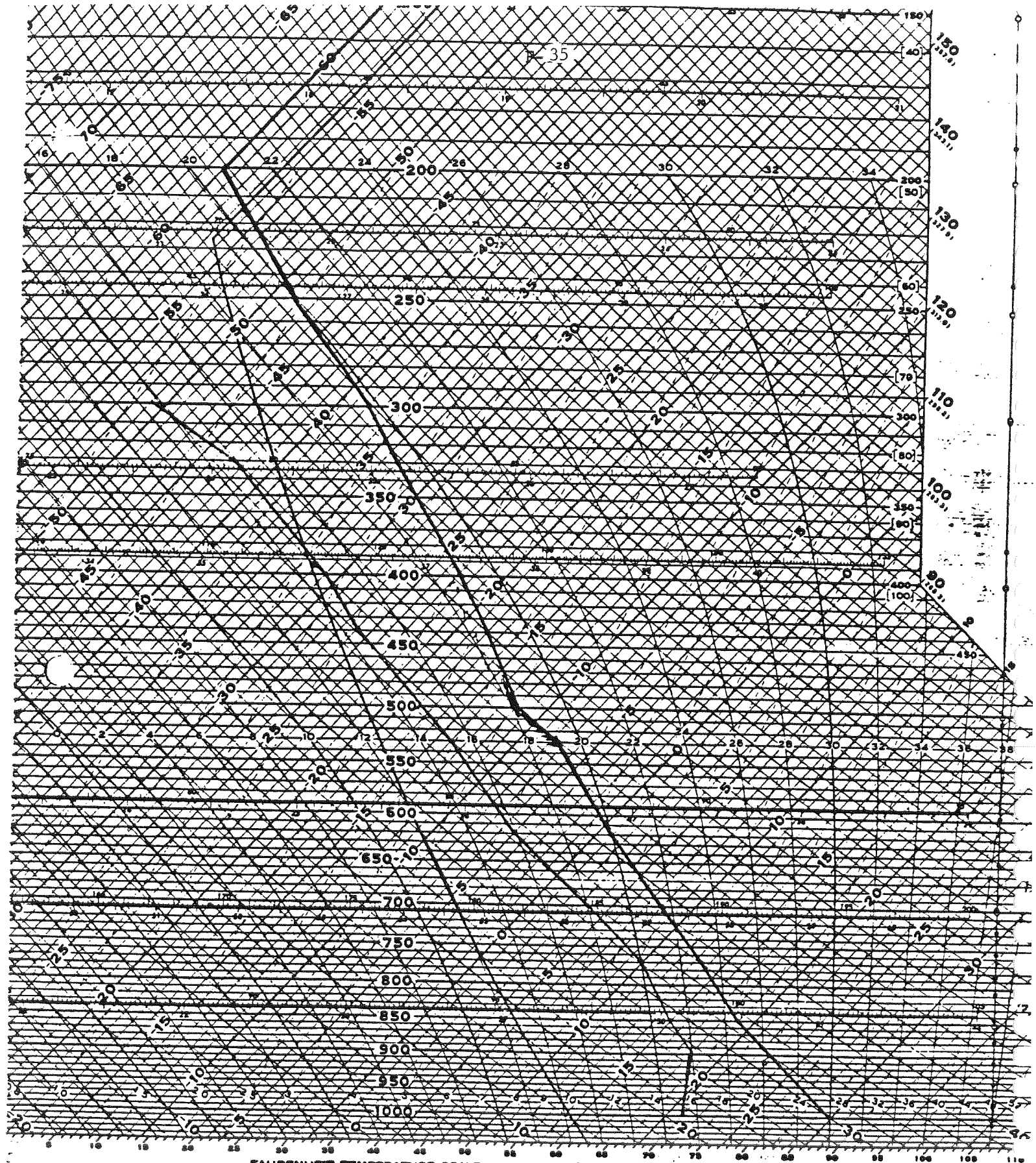
gradient wind speed \_\_\_\_\_

gradient wind direction \_\_\_\_\_

relative vorticity (use geostrophic wind) \_\_\_\_\_

absolute vorticity (use geostrophic wind) \_\_\_\_\_

absolute vorticity advection (use geostrophic wind) \_\_\_\_\_



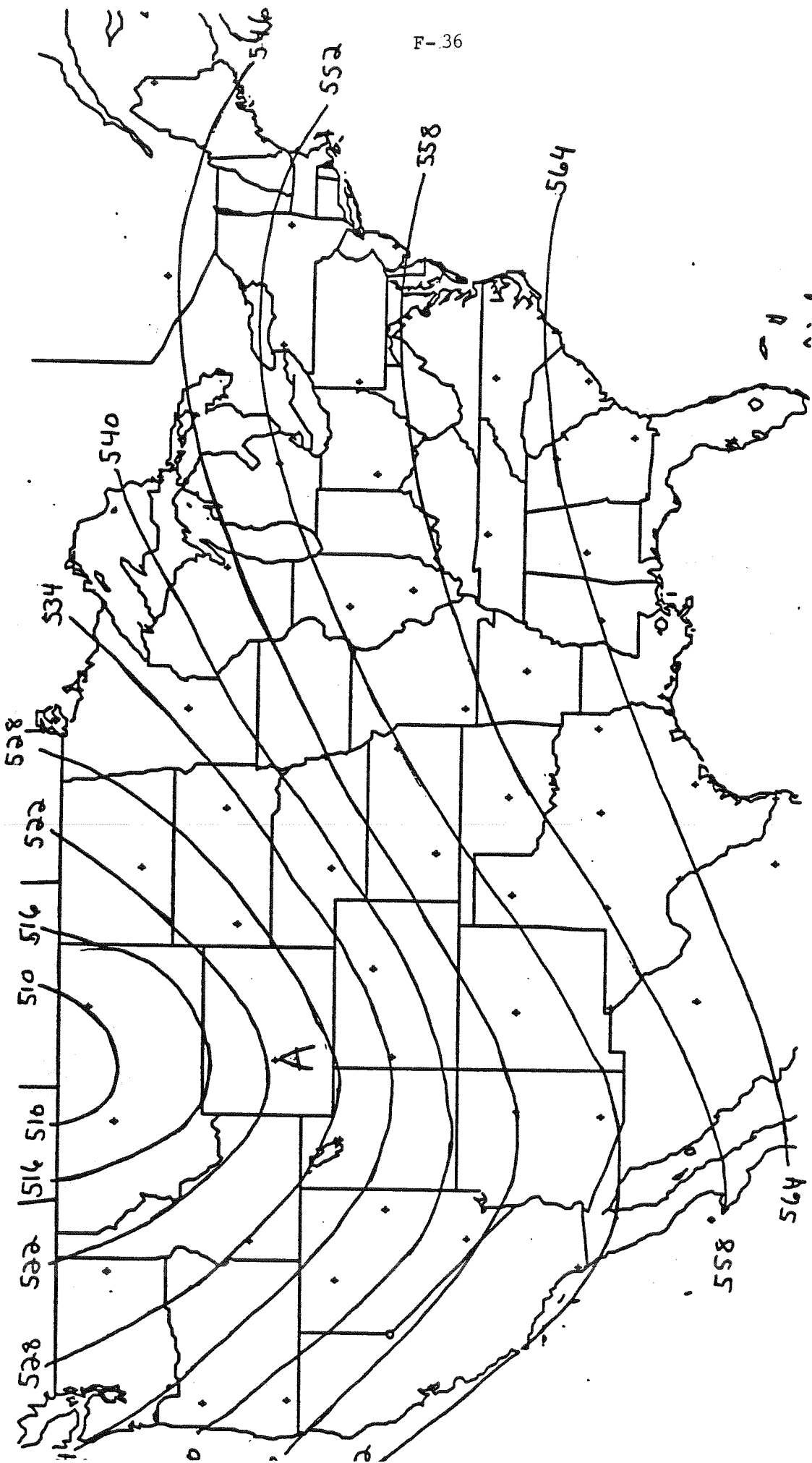
FAHRENHEIT TEMPERATURE SCALE

FORM	NUMBER	STATION
(GCT)	TIME (GCT)	DATE (GCT)

This chart is the property of the U.S. Weather Bureau. It is loaned to you for your use only. It is not to be reproduced, sold, or otherwise disposed of without the express permission of the U.S. Weather Bureau.

Lithographed by DMAAC 8-76

B  
CHART CURRENT



Contour interval 60m  
Height in decimeters

1 cm = 200 km

4. Given the attached 700 mb analysis, calculate the following at point B. Show work on a separate sheet.

geostrophic wind speed \_\_\_\_\_

geostrophic wind direction \_\_\_\_\_

temperature advection (use geostrophic wind) \_\_\_\_\_

5. Given the Figures below, write in the letter of the definition which most closely relates the two.

inactive stationary front \_\_\_\_\_

active stationary front \_\_\_\_\_

inactive warm front \_\_\_\_\_

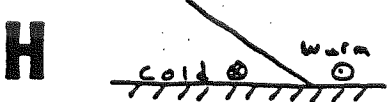
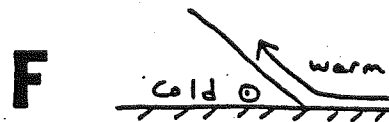
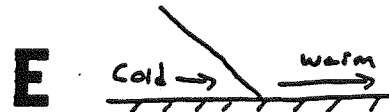
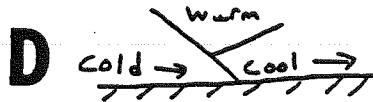
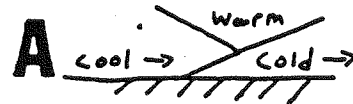
active warm front \_\_\_\_\_

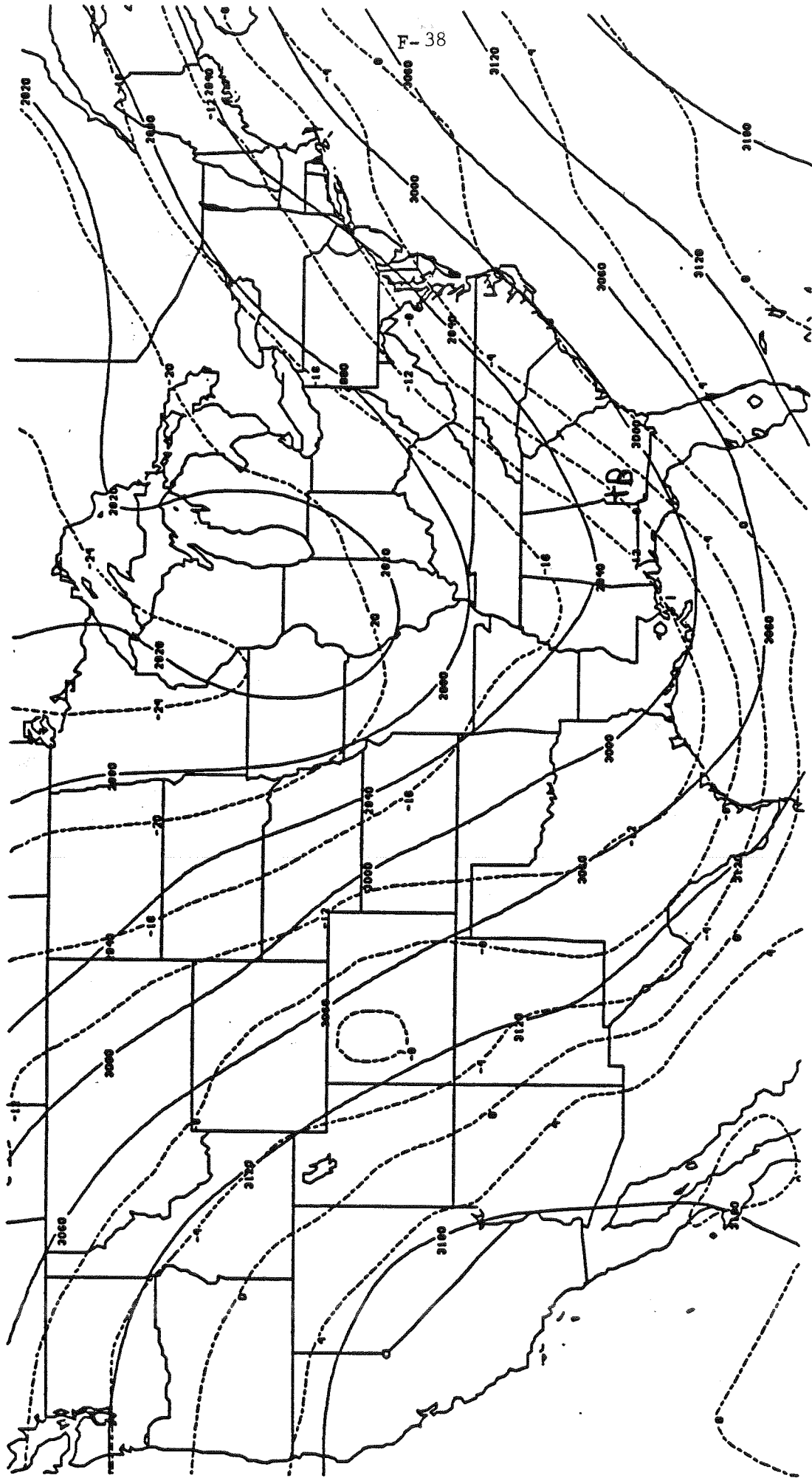
inactive cold front \_\_\_\_\_

active cold front \_\_\_\_\_

cold occlusion \_\_\_\_\_

warm occlusion \_\_\_\_\_





1 cm = 200 km

Height in meters Contour interval: 60m  
 Temperature in °C Isotherm interval: 4°C

R



6. Given the 1000 mb and 500 mb geostrophic winds drawn below, and  $Z_{1000} = 30$  m and  $Z_{500} = 5520$  m, calculate the following for  $43^\circ$  N.

thermal wind ( $m\ s^{-1}$ ) at A \_\_\_\_\_

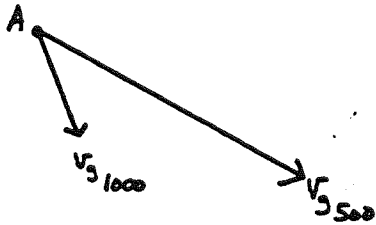
1000 - 500 mb thickness (m) at A \_\_\_\_\_

1000 - 500 mb thickness advection (m/hr) at A \_\_\_\_\_

1000 - 500 mb mean layer temperature ( $^\circ C$ ) at A \_\_\_\_\_

1000 - 500 mb mean layer temperature advection ( $^\circ C/hr$ ) at A \_\_\_\_\_

$1\ cm = 10^3\ m/s$



7. Plot the surface station model for the following observations at a location at  $40^\circ N$ . Temperature =  $80^\circ F$ ; dew point temperature =  $70^\circ F$ ; visibility = 5 miles; wind = 10 knots from the southeast; obscured, light thunderstorms; mean sea level pressure = 1020 mb; pressure falling and then steady over the past 3 hours; pressure change is minus 0.3 mb.

8. Plot the 500 mb station model for the following observations at a location at 40°N. Temperature = -25°C; dew point temperature = -29°C; wind = 35 knots from the south; a height of 5320 meters; and a 12 hour height change of minus 120 meters.

9. Give representative values of temperature and dew point temperature for the following air mass types in the summer.

Summer

*mT*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

*mP*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

*cP*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

*cA*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

10. Given the attached NGM forecast model out, what are the values of the following variables at point A. Give units.

700 mb height \_\_\_\_\_

700 mb relative humidity \_\_\_\_\_

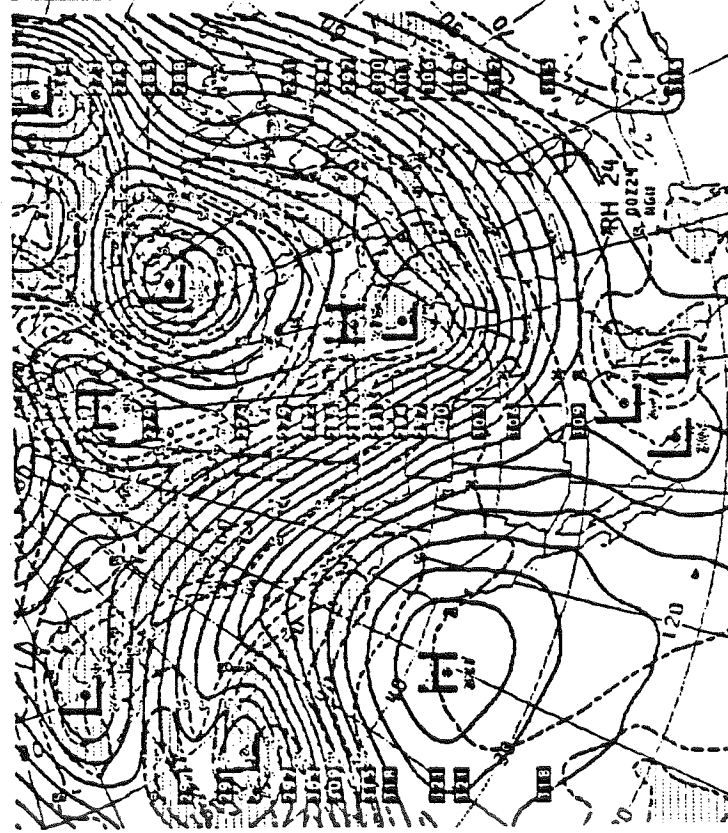
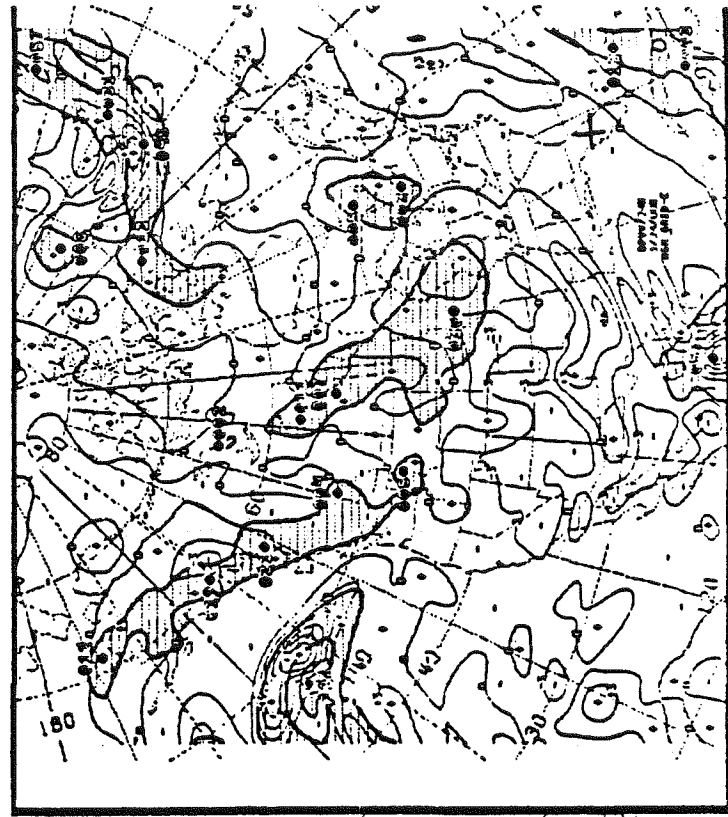
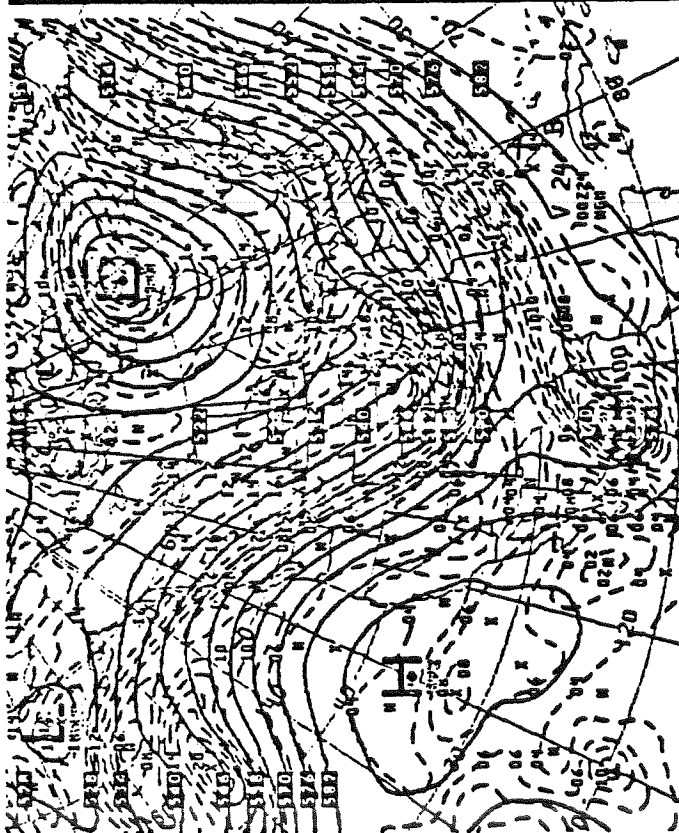
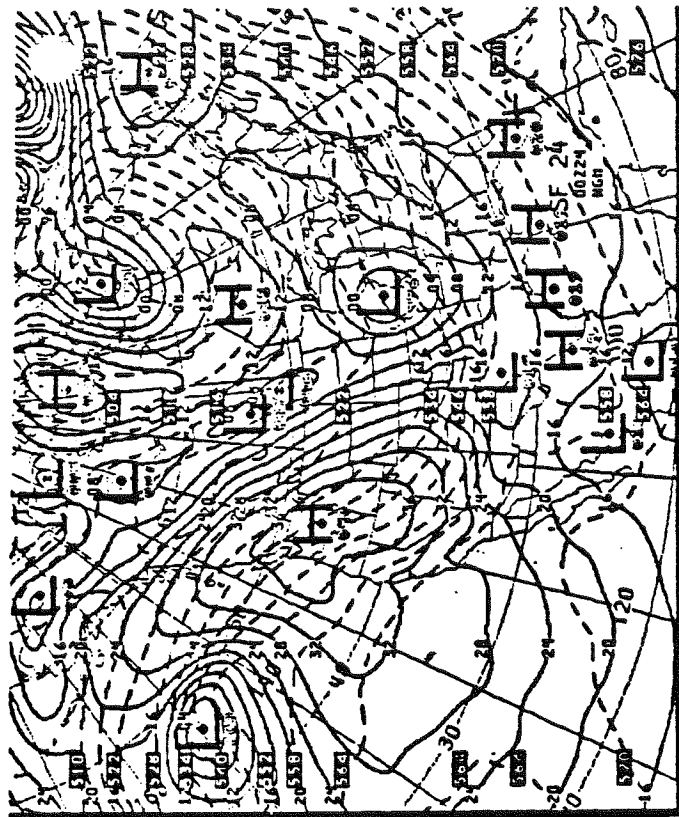
500 mb height \_\_\_\_\_

500 mb absolute vorticity \_\_\_\_\_

surface pressure \_\_\_\_\_

1000 - 500 mb thickness \_\_\_\_\_

vertical motion at 700 mb \_\_\_\_\_



Fall 1987

FINAL

AT 540

**PART 1: SOUNDING PLOTTING AND INTERPRETATION (Optional, upon request; graded separately.)**

From the coded data provided, fill in the following form. Be sure to include units. In some cases, missing is an acceptable answer.

PRESSURE	TEMPERATURE	DEW POINT	HEIGHT	WIND SPEED	WIND DIRECTION
1000 mb	_____	_____	_____	_____	_____
850 mb	_____	_____	_____	_____	_____
700 mb	_____	_____	_____	_____	_____
500 mb	_____	_____	_____	_____	_____
300 mb	_____	_____	_____	_____	_____
200 mb	_____	_____	_____	_____	_____

For the surface, list the following:

- pressure
- temperature
- dew point
- wind speed
- wind direction

Fill out the following information for 5 significant levels which are not mandatory levels and which are below 700 mb.

	PRESSURE	TEMPERATURE	DEW POINT
1.	_____	_____	_____
2.	_____	_____	_____
3.	_____	_____	_____
4.	_____	_____	_____
5.	_____	_____	_____

Give the wind speed and direction for the following heights:

HEIGHT	WIND SPEED	WIND DIRECTION
1000 ft.	_____	_____
3000 ft.	_____	_____
6000 ft.	_____	_____
9000 ft.	_____	_____
15000 ft.	_____	_____
20000 ft.	_____	_____
27000 ft.	_____	_____

RAOBB  
ENTER STATION ID NUMBER

F- 45

STATION: 72407

ENTER TTAA FOR MANDATORY LEVELS, OR TTBB FOR SIGNIFICANT LEVELS  
LEVEL:

^C interrupt

SELECTION: RAOBT

ENTER 5 POSITION STATION ID

STATION: 72407

ENTER DAY OF MONTH (e.g. 22)

DATE: 1,

Enter GMT TIME (e.g. 12)

TIME: 12

07 TTAA 51121 72407 99997 03040 28007 00502 // //

85309 00957 30518 70859 04367 25528 50543 20380 26535 40705

32380 24535 30900 465// 24554 25022 467// 25065 20169 487//

24567 15357 531// 25077 10615 595// 23044 88321 465// 24042

77148 25077 40830 51515 10164 00014 10194 31019 26528=

72407 TTBB 5112/ 72407 00997 03040 11994 03456 22964 03239

33832 01356 44811 01062 55781 00566 66763 00280 77644 07780

88630 09157 99594 11760 11581 12380 22533 18363 33529 18180

44400 32380 55353 40163 66321 465// 77163 497// 88100 595//=

FPBB 51120 72407 90012 28007 30022 32523 90345 33018 32517

28027 90678 27529 26529 25527 909// 25528 91245 25029 25031

25530 9167/ 26031 27034 92057 25538 25037 24039 93035 24557

25065 24564 94235 24570 24559 25077 947// 24549 9502/ 23550

23046=

SELECTION:

Plot the following sounding on the SKEW-T Log-P diagram.

PRESSURE (mb)	TEMPERATURE (C)	DEW POINT (C)
1016	9.4	8.8
1000	8.4	7.6
970	8.6	7.1
950	12.4	10.8
941	12.6	11.0
850	7.4	5.8
700	0.0	-5.0
673	0.0	-5.0
500	-15.5	-19.0
471	-19.1	-23.0
454	-22.3	-30.3
400	-27.7	-36.7
319	-39.9	-45.9
300	-43.7	-
250	-53.5	-
213	-62.1	-
200	-60.3	-
158	-59.3	-
150	-61.7	-
133	-65.1	-
100	-68.7	-



From this sounding, obtain the following values at 1000, 700, and 500 mb. Give a one or two sentence explanation on how each was determined. Show all your work on the tracing paper given. Use one piece for each level.

	1000	700	500
$\theta$	_____	_____	_____
<i>LCL</i>	_____	_____	_____
$T_E$	_____	_____	_____
$\theta_E$	_____	_____	_____
$\theta_W$	_____	_____	_____
$T_W$	_____	_____	_____

From this sounding, answer the following questions. Show all work and briefly explain how each question is answered.

1. At what pressure is the tropopause?

2. If a parcel at the surface is lifted to 200 mb assuming that all water which condenses immediately falls out of the parcel, give the following values for the parcel at 200 mb.

Temperature \_\_\_\_\_

Dew point \_\_\_\_\_

Mixing ratio \_\_\_\_\_

If the parcel originally has 2.0 kg of dry air, how much water fell out of the parcel assuming no entrainment?

3. Assume the surface heats to 29° C and that the dew point is 8.8° C (the same as in the sounding); up to what pressure will the parcel be positively buoyant?

4. What surface temperature is needed to get a surface parcel with an equilibrium level of 250 mb?

5. A warm front is in the vicinity. At what pressure is the top of the warm front?

6. This sounding is for a November day at 12Z at Atlantic City, New Jersey. The weather there most likely is:

- a) mostly clear
- b) cloudy with rain
- c) cloudy with thunderstorms

**PART 2: CALCULATION OF PHYSICAL VALUES (Optional, upon request; graded separately.)**

This part of the exam is designed to see if you understand the physical meaning of the mathematical values and to give you insight into the structure of weather systems. Included are two maps with gridded data at 500 mb and 700 mb with hand drawn contours.

Using only the gridded data set, you will calculate for 1 to 3 stations:

- geostrophic wind at 500 mb and 700 mb
- 500 mb to 700 mb thermal wind
- 500 mb to 700 mb thickness
- 500 mb to 700 mb mean layer temperature
- 500 mb geostrophic relative vorticity
- 500 mb geostrophic absolute vorticity
- 500 mb to 700 mb mean layer temperature advection
- 500 mb geostrophic vorticity advection

Assume a constant  $f = 10^{-4}$ . The contours are provided to help determine if the answers are reasonable. The gridded data along the x and y axis suggest an easy way to calculate the values (I'll give hints in the exam). Assume a uniform spacing of 100 km between grid points.

The stations are underlined grid values on the maps. One is near Williamsport, Pennsylvania (PA); one is near Dallas, Texas (TX), and one is east of Lake Tahoe, Nevada (NV).

The heights for these stations are:

	500 mb	700 mb
PA	5489	2895
TX	5603	3025
NV	5641	3060

1. GEOSTROPHIC WINDS AT 500 MB AND 700 MB. Filling in the following table may help (HINT).  
Be sure to show the equations and values used.

For 500 mb:

Components of the Wind			
$u_g$	$v_g$	wind speed	wind direction

PA

TX

NV

For 700 mb:

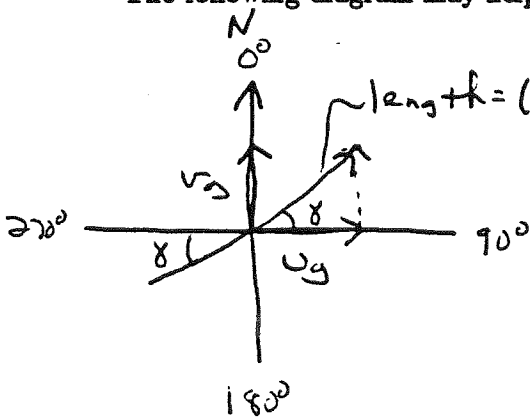
Components of the Wind			
$u_g$	$v_g$	wind speed	wind direction

PA

TX

NV

The following diagram may help:



$$\gamma = \arctan\left(\frac{v_g}{u_g}\right)$$

2. THERMAL WINDS. Fill in the following table. There is an easy way to calculate the thermal wind using the x and y components. Use the same hints as in question 1. As always, be sure to show the equation and values used.

Components of the Wind			
$u_g$	$v_g$	wind speed	wind direction
PA			
TX			
NV			

3. THICKNESS. Calculate the 500 mb to 700 mb layer thickness.

Thickness
PA
TX
NV

4. MEAN LAYER TEMPERATURE. Give the 500 mb to 700 mb mean layer temperature for the three stations. Show the equations and values used.

Mean Layer Temperature
PA
TX
NV

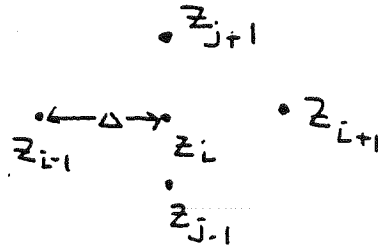
5. RELATIVE GEOSTROPHIC VORTICITY. Show that on a constant pressure surface with  $f$  being constant that:

$$\zeta_g = \hat{k} \cdot \nabla \times \vec{v}_g = \frac{g}{f} \nabla_p^2 z = \frac{g}{f} \left( \frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2} \right)$$

A Laplacian can be approximated by:

$$\nabla^2 z \approx \frac{z_{i+1} + z_{i-1} + z_{j+1} + z_{j-1} - 4z_i}{\Delta^2}$$

$$\Delta x = \Delta y = \Delta$$



Writing the relative vorticity equation in natural coordinates shows that there are two components to vorticity. Write the relative vorticity equation in natural coordinates and state what the terms are. Indicate when each term gives a positive and negative contribution to vorticity.

We have shown that there are two ways to express vorticity. Using the Laplacian form of the vorticity equation, make up "typical" height values at 500 mb to show how each component of the natural form contributes to positive or negative relative vorticity. Use the diagram below.

	First Component	Second Component
P C T S O D		
	$\nabla_p^2 z \approx$	$\nabla_p^2 z \approx$
V A T E		
	$\nabla_p^2 z \approx$	$\nabla_p^2 z \approx$

Using the approximation for the Laplacian, calculate the relative geostrophic vorticity. Remember to show all your work.

Relative Geostrophic Vorticity

PA

TX

NV



6. **ABSOLUTE GEOSTROPHIC VORTICITY.** Using values from part 5, give the absolute geostrophic vorticity for the three stations. (Make up reasonable values for relative vorticity if you didn't get answers for part 5).

Absolute Vorticity

PA

TX

NV

7. **MEAN LAYER TEMPERATURE ADVECTION.** Give the 500 mb - 700 mb mean layer temperature advection for the three stations. Show the equations used and the values put into the equations. Is advection alone causing a mean temperature increase or decrease?

This problem can be easily done if you calculate the x and y components of the advection, then add them together.

Mean Layer Temperature Advection      Increase or Decrease?

PA

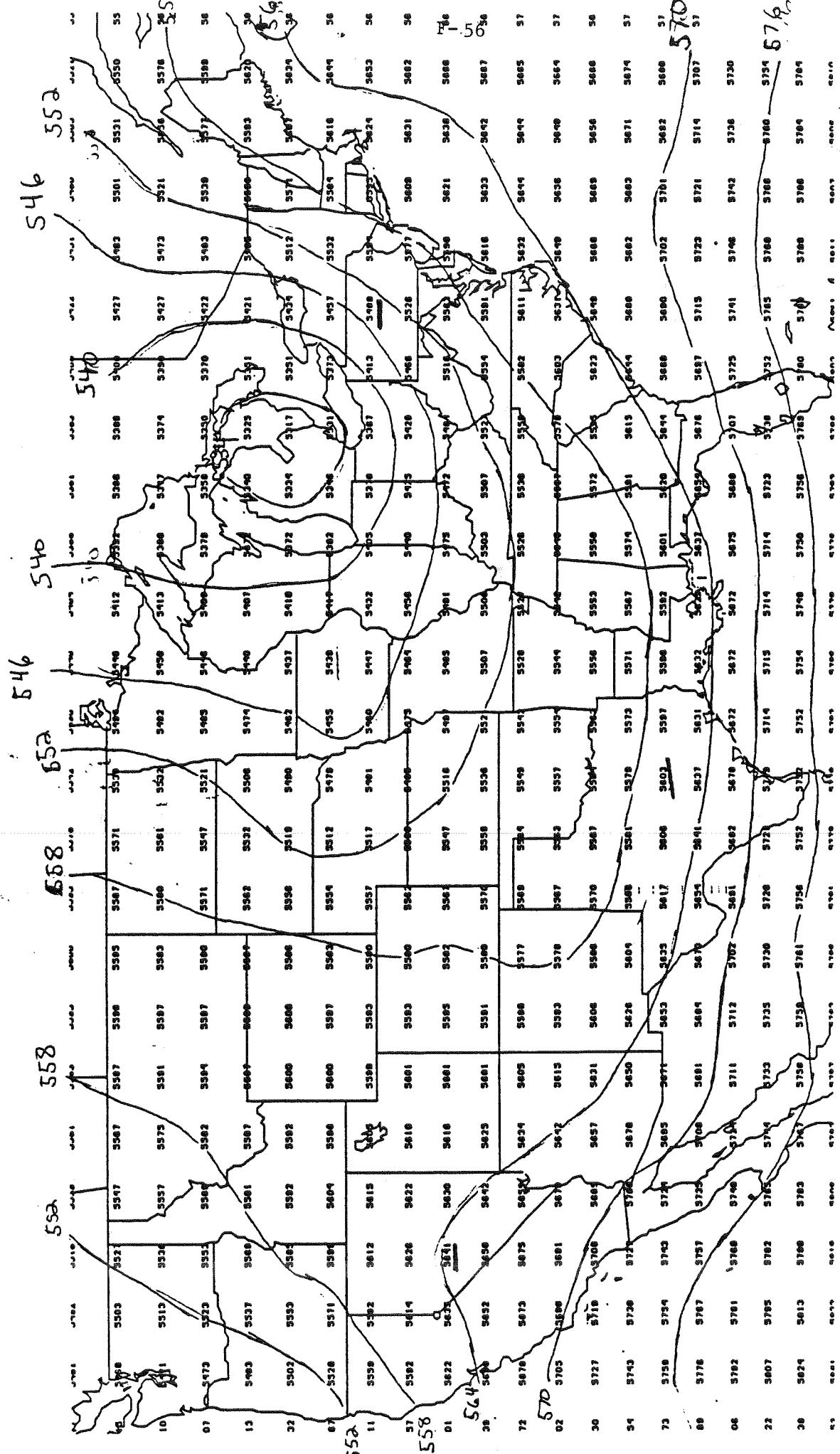
TX

NV

8. **GEOSTROPHIC VORTICITY ADVECTION.** For ONLY Williamsport (PA), calculate the advection of the geostrophic vorticity at 500 mb. Show the equation used and the values used. Look at problems 5 and 7 for hints.

Geostrophic Vorticity Advection

PA



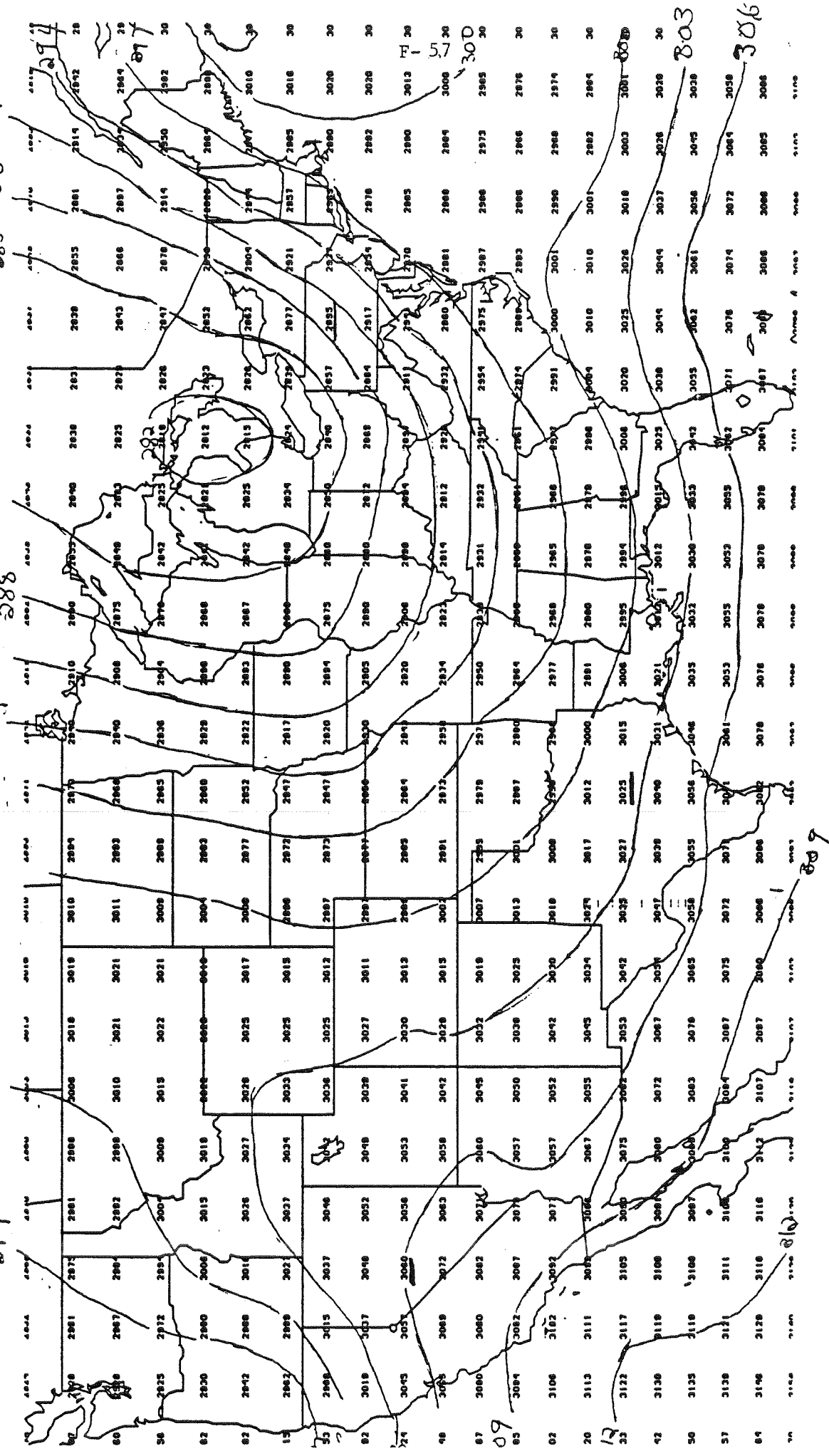
500mb Grid Spacing = 100km

294 291 288 285

288 285 282 279

297 300 303 306

309 312 315 318



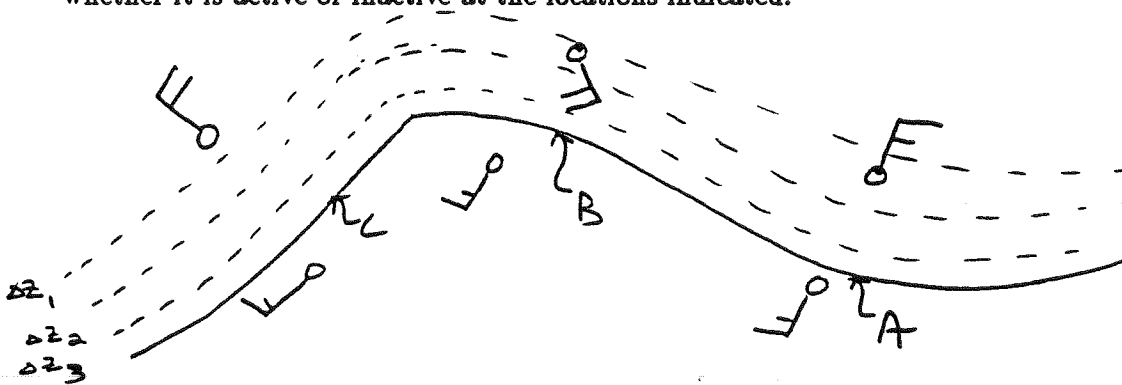
700 mb Grid spacing = 100km

**PART 3: Required**

1. Refer to the satellite photo posted on the blackboard. Indicate the most likely explanation for the specified clouds.

- A. \_\_\_\_\_
- B. \_\_\_\_\_
- C. \_\_\_\_\_
- D. \_\_\_\_\_
- E. \_\_\_\_\_

2. Given the extratropical cyclone and observed winds, infer as best you can, what type of front and whether it is active or inactive at the locations indicated:

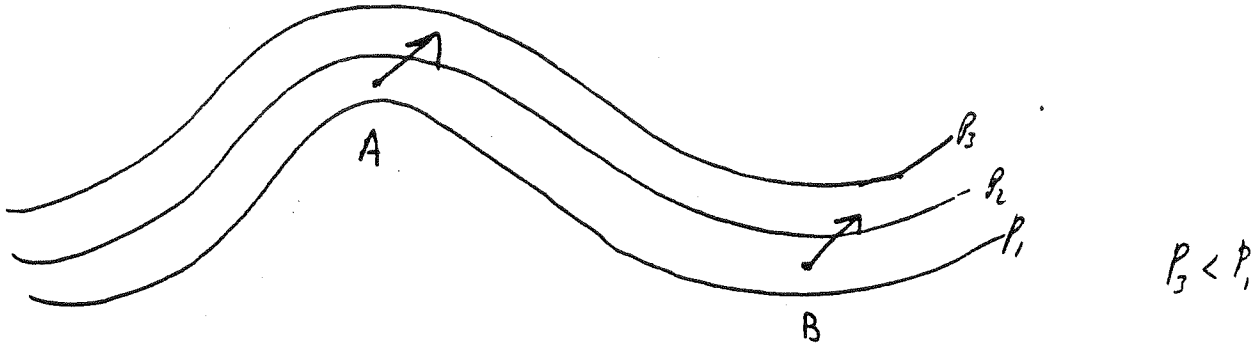


- A. \_\_\_\_\_
- B. \_\_\_\_\_
- C. \_\_\_\_\_

3. Write the form of the geostrophic wind in an isentropic coordinate system. Show your work.

$\vec{V} = \underline{\hspace{2cm}}$

4. Given the pressure distribution below, draw a balance of forces that would result in a non-accelerating wind velocity at points A and B.



5. Given a southward moving  $10 \text{ ms}^{-1}$  parcel with constant horizontal velocity shear and curvature of trajectory, calculate the change of the lapse rate as the parcel moves from  $50^\circ\text{N}$  to  $40^\circ\text{N}$ . Assume a beta-plane centered at  $45^\circ\text{N}$ , and an initial lapse rate of  $\left. \frac{\partial\theta}{\partial p} \right|_{50^\circ\text{N}} = 10^\circ\text{C}/100 \text{ mb}$ .

$$\left. \frac{\partial\theta}{\partial p} \right|_{40^\circ\text{N}} = \underline{\hspace{2cm}} \text{ } ^\circ\text{C}/\text{km}$$

Using this information, assuming  $w = 0$  at the ground, and the wind is a constant up to 100 mb above the surface, estimate vertical motion in  $\text{cm s}^{-1}$  at 300 mb above the surface.

$$w = \underline{\hspace{2cm}} \text{ cm s}^{-1}$$

6. Properly connect the left and right sides.

ITCZ	region of extremely low thickness
northeast trades	upper branch of Hadley cell
polar front	low level convergence of trade winds
arctic high	demarcation between tropical and polar origin air
subtropical jet	lower branch of Hadley cell

7. Referring to the surface weather map for 12Z today, indicate what synoptic category occurs at the points listed below.

A. \_\_\_\_\_

B. \_\_\_\_\_

C. \_\_\_\_\_

D. \_\_\_\_\_

E. \_\_\_\_\_

8. Give the meaning of the following acronyms. For the ones that are models, also give their number of vertical levels and approximate horizontal grid intervals at 45°N.

		LEVELS (if applicable)	Horizontal Grid Resolution (if applicable)
NGM:	_____	_____	_____
LFM:	_____	_____	_____
RAFS:	_____	_____	_____
MRF:	_____	_____	_____
MOS:	_____	_____	_____
DIFAX:	_____	_____	_____
MFM:	_____	_____	_____

9. Define in a few sentences, each of the following two concepts:

Perfect Prog:

Method of Model Output Statistics:

Finally, for a 5% bonus on top of your course grade, forecast the temperature on the foyer thermometer at 1 p.m. Friday. If you equal or are closer to my forecast, you earn the 5%.

Good luck! I enjoyed having you in class this fall!

R.A. Pielke

Fall 1987

Test  
AT 540 (3 hours)

Using the attached 500 mb and 700 mb analyzed maps, perform the following calculations for

- Denver
- Chicago
- Washington, D.C.
- Phoenix

Their locations are indicated on the maps. The answer sheet is attached. Tracing paper is added for convenience in your calculations.

1. compute the geostrophic and gradient winds
2. compute the 700 mb to 500 mb thermal wind
3. compute the 700 mb to 500 mb thickness
4. compute the 700 mb to 500 mb mean layer temperature
5. compute the layer-mean temperature advection
6. compute the geostrophic relative vorticity at 500 mb
7. compute the absolute vorticity at 500 mb
8. compute the 500 mb absolute vorticity advection

---

Use  $f = 10^{-4} \text{ sec}^{-1}$  for each city. Show your equations and your work. Make sure you give dimensional units.

**BONUS:** Forecast the temperature on the digital thermometer in the foyer at 1 p.m., 48 hours from today. If you are equal or are closer than my forecast, we will add 5% to your grade.

attachments: answer sheet, and height analyzed 500 mb and 700 mb fields



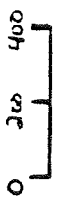
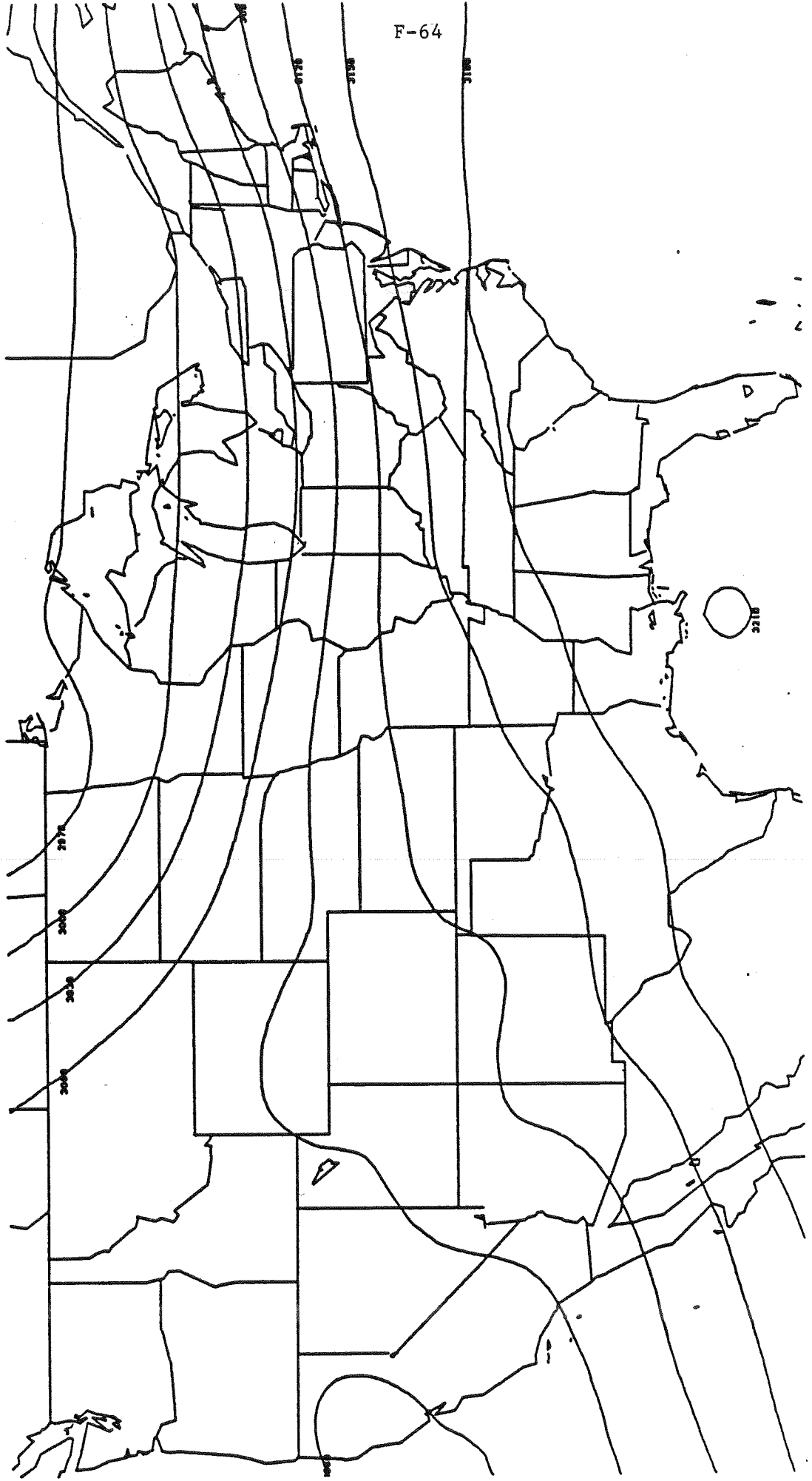
Name: \_\_\_\_\_

Fall 1987  
 AT540  
 (Answer Sheet)

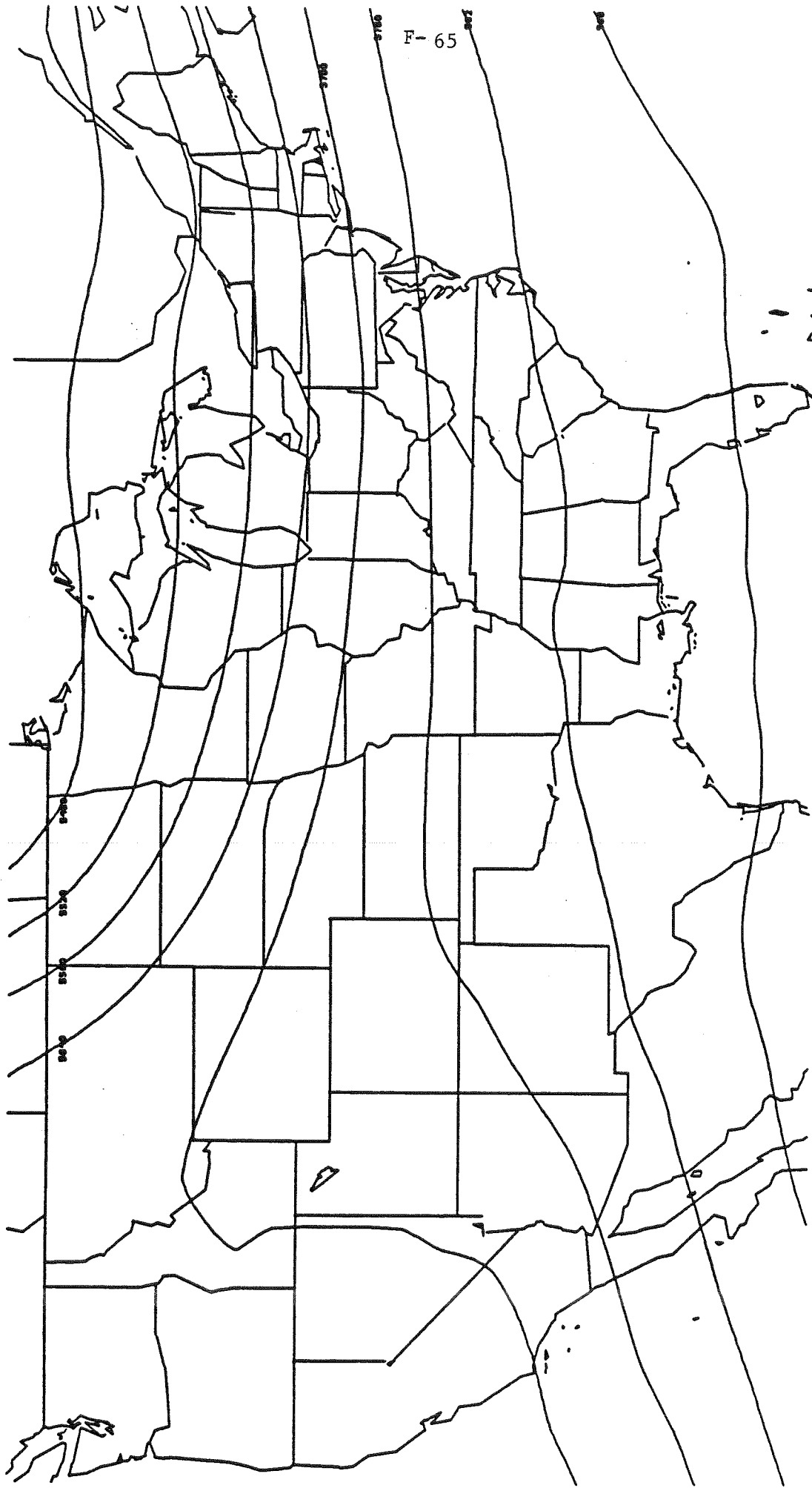
		Denver	Chicago	Washington, D.C.	Phoenix
geostrophic wind	500 mb	_____	_____	_____	_____
	700 mb	_____	_____	_____	_____
gradient wind	500 mb	_____	_____	_____	_____
	700 mb	_____	_____	_____	_____
700 mb to 500 mb thermal wind		_____	_____	_____	_____
700 mb to 500 mb thickness		_____	_____	_____	_____
700 mb to 500 mb mean layer temperature		_____	_____	_____	_____
layer mean temperature advection		_____	_____	_____	_____
500 mb geostrophic relative vorticity		_____	_____	_____	_____
500 mb absolute vorticity		_____	_____	_____	_____
500 mb absolute vorticity advection		_____	_____	_____	_____

Temperature Forecast \_\_\_\_\_

F-64



Scale 1cm = 200km  
2.1 1.1 1.1 2.2



Scale km=200km

Contour interval: 60 m

AT 540

Thermodynamic Test - 2 Hours

1. Attached is a plotted thermodynamic diagram. Obtain the following values from the sounding.

850 mb	700 mb	500 mb	300 mb	
_____	_____	_____	_____	$T_D$
_____	_____	_____	_____	$T_W$
_____	_____	_____	_____	$T$
_____	_____	_____	_____	$T_E$
_____	_____	_____	_____	$\theta$
_____	_____	_____	_____	$\theta_W$
_____	_____	_____	_____	$\theta_E$
_____	_____	_____	_____	$e$
_____	_____	_____	_____	$LCL$

(from the stated pressure)

2. Using 1000 mb as your lower level, compute the  $LFC$  and the  $EL$  using

	<u><math>LFC</math></u>	<u><math>EL</math></u>
i) the given value of $T_D$ and $T$	_____	_____
ii) the given value of $T_D$ and $T + 5^\circ C$	_____	_____
iii) the given value to $T$ and $T_D = T$	_____	_____
iv) the value of $T_C$ using the value of $w$ at $T_D$ to represent the moisture up to the $CCL$	_____	_____
Give the value of $T_C =$ _____		
and $CCL =$ _____		

3. Given the attached raw data, provide the following values

height(meters)	wind(knots)
Z <sub>850 mb</sub> _____	5,000 feet _____
Z <sub>700 mb</sub> _____	10,000 feet _____
Z <sub>500 mb</sub> _____	15,000 feet _____
Z <sub>300 mb</sub> _____	20,000 feet _____
Z <sub>200 mb</sub> _____	25,000 feet _____

pressure(mb)    temperature (°C)    dew point temperature(°C)  
 for 5 significant levels that are not standard levels  
 and that are lower than 300 mb

_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____

Remember to include units. Good luck on test.

ENTER 5 POSITION STATION ID

F-68

STATION: 72407

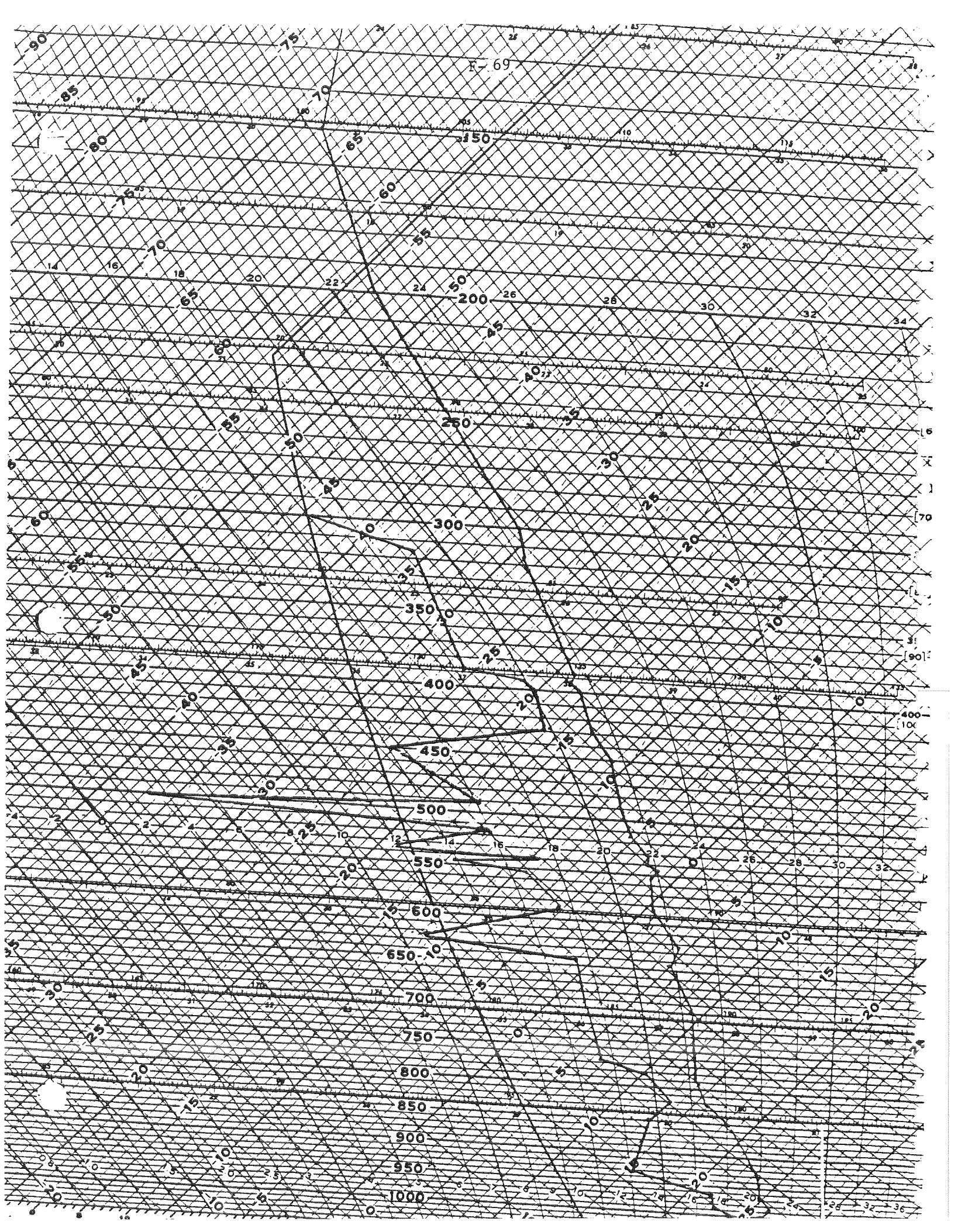
ENTER DAY OF MONTH (e.g. 22)

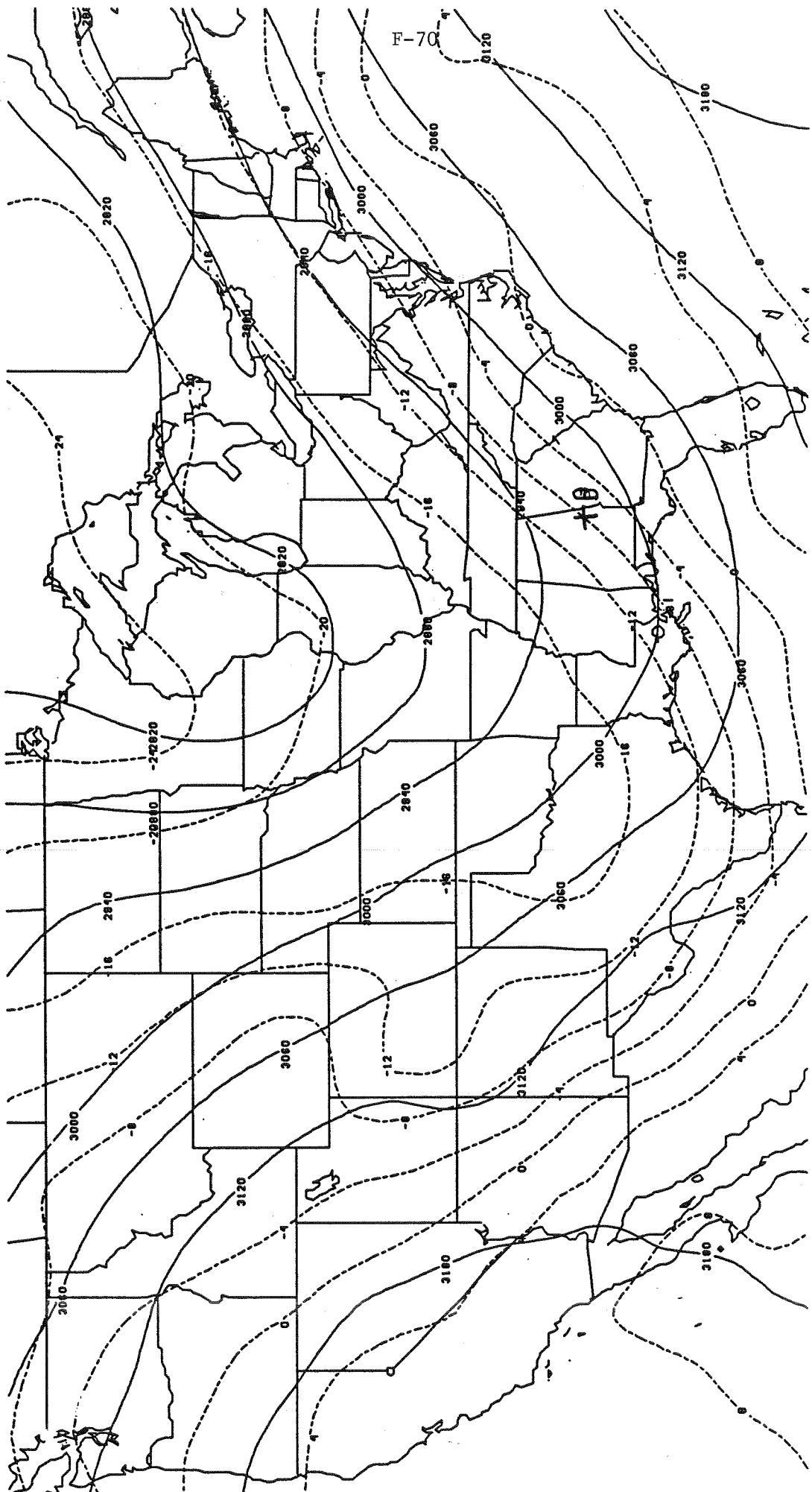
DATE: 27

Enter GMT TIME (e.g. 12)

TI : 12

72407 TAA 77121 72407 99021 13226 33505 00196 17660 35010  
85566 08633 30521 70142 02580 31032 50578 12780 30034 40745  
25165 29537 30947 411// 29539 25069 499// 30043 20212 583//  
29543 15391 621// 28046 10642 613// 27030 88175 619// 28051  
77999 51515 10164 00008 10194 33013 31029=  
12407 TTBB 7712/ 72407 00021 13226 11008 17260 22994 17860  
33895 12059 44850 08633 55732 00008 66703 02925 77700 02580  
88697 00190 99676 01680 11575 07567 22553 07980 33500 12780  
44307 39963 55175 619// 66139 603// 77130 631// 88100 613//=  
PPBB 77120 72407 90012 33505 35512 34510 90345 32013 31516  
30521 90678 31523 32028 31032 909// 30536 91246 31524 31022  
30029 92015 30034 29534 30037 93045 29537 30534 30043 938//  
29556 94135 28538 28057 28536 946// 28047 9503/ 27035 27532=  
40000328  
SELECTION:





Height in meters Contour interval: 60m  
 Temperature in °C Isotherm interval: 4°C

A

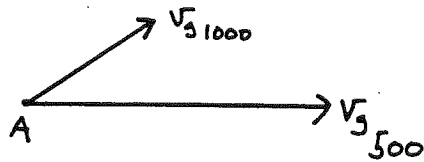
1cm=200m



6. Given the 1000 mb and 500 mb geostrophic winds drawn below, and  $Z_{1000} = 30$  m and  $Z_{500} = 5520$  m, calculate the following for  $43^\circ$  N.

- thermal wind ( $\text{m s}^{-1}$ ) at A \_\_\_\_\_
- 1000 - 500 mb thickness (m) at A \_\_\_\_\_
- 1000 - 500 mb thickness advection (m/hr) at A \_\_\_\_\_
- 1000 - 500 mb mean layer temperature ( $^\circ\text{C}$ ) at A \_\_\_\_\_
- 1000 - 500 mb mean layer temperature advection ( $^\circ\text{C/hr}$ ) at A \_\_\_\_\_

$1\text{cm} = 10\text{m/s}$



7. Plot the surface station model for the following observations at a location at  $40^\circ\text{N}$ . Temperature =  $34^\circ\text{F}$ ; dew point temperature =  $20^\circ\text{F}$ ; visibility = 7 miles; wind = 15 knots from the northwest; overcast, light snow; mean sea level pressure = 1013 mb; pressure rising and then steady over the past 3 hours; pressure change is plus 1.3 mb.

8. Plot the 500 mb station model for the following observations at a location at 40°N. Temperature = -15°C; dew point temperature = -17°C; wind = 75 knots from the east; a height of 5520 meters; and a 12 hour height change of plus 70 meters.

9. Give representative values of temperature and dew point temperature for the following air mass types in the summer.

Summer

*mT*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

*mP*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

*cP*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

*cA*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

10. Given the attached NGM forecast model out, what are the values of the following variables at point A. Give units.

700 mb height \_\_\_\_\_

700 mb relative humidity \_\_\_\_\_

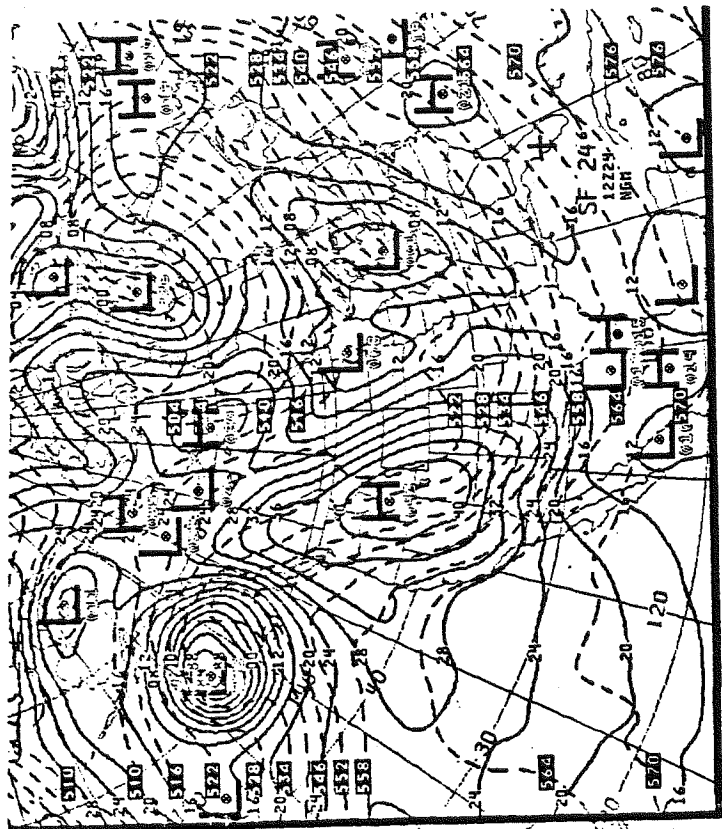
500 mb height \_\_\_\_\_

500 mb absolute vorticity \_\_\_\_\_

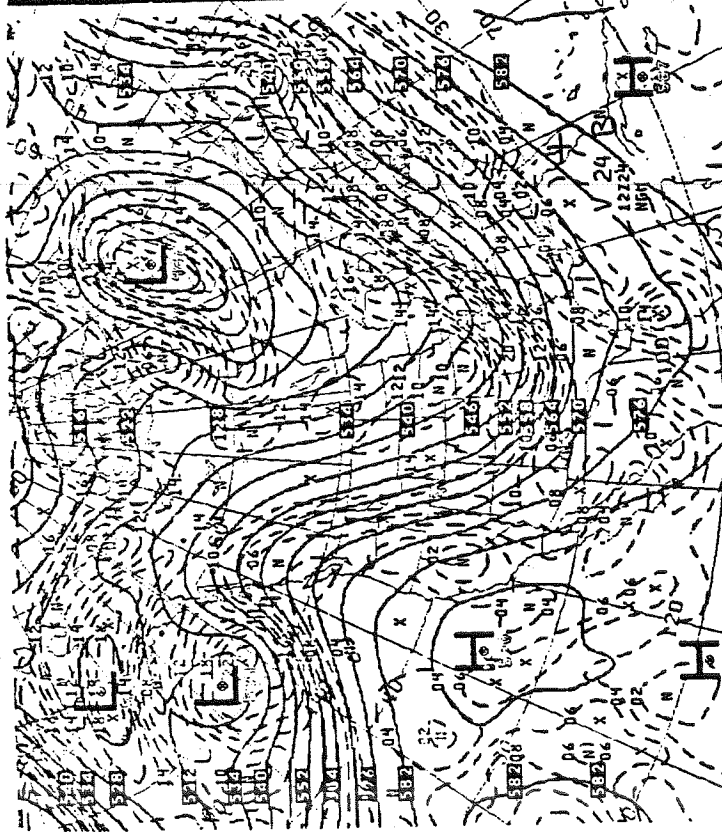
surface pressure \_\_\_\_\_

1000 - 500 mb thickness \_\_\_\_\_

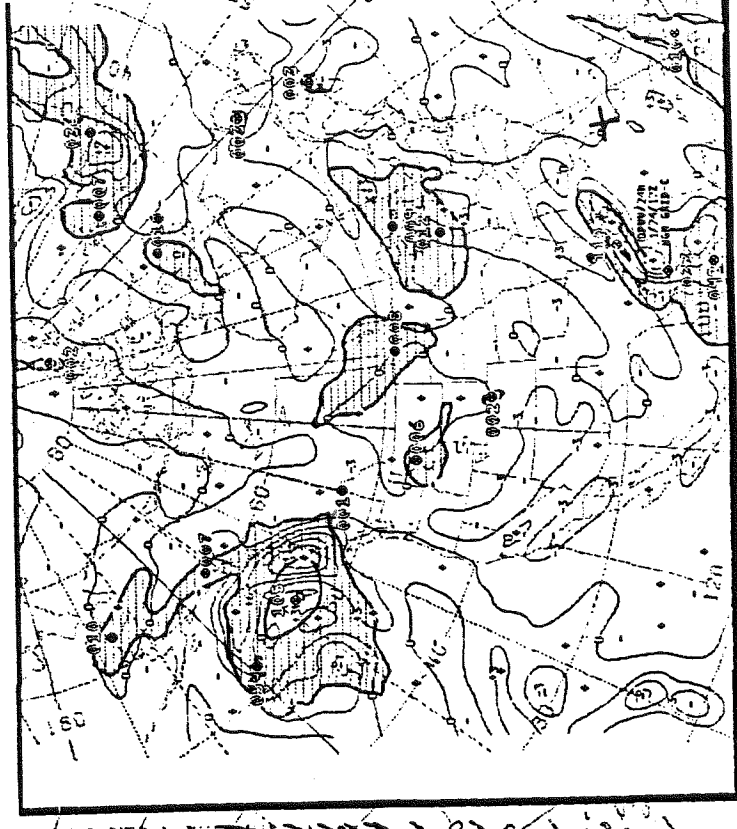
vertical motion at 700 mb \_\_\_\_\_



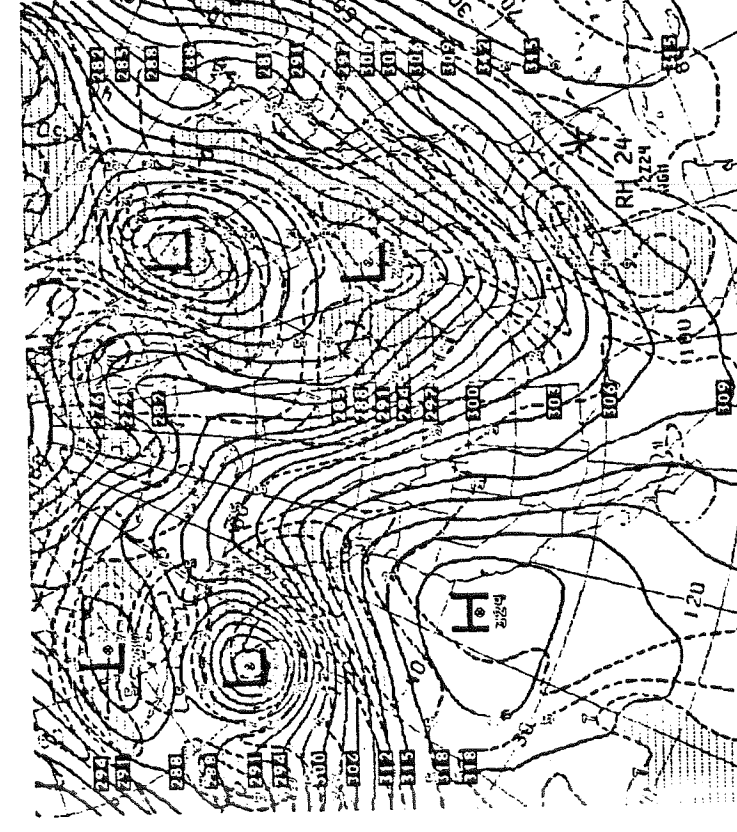
U.S. DEPT. OF COMMERCE  
NOAA/NWS/ATLANTA  
HSL PRES/1000-500 THK VALID 12Z SUN 24 JAN 88



U.S. DEPT. OF COMMERCE  
NOAA/NWS/ATLANTA  
HSL PRES/1000-500 THK VALID 12Z SUN 24 JAN 88



U.S. DEPT. OF COMMERCE  
NOAA/NWS/ATLANTA  
HSL PRES/1000-500 THK VALID 12Z SUN 24 JAN 88



U.S. DEPT. OF COMMERCE  
NOAA/NWS/ATLANTA  
HSL PRES/1000-500 THK VALID 12Z SUN 24 JAN 88

Fall 1987

**Atmospheric Dynamics**

1. (a) Derive the vorticity equation from first principles after making the following assumptions
  - the ideal gas law applies
  - density fluctuations are ignored except when multiplied by gravity
  
- (b) From the derived vorticity equation, write out the vertical component and physically explain each term in the resultant equation. Use a sketch where appropriate, to illustrate how each term causes a change in vertical vorticity.

Fall 1987

Weather Systems

1. Given the following thermodynamic diagrams, plot a representative
  - sounding that you would expect in Fairbanks, Alaska in December
  - sounding that you would expect in Fort Collins, Colorado in July
  - sounding that you would expect in Miami, Florida in July

Temperature, dew point temperature, and wind as normally plotted on these diagrams should be included.

Write on each sounding, using surface values, the values of

- *LCL*
- $T_w$
- *LFC*
- *EL*
- *w*

Finally, in a paragraph, describe your rationale for the illustrative sounding.

attachment: 3 skew-T's

Fall 1988

**FINAL**

**AT 540 Re-Exam**

Open Book/Open Notes - Keep Analyses attached

1. Given the attached sounding, decode the following information.

<u>Mandatory Levels</u>	Wind Speed	Wind Direction	T(° C)	T <sub>d</sub> (° C)	Z (m)	p (mb)
Surface	_____	_____	_____	_____	_____	_____
1000 mb	_____	_____	_____	_____	_____	_____
850 mb	_____	_____	_____	_____	_____	_____
700 mb	_____	_____	_____	_____	_____	_____
500 mb	_____	_____	_____	_____	_____	_____
300 mb	_____	_____	_____	_____	_____	_____
200 mb	_____	_____	_____	_____	_____	_____

<u>Significant Levels</u> (Choose two)	T(° C)	T <sub>d</sub> (° C)
_____ (mb)	_____ ° C	_____ ° C
_____ (mb)	_____ ° C	_____ ° C

7 J4 TTAA 70121 72304 99015 16407 19006 00130 19601 20019  
85515 11408 21540 70114 02861 25042 50575 11980 26049 40743  
22180 25566 30948 37957 26545 25070 489// 27567 20213 625//  
///// 15388 675// 27598 10631 715// 27555 88160 673// /////  
77158 27601 4//12 51515 10164 00003 10194 21034 23041=  
72304 TTBB 7012/ 72304 00015 16407 11000 19601 22998 19811  
33837 10608 44833 08050 55831 08638 66827 06862 77812 10469  
88776 08261 99771 08270 11666 00058 22638 02721 33608 05912  
44597 06941 55559 11513 66557 11525 77553 10180 88541 08180  
99400 22180 11351 29980 22335 31547 33289 39957 44200 625//  
PPBB 70120 72304 90012 19006 21032 21537 90346 21037 21039  
22542 90789 23042 23040 24040 91024 24541 24539 25541 916//  
25552 92056 25051 25567 25567 93025 26545 26546 27567 945//  
27601 95013 27590 27589 27556=

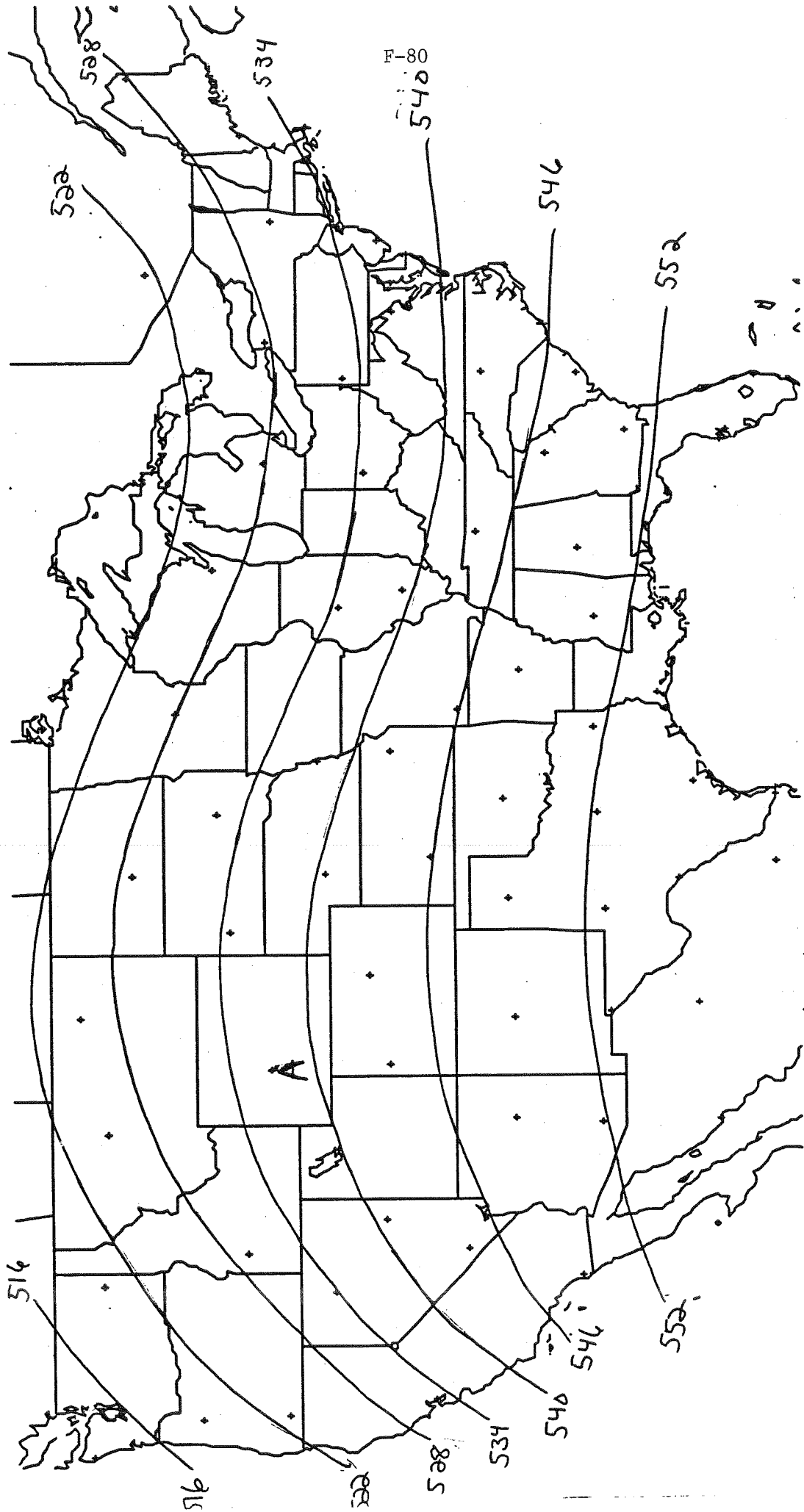


2. Given the attached plotted sounding, calculate the following information using surface values. Show work on a separate sheet.

- LCL* \_\_\_\_\_
- CCL* \_\_\_\_\_
- EL* a) using  $T_c$  \_\_\_\_\_
- b) using observed  $T$  \_\_\_\_\_
- $T_c$  \_\_\_\_\_
- $T_w$  \_\_\_\_\_
- $\theta$  \_\_\_\_\_
- $\theta_w$  \_\_\_\_\_
- $\theta_E$  \_\_\_\_\_

3. Given the attached 500 mb analysis, calculate the following at location A. Show work on a separate sheet.

- geostrophic wind speed \_\_\_\_\_
- geostrophic wind direction \_\_\_\_\_
- gradient wind speed \_\_\_\_\_
- gradient wind direction \_\_\_\_\_
- relative vorticity (use geostrophic wind) \_\_\_\_\_
- absolute vorticity (use geostrophic wind) \_\_\_\_\_
- absolute vorticity advection (use geostrophic wind) \_\_\_\_\_



Contour interval 60m  
 Height in decameters

1cm = 200km

4. Given the attached 700 mb analysis, calculate the following at point B. Show work on a separate sheet.

geostrophic wind speed \_\_\_\_\_

geostrophic wind direction \_\_\_\_\_

temperature advection (use geostrophic wind) \_\_\_\_\_

5. Given the Figures below, write in the letter of the definition which most closely relates the two.

inactive cold front \_\_\_\_\_

active cold front \_\_\_\_\_

cold occlusion \_\_\_\_\_

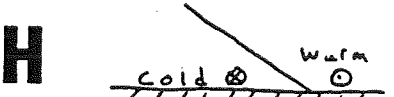
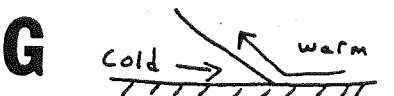
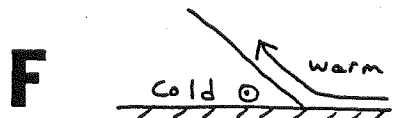
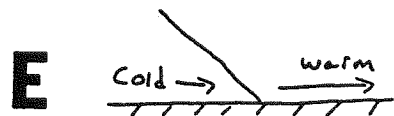
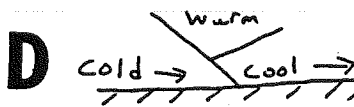
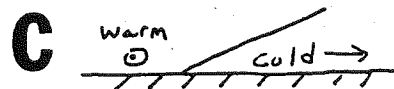
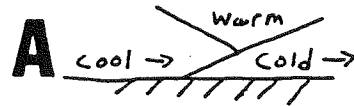
warm occlusion \_\_\_\_\_

inactive warm front \_\_\_\_\_

active warm front \_\_\_\_\_

inactive stationary front \_\_\_\_\_

active stationary front \_\_\_\_\_



Fall 1988

**FINAL**

**AT 540 Re-Exam**

Open Book/Open Notes - Keep Analyses attached

1. Given the attached sounding, decode the following information.

<u>Mandatory Levels</u>	Wind Speed	Wind Direction	T(° C)	T <sub>d</sub> (° C)	Z (m)	p (mb)
Surface	_____	_____	_____	_____	_____	_____
1000 mb	_____	_____	_____	_____	_____	_____
850 mb	_____	_____	_____	_____	_____	_____
700 mb	_____	_____	_____	_____	_____	_____
500 mb	_____	_____	_____	_____	_____	_____
300 mb	_____	_____	_____	_____	_____	_____
200 mb	_____	_____	_____	_____	_____	_____

<u>Significant Levels</u> (Choose two)	T(° C)	T <sub>d</sub> (° C)
_____ (mb)	_____ ° C	_____ ° C
_____ (mb)	_____ ° C	_____ ° C

72407 TAA 70122 72407 99015 03204 12012 00140 02809 12020  
85461 07215 21049 70046 00419 26050 50568 13743 // 40734  
25350 // 30937 403// 25570 25058 511// 26098 20200 621//  
26641 88999 66160 26700 462// 51515 10164 00008 10194 16034  
24553=  
72407 TTBB 7012/ 72407 00015 03204 11898 02413 22842 07415  
33771 05219 44500 13743 55301 39956 66220 587// 77172 681//  
88159 683//=  
PPBB 70120 72407 90012 12012 12528 15032 90346 16534 18542  
22551 90789 24054 25056 25556 9123/ 25551 26539 9268/ 25562  
24550 93057 25069 26105 26589 94023 27148 26648 26700=  
64700328

2. Given the attached plotted sounding, calculate the following information using surface values. Show work on a separate sheet.

*LCL* \_\_\_\_\_

*CCL* \_\_\_\_\_

*EL* a) using  $T_c$  \_\_\_\_\_

b) using observed  $T$  \_\_\_\_\_

$T_c$  \_\_\_\_\_

$T_w$  \_\_\_\_\_

$\theta$  \_\_\_\_\_

$\theta_w$  \_\_\_\_\_

$\theta_E$  \_\_\_\_\_

3. Given the attached 500 mb analysis, calculate the following at location A. Show work on a separate sheet.

geostrophic wind speed \_\_\_\_\_

geostrophic wind direction \_\_\_\_\_

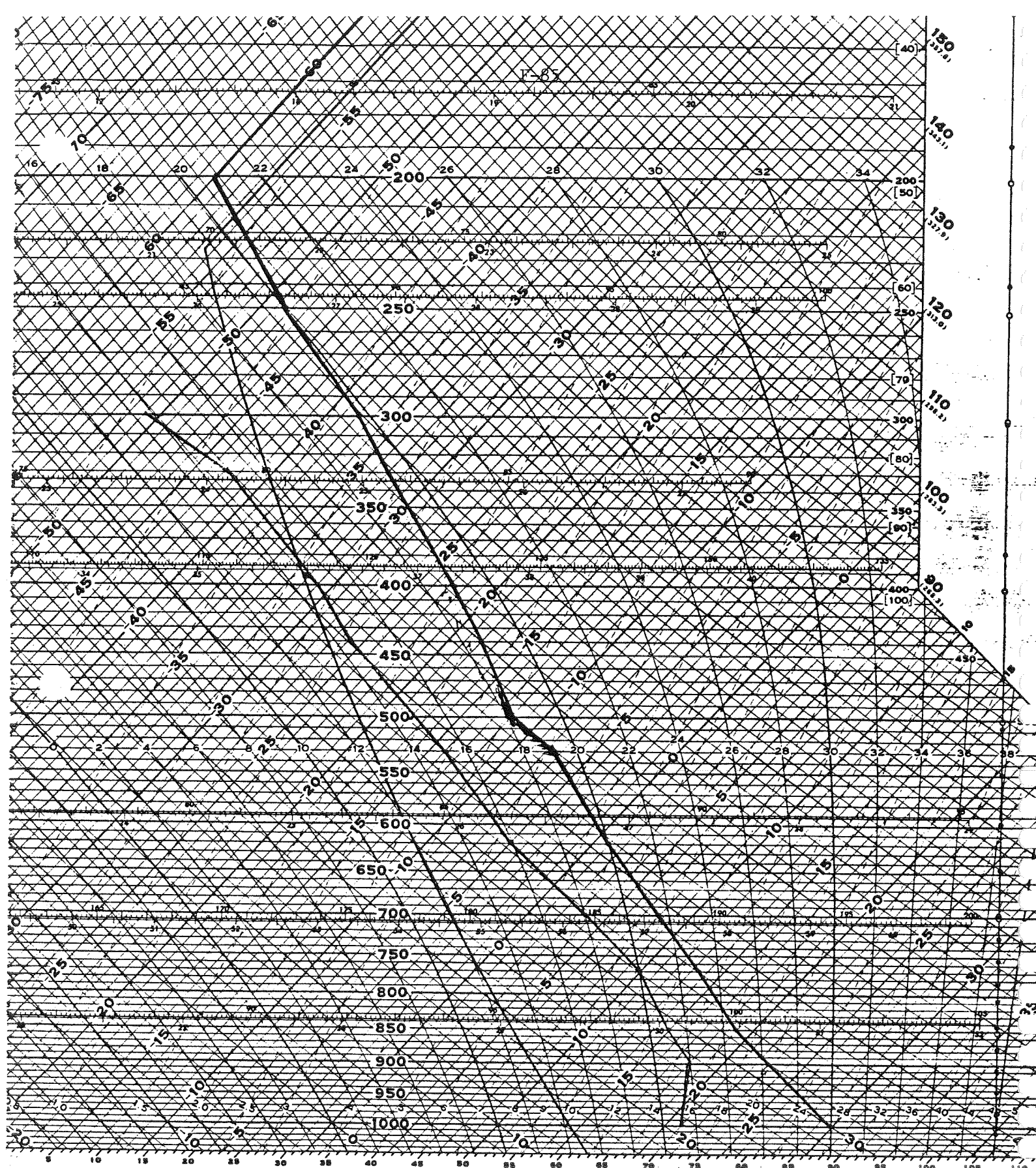
gradient wind speed \_\_\_\_\_

gradient wind direction \_\_\_\_\_

relative vorticity (use geostrophic wind) \_\_\_\_\_

absolute vorticity (use geostrophic wind) \_\_\_\_\_

absolute vorticity advection (use geostrophic wind) \_\_\_\_\_



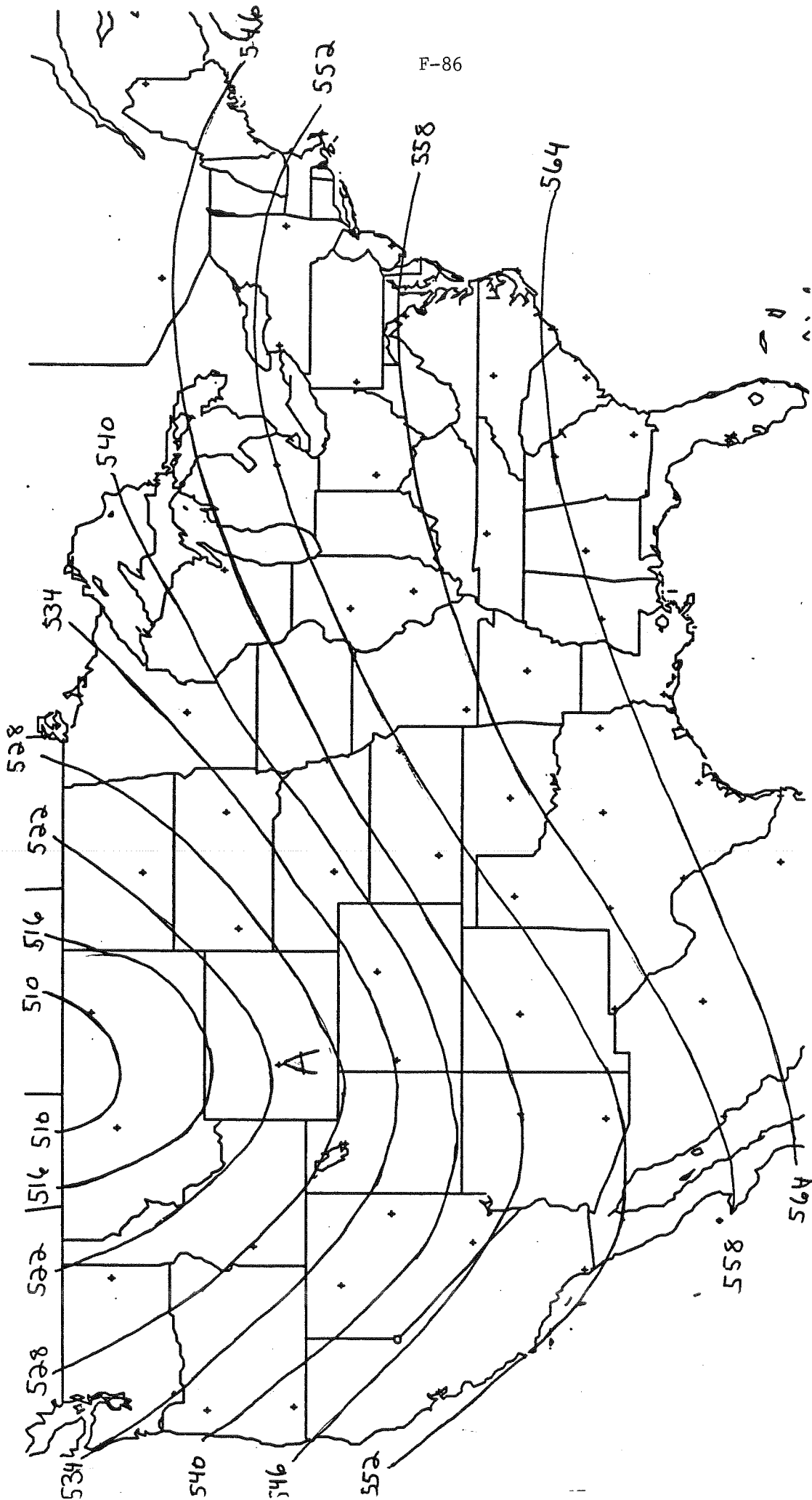
FAHRENHEIT TEMPERATURE SCALE

ION	NUMBER	STATION
(GCT)	TIME (GCT)	DATE (GCT)

Use the space in the improvement of SCS  
 Weather Plotting Charts by reporting to  
 the appropriate  
 Headquarters, Lt. Col. Air Weather Service or  
 Director, Naval Oceanography and  
 Hydrography.

Lithographed by DMAAC 8-76

B  
 CHART CURRE



F-86

Contour interval 60m  
Height in decimeters

200km



4. Given the attached 700 mb analysis, calculate the following at point B. Show work on a separate sheet.

geostrophic wind speed \_\_\_\_\_

geostrophic wind direction \_\_\_\_\_

temperature advection (use geostrophic wind) \_\_\_\_\_

5. Given the Figures below, write in the letter of the definition which most closely relates the two.

inactive stationary front \_\_\_\_\_

active stationary front \_\_\_\_\_

inactive warm front \_\_\_\_\_

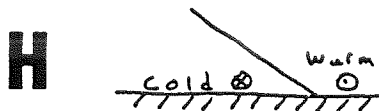
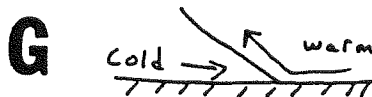
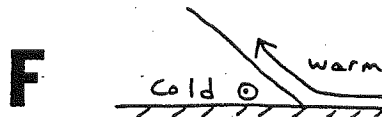
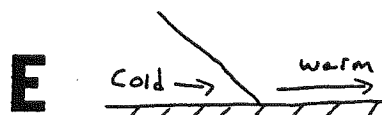
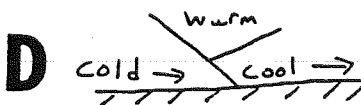
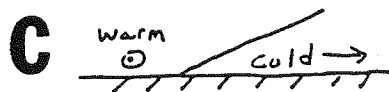
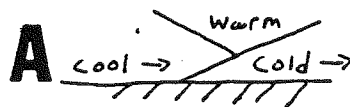
active warm front \_\_\_\_\_

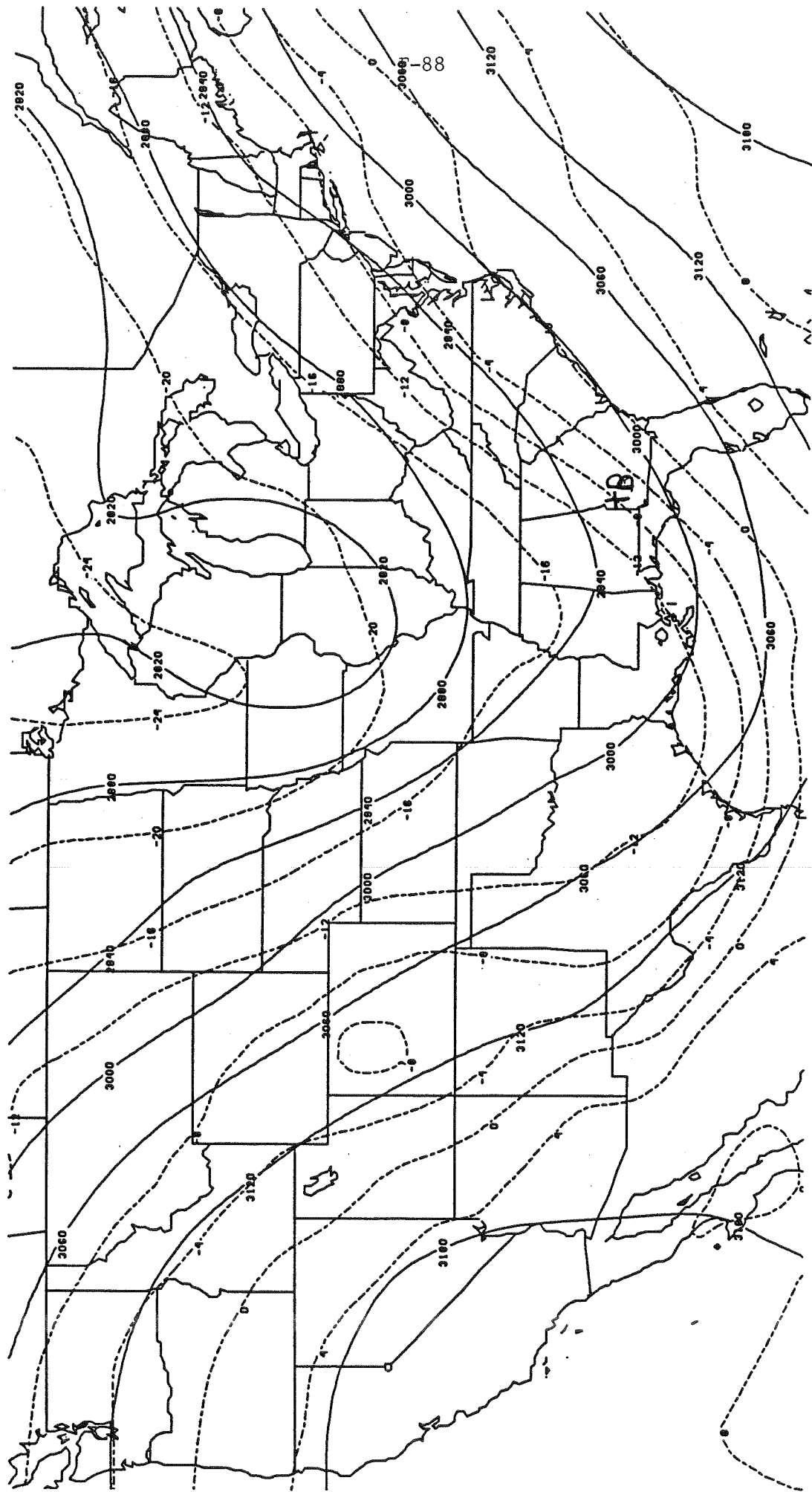
inactive cold front \_\_\_\_\_

active cold front \_\_\_\_\_

cold occlusion \_\_\_\_\_

warm occlusion \_\_\_\_\_





1 cm = 200 km

Height in meters Contour interval: 60M  
 Temperature in °C Isotherm interval: 4°C

B

6. Given the 1000 mb and 500 mb geostrophic winds drawn below, and  $Z_{1000} = 30$  m and  $Z_{500} = 5520$  m, calculate the following for  $43^\circ$  N.

thermal wind ( $m\ s^{-1}$ ) at A \_\_\_\_\_

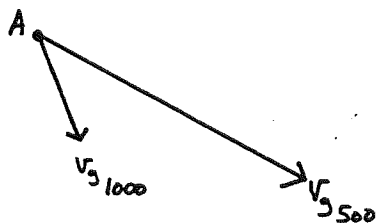
1000 - 500 mb thickness (m) at A \_\_\_\_\_

1000 - 500 mb thickness advection (m/hr) at A \_\_\_\_\_

1000 - 500 mb mean layer temperature ( $^\circ C$ ) at A \_\_\_\_\_

1000 - 500 mb mean layer temperature advection ( $^\circ C/hr$ ) at A \_\_\_\_\_

$1\ cm = 10^m/s$



7. Plot the surface station model for the following observations at a location at  $40^\circ N$ . Temperature =  $80^\circ F$ ; dew point temperature =  $70^\circ F$ ; visibility = 5 miles; wind = 10 knots from the southeast; obscured, light thunderstorms; mean sea level pressure = 1020 mb; pressure falling and then steady over the past 3 hours; pressure change is minus 0.3 mb.

8. Plot the 500 mb station model for the following observations at a location at 40°N. Temperature = -25°C; dew point temperature = -29°C; wind = 35 knots from the south; a height of 5320 meters; and a 12 hour height change of minus 120 meters.

9. Give representative values of temperature and dew point temperature for the following air mass types in the summer.

## Summer

*mT*  $T =$  \_\_\_\_\_  $T_D =$  \_\_\_\_\_

*mP*  $T =$  \_\_\_\_\_  $T_D =$  \_\_\_\_\_

*cP*  $T =$  \_\_\_\_\_  $T_D =$  \_\_\_\_\_

*cA*  $T =$  \_\_\_\_\_  $T_D =$  \_\_\_\_\_

10. Given the attached NGM forecast model out, what are the values of the following variables at point A. Give units.

700 mb height \_\_\_\_\_

700 mb relative humidity \_\_\_\_\_

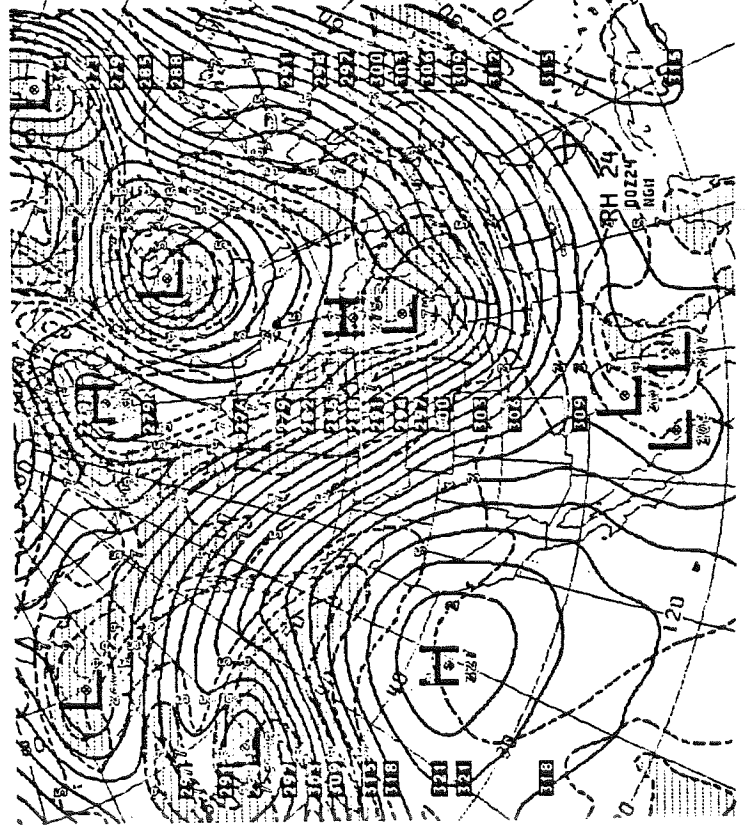
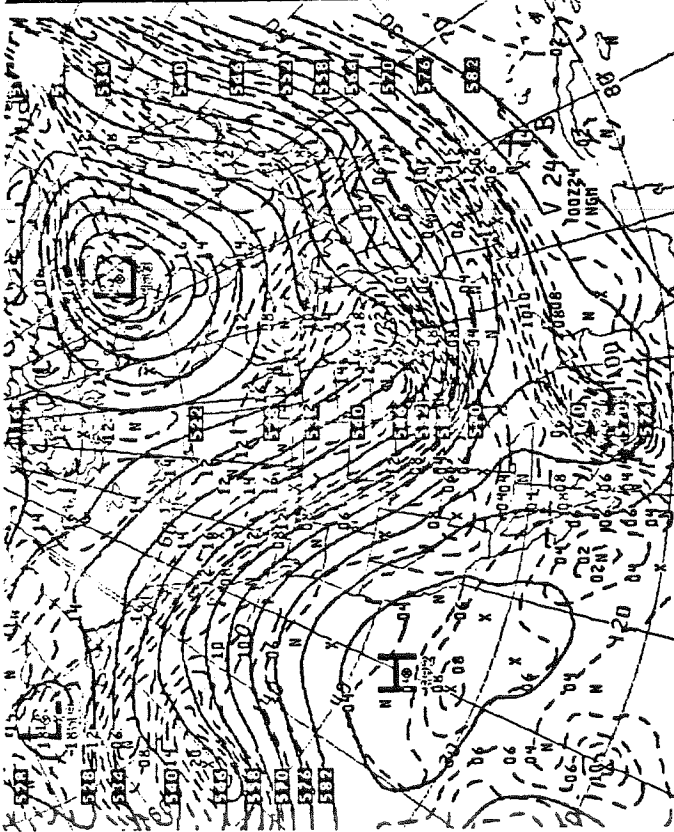
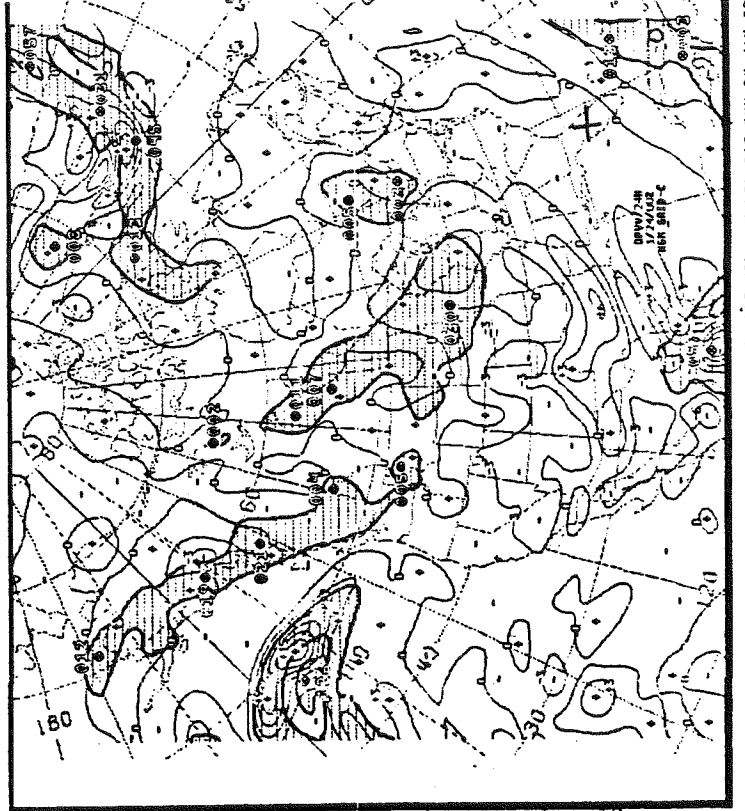
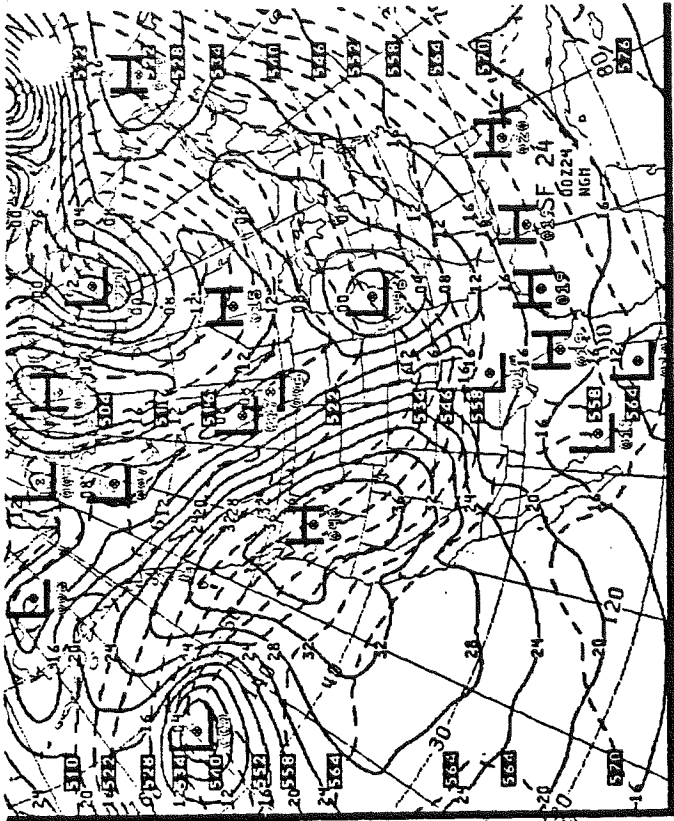
500 mb height \_\_\_\_\_

500 mb absolute vorticity \_\_\_\_\_

surface pressure \_\_\_\_\_

1000 - 500 mb thickness \_\_\_\_\_

vertical motion at 700 mb \_\_\_\_\_



Fall 1988

**FINAL**

**AT 540 Re-Exam**

Open Book/Open Notes - Keep Analyses attached

1. Given the attached sounding, decode the following information.

<u>Mandatory Levels</u>	Wind Speed	Wind Direction	T(° C)	T <sub>d</sub> (° C)	Z (m)	p (mb)
Surface	_____	_____	_____	_____	_____	_____
1000 mb	_____	_____	_____	_____	_____	_____
850 mb	_____	_____	_____	_____	_____	_____
700 mb	_____	_____	_____	_____	_____	_____
500 mb	_____	_____	_____	_____	_____	_____
300 mb	_____	_____	_____	_____	_____	_____
200 mb	_____	_____	_____	_____	_____	_____

<u>Significant Levels</u> (Choose two)	T(° C)	T <sub>d</sub> (° C)
_____ (mb)	_____ ° C	_____ ° C
_____ (mb)	_____ ° C	_____ ° C

C

72213 TTAA 70121 72213 99007 18433 18012 00103 18419 18017  
85491 13412 23538 70105 04862 23049 50577 10180 23558 40746  
21380 23562 30951 37349 25069 25075 477// 25593 20219 559//  
25101 15398 651// 25565 10639 749// 24570 88999 77189 25113  
42048 51515 10164 00002 10194 21036 23542=  
72213 TTBB 7012/ 72213 00007 18433 11972 16809 22943 18017  
33787 10830 44724 06037 55690 05080 66663 04080 77583 04980  
88557 08361 99553 07980 11540 06380 22451 13580 33400 21380  
44365 27365 55353 28541 66285 39956 77218 551// 88100 749//=  
PPBB 70120 72213 90012 18012 19031 20040 90346 21540 23038  
24039 90789 24041 23541 23544 91234 22059 22060 22560 9167/  
23561 23562 92056 23058 23563 23563 929// 25076 93024 25074  
25568 25591 9358/ 25592 26107 94014 25097 25113 26568 9503/  
25575 24571=

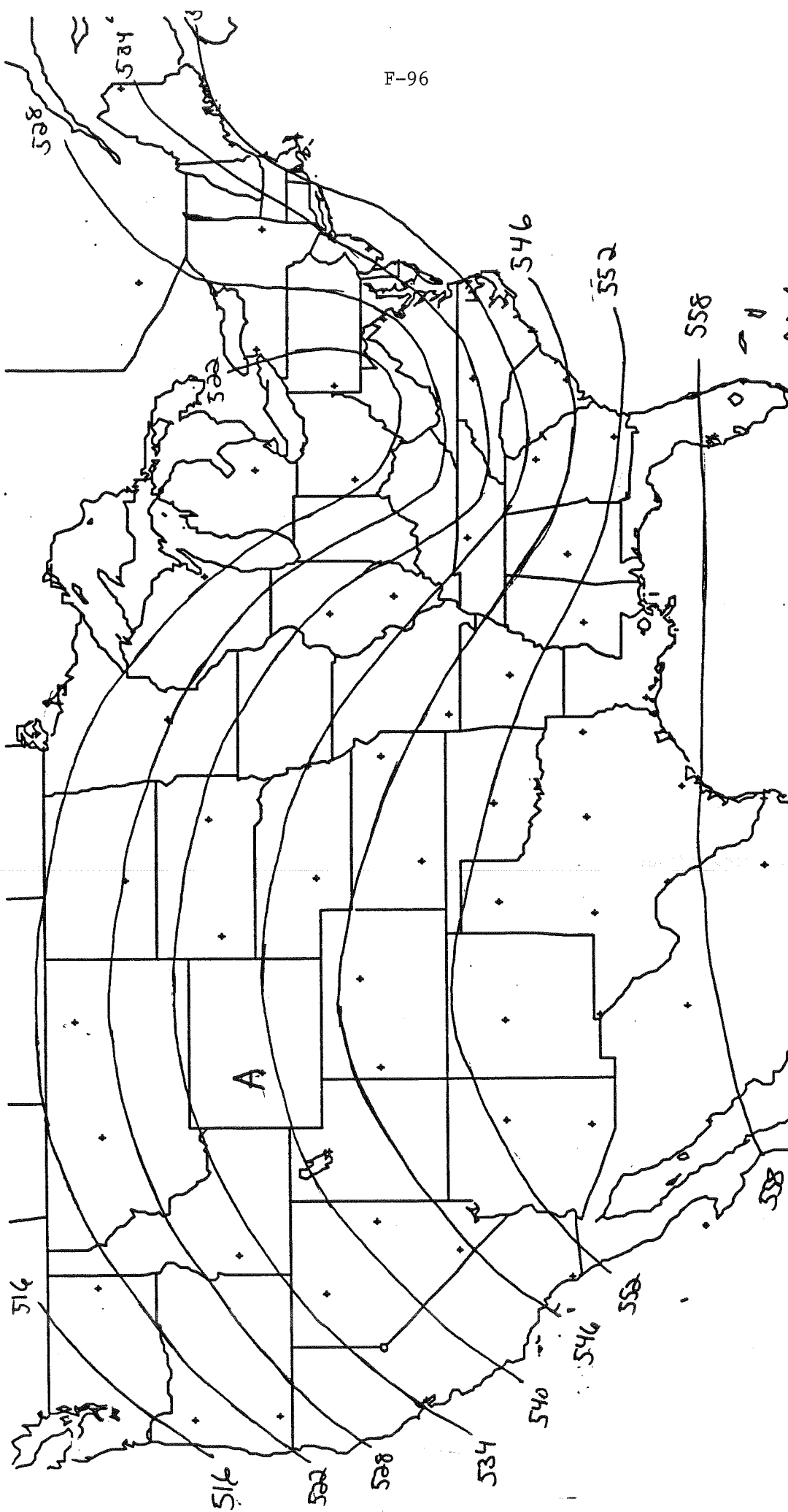


2. Given the attached plotted sounding, calculate the following information using surface values. Show work on a separate sheet.

- LCL* \_\_\_\_\_
- CCL* \_\_\_\_\_
- EL* a) using  $T_c$  \_\_\_\_\_
- b) using observed  $T$  \_\_\_\_\_
- $T_c$  \_\_\_\_\_
- $T_w$  \_\_\_\_\_
- $\theta$  \_\_\_\_\_
- $\theta_w$  \_\_\_\_\_
- $\theta_E$  \_\_\_\_\_

3. Given the attached 500 mb analysis, calculate the following at location A. Show work on a separate sheet.

- geostrophic wind speed \_\_\_\_\_
- geostrophic wind direction \_\_\_\_\_
- gradient wind speed \_\_\_\_\_
- gradient wind direction \_\_\_\_\_
- relative vorticity (use geostrophic wind) \_\_\_\_\_
- absolute vorticity (use geostrophic wind) \_\_\_\_\_
- absolute vorticity advection (use geostrophic wind) \_\_\_\_\_



Contour interval 60m  
 Height in decameters

1cm = 200km

4. Given the attached 700 mb analysis, calculate the following at point B. Show work on a separate sheet.

geostrophic wind speed \_\_\_\_\_

geostrophic wind direction \_\_\_\_\_

temperature advection (use geostrophic wind) \_\_\_\_\_

5. Given the Figures below, write in the letter of the definition which most closely relates the two.

cold occlusion \_\_\_\_\_

warm occlusion \_\_\_\_\_

inactive cold front \_\_\_\_\_

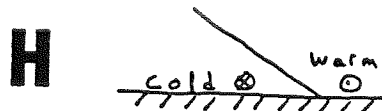
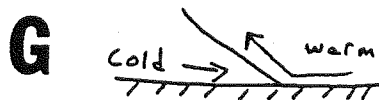
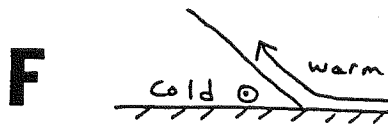
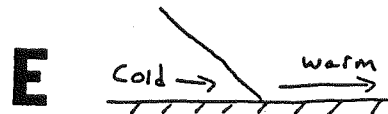
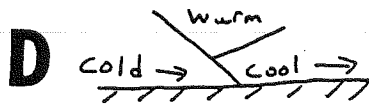
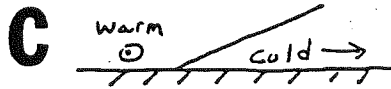
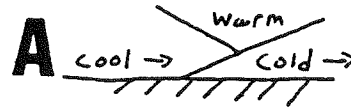
active cold front \_\_\_\_\_

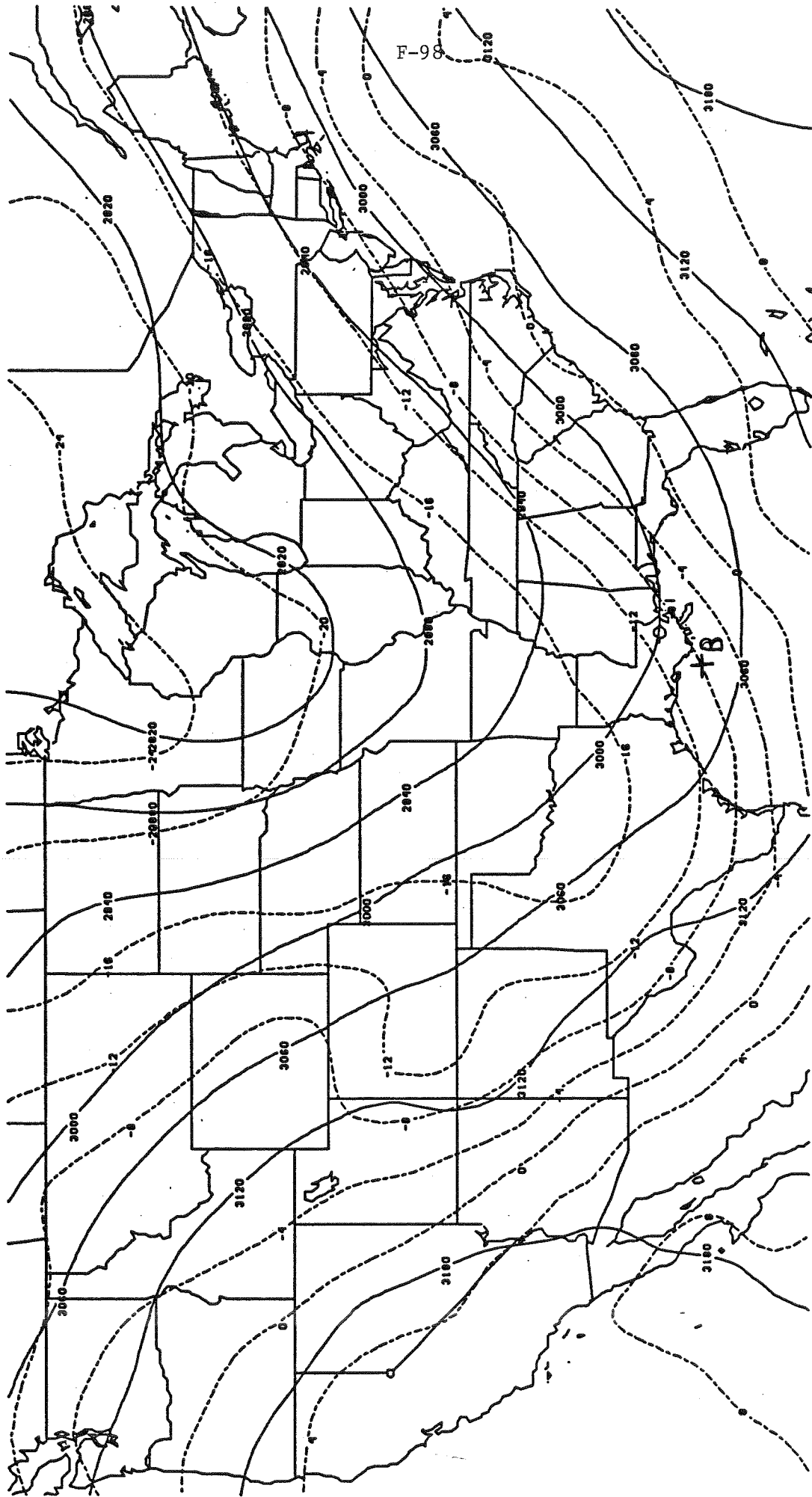
active warm front \_\_\_\_\_

inactive warm front \_\_\_\_\_

inactive stationary front \_\_\_\_\_

active stationary front \_\_\_\_\_





Height in meters Contour interval: 60m  
 Temperature in °C Isotherm interval: 4°C

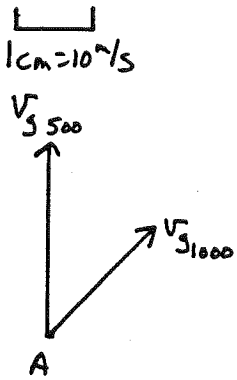
1 cm = 200 km

660123/1200 : 660123/1200 700 MB MBRE

C

6. Given the 1000 mb and 500 mb geostrophic winds drawn below, and  $Z_{1000} = 30$  m and  $Z_{500} = 5520$  m, calculate the following for  $43^\circ$  N.

- thermal wind ( $m\ s^{-1}$ ) at A \_\_\_\_\_
- 1000 - 500 mb thickness (m) at A \_\_\_\_\_
- 1000 - 500 mb thickness advection (m/hr) at A \_\_\_\_\_
- 1000 - 500 mb mean layer temperature ( $^\circ C$ ) at A \_\_\_\_\_
- 1000 - 500 mb mean layer temperature advection ( $^\circ C/hr$ ) at A \_\_\_\_\_



7. Plot the surface station model for the following observations at a location at  $40^\circ N$ . Temperature =  $23^\circ F$ ; dew point temperature =  $10^\circ F$ ; visibility = 6 miles; wind = 30 knots from the southwest; partly cloudy, light snow; mean sea level pressure = 1002 mb; pressure rising over the past 3 hours; pressure change is plus 2.6 mb.

8. Plot the 500 mb station model for the following observations at a location at 40°N. Temperature = -10°C; dew point temperature = -25°C; wind = 115 knots from the west; a height of 5460 meters; and a 12 hour height change of plus 10 meters.

9. Give representative values of temperature and dew point temperature for the following air mass types in the summer.

Summer

*mT*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

*mP*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

*cP*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

*cA*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

10. Given the attached NGM forecast model out, what are the values of the following variables at point A. Give units.

700 mb height \_\_\_\_\_

700 mb relative humidity \_\_\_\_\_

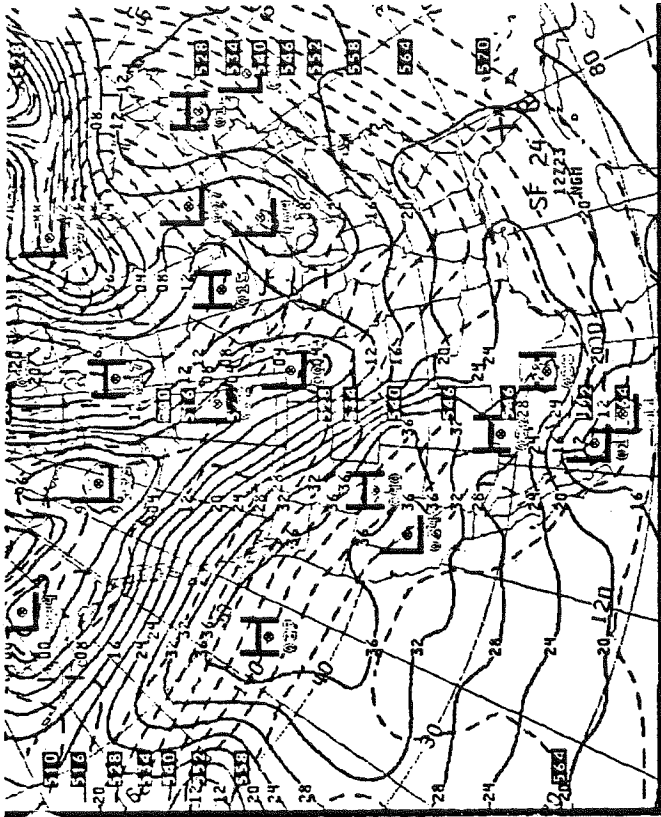
500 mb height \_\_\_\_\_

500 mb absolute vorticity \_\_\_\_\_

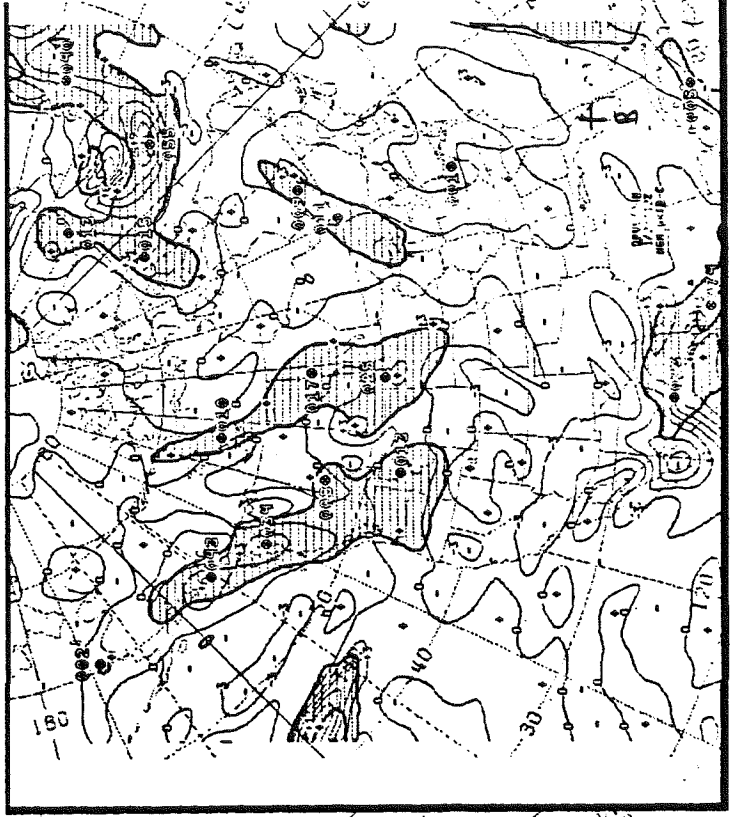
surface pressure \_\_\_\_\_

1000 - 500 mb thickness \_\_\_\_\_

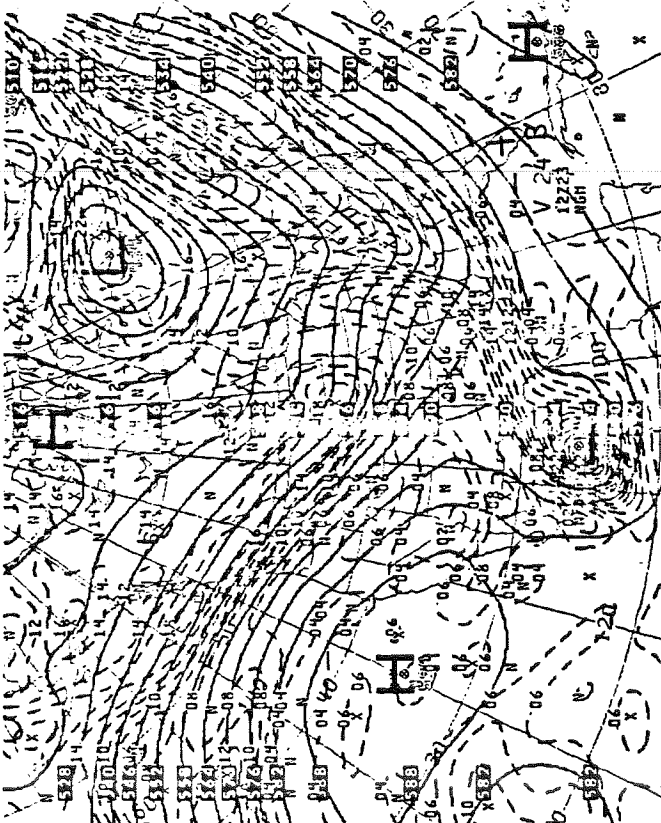
vertical motion at 700 mb \_\_\_\_\_



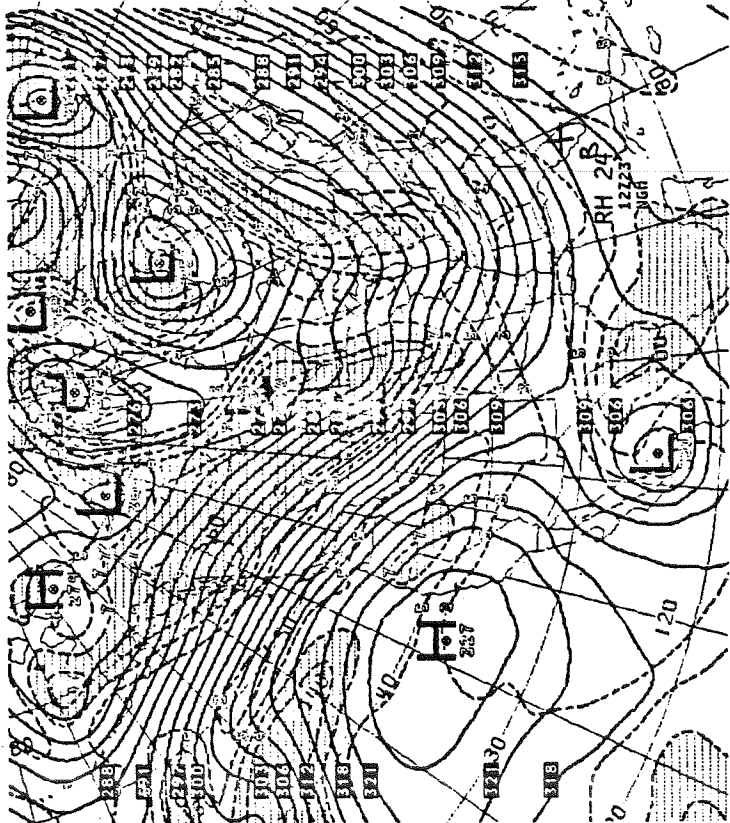
U.S. DEPT OF COMMERCE  
 NOAA/NWS/ATLANTA WASHINGTON 0185 .. 24HR FCST  
 HSL PRES/1000-500 THK VALID 12Z SAT 23 JAN 88



U.S. DEPT OF COMMERCE  
 NOAA/NWS/ATLANTA WASHINGTON 0185 .. 24HR FCST  
 PRECIP./700 VERT VEL VALID 12Z SAT 23 JAN 88



U.S. DEPT OF COMMERCE  
 NOAA/NWS/ATLANTA WASHINGTON 0185 .. 24HR FCST  
 HEIGHTS/500MB VALID 12Z SAT 23 JAN 88



U.S. DEPT OF COMMERCE  
 NOAA/NWS/ATLANTA WASHINGTON 0185 .. 24HR FCST  
 700 HEIGHT/REL HUMIDITY VALID 12Z SAT 23 JAN 88



Fall 1988

**FINAL**

**AT 540 Re-Exam**

Open Book/Open Notes - Keep Analyses attached

1. Given the attached sounding, decode the following information.

<u>Mandatory Levels</u>	Wind Speed	Wind Direction	T(° C)	T <sub>d</sub> (° C)	Z (m)	p (mb)
Surface	_____	_____	_____	_____	_____	_____
1000 mb	_____	_____	_____	_____	_____	_____
850 mb	_____	_____	_____	_____	_____	_____
700 mb	_____	_____	_____	_____	_____	_____
500 mb	_____	_____	_____	_____	_____	_____
300 mb	_____	_____	_____	_____	_____	_____
200 mb	_____	_____	_____	_____	_____	_____

<u>Significant Levels</u> (Choose two)	T(° C)	T <sub>d</sub> (° C)
_____ (mb)	_____ ° C	_____ ° C
_____ (mb)	_____ ° C	_____ ° C

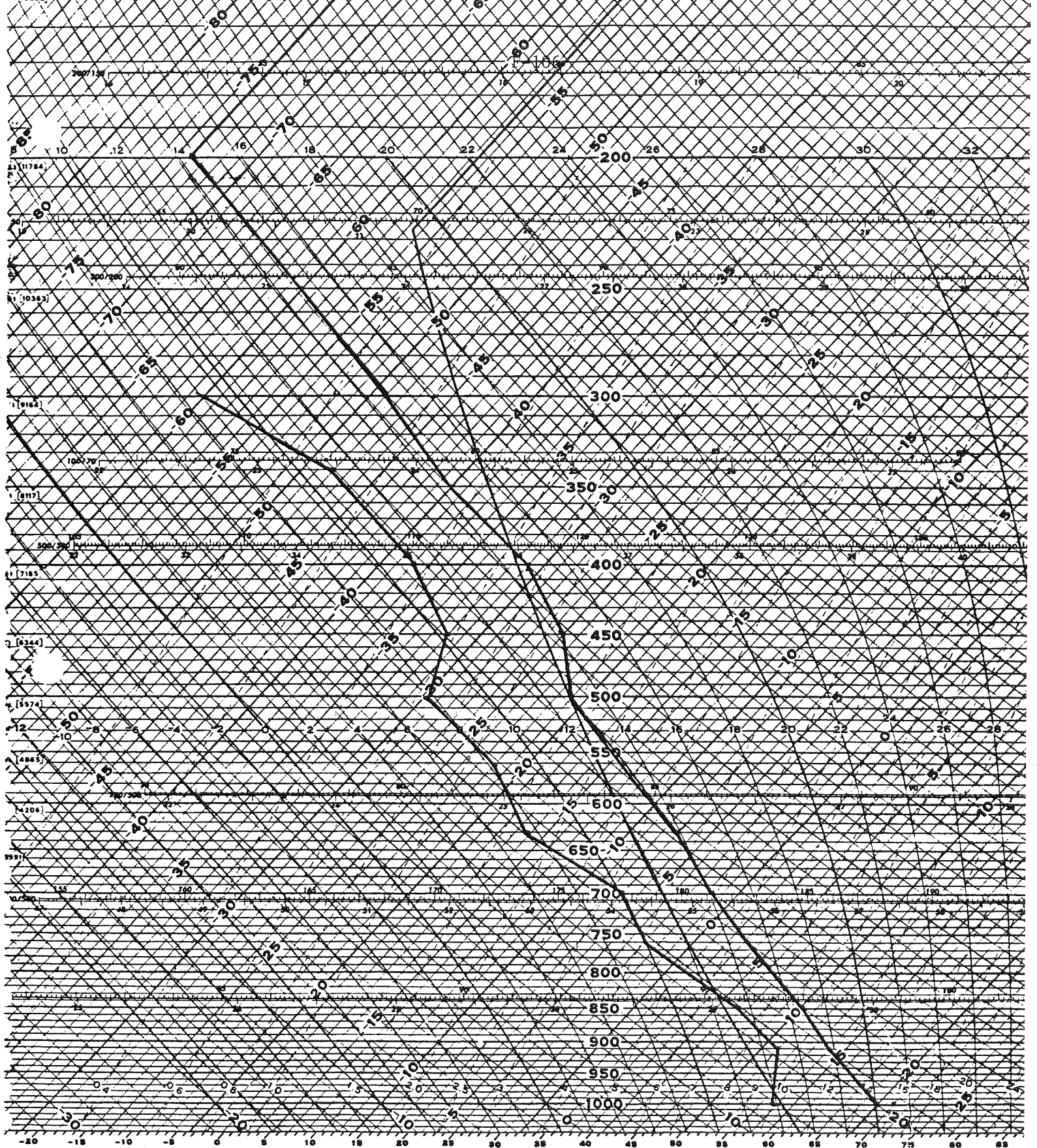
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28556 24112 30926 415// 22135 25047 521// 22644 20188 601//  
01168 15365 601// 25611 10617 653// 24072  
166 661// 24669  
2402 TTBB 7512/ 72402 00015 04226 11000 04427 22988 06859  
33967 09667 44869 02660 55837 01219 66681 07304 77661 05302  
88553 11703 99469 20518 11451 22756 22407 28556 33350 32550  
44317 38756 55222 583// 66166 661// 77150 601// 88109 619//  
99100 653//=  
PPBB 75120 72402 90012 18008 27513 24011 90345 21014 20519  
19523 90678 21021 21024 21028 909// 21035 91246 22058 23057  
23067 92058 23579 23625 22126 9305/ 22134 22646 94269 24683  
25084 23087 95013 23589 24587 24071=

2. Given the attached plotted sounding, calculate the following information using surface values. Show work on a separate sheet.

- LCL* \_\_\_\_\_
- CCL* \_\_\_\_\_
- EL* a) using  $T_c$  \_\_\_\_\_
- b) using observed  $T$  \_\_\_\_\_
- $T_c$  \_\_\_\_\_
- $T_w$  \_\_\_\_\_
- $\theta$  \_\_\_\_\_
- $\theta_w$  \_\_\_\_\_
- $\theta_E$  \_\_\_\_\_

3. Given the attached 500 mb analysis, calculate the following at location A. Show work on a separate sheet.

- geostrophic wind speed \_\_\_\_\_
- geostrophic wind direction \_\_\_\_\_
- gradient wind speed \_\_\_\_\_
- gradient wind direction \_\_\_\_\_
- relative vorticity (use geostrophic wind) \_\_\_\_\_
- absolute vorticity (use geostrophic wind) \_\_\_\_\_
- absolute vorticity advection (use geostrophic wind) \_\_\_\_\_



FAHRENHEIT TEMPERATURE SCALE

NUMBER	STATION
TIME (GCT)	DATE (GCT)

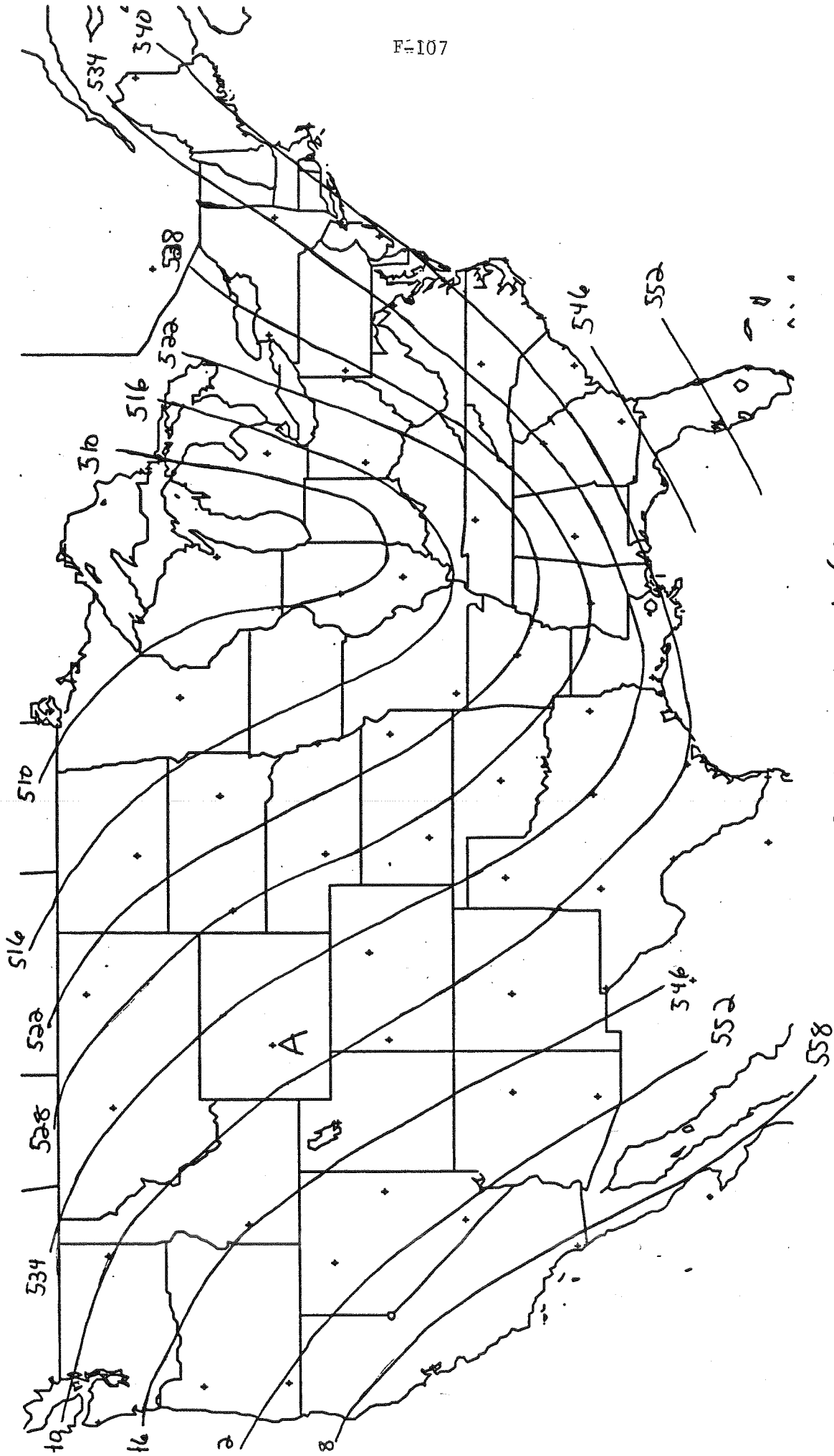
NUMBER	STATION
TIME (GCT)	DATE (GCT)

(D)

Users are urged to the improvement of SCS  
Weather Plotting Charts by reporting to  
corrections and omissions to the appropriate  
Headquarters, Lt. Col. Air Weather Service or  
Director, Naval Oceanography and Hydrography.

Lithographed by DMAAC 8-76

D



Contour interval 60m  
 Height in decimeters

1cm=200km

4. Given the attached 700 mb analysis, calculate the following at point B. Show work on a separate sheet.

geostrophic wind speed \_\_\_\_\_

geostrophic wind direction \_\_\_\_\_

temperature advection (use geostrophic wind) \_\_\_\_\_

5. Given the Figures below, write in the letter of the definition which most closely relates the two.

warm occlusion \_\_\_\_\_

cold occlusion \_\_\_\_\_

inactive cold front \_\_\_\_\_

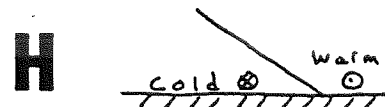
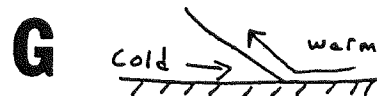
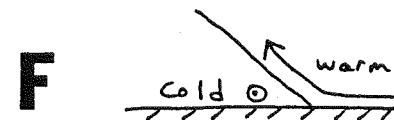
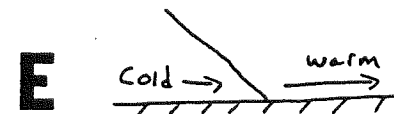
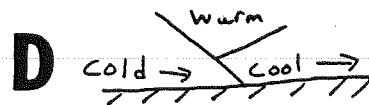
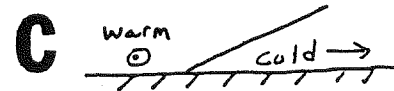
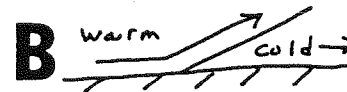
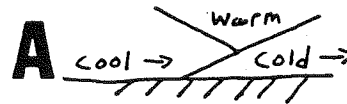
inactive warm front \_\_\_\_\_

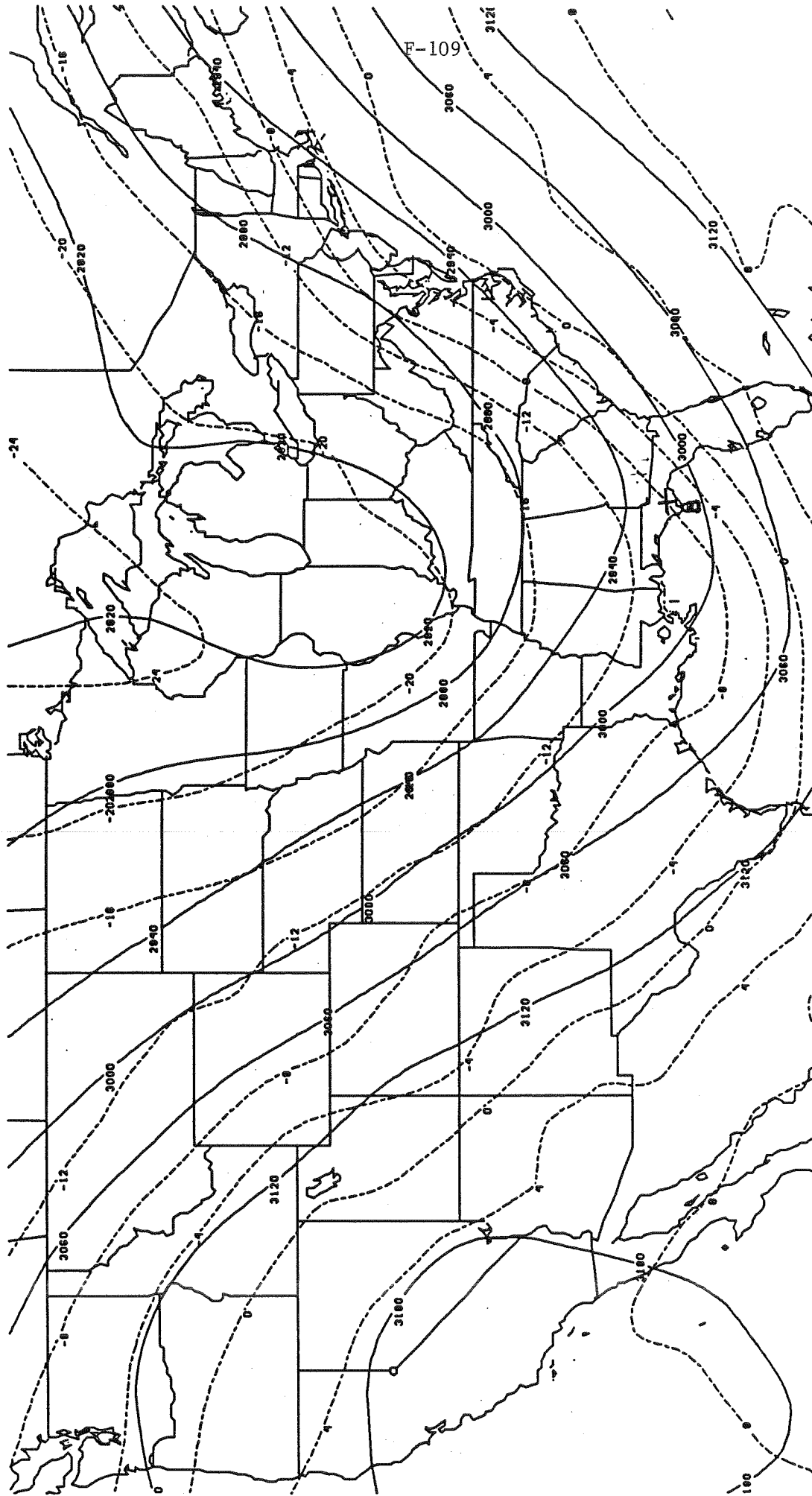
active cold front \_\_\_\_\_

active warm front \_\_\_\_\_

inactive stationary front \_\_\_\_\_

active stationary front \_\_\_\_\_





Height in meters Contour interval: 60m  
 Temperature in °C Isotherm interval: 4°C

1 cm = 200 km

6. Given the 1000 mb and 500 mb geostrophic winds drawn below, and  $Z_{1000} = 30$  m and  $Z_{500} = 5520$  m, calculate the following for  $43^\circ$  N.

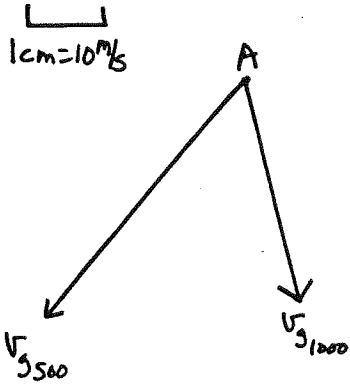
thermal wind ( $\text{m s}^{-1}$ ) at A \_\_\_\_\_

1000 - 500 mb thickness (m) at A \_\_\_\_\_

1000 - 500 mb thickness advection ( $\text{m/hr}$ ) at A \_\_\_\_\_

1000 - 500 mb mean layer temperature ( $^\circ\text{C}$ ) at A \_\_\_\_\_

1000 - 500 mb mean layer temperature advection ( $^\circ\text{C/hr}$ ) at A \_\_\_\_\_



7. Plot the surface station model for the following observations at a location at  $40^\circ\text{N}$ . Temperature =  $20^\circ\text{F}$ ; dew point temperature =  $15^\circ\text{F}$ ; visibility = 8 miles; wind = 5 knots from the north; scattered clouds, snow showers; mean sea level pressure = 938 mb; pressure falling over the past 3 hours; pressure change is minus 1.3 mb.



8. Plot the 500 mb station model for the following observations at a location at 40°N. Temperature = -20°C; dew point temperature = -31°C; wind = 55 knots from the north; a height of 5580 meters; and a 12 hour height change of minus 80 meters.

9. Give representative values of temperature and dew point temperature for the following air mass types in the summer.

Summer

*mT*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

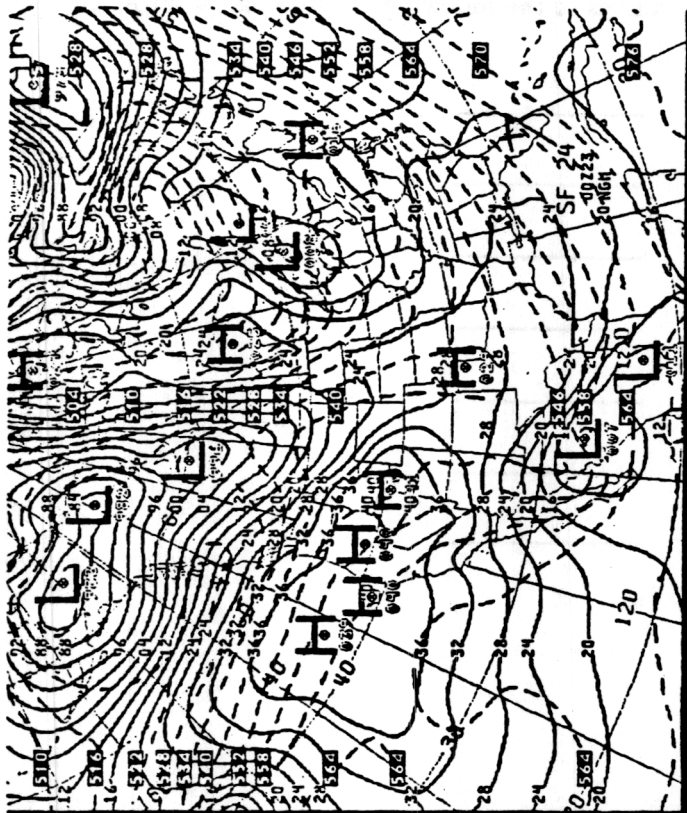
*mP*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

*cP*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

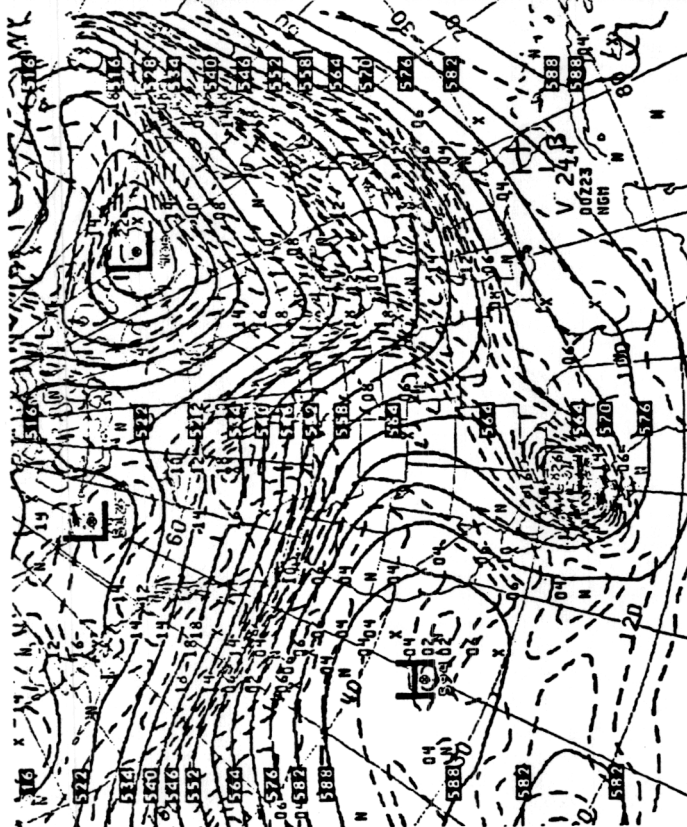
*cA*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

10. Given the attached NGM forecast model out, what are the values of the following variables at point A. Give units.

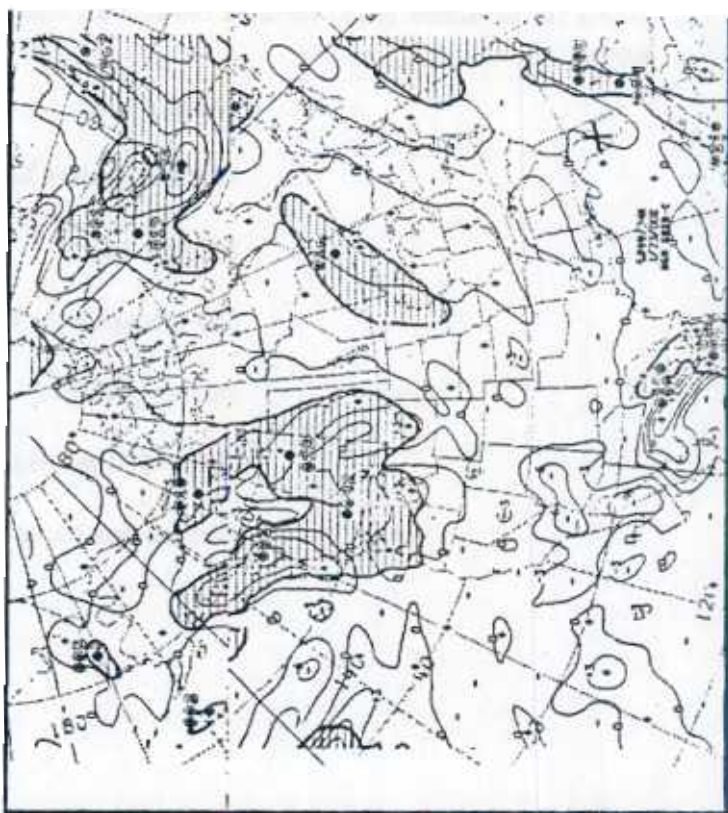
- 700 mb height \_\_\_\_\_
- 700 mb relative humidity \_\_\_\_\_
- 500 mb height \_\_\_\_\_
- 500 mb absolute vorticity \_\_\_\_\_
- surface pressure \_\_\_\_\_
- 1000 - 500 mb thickness \_\_\_\_\_
- vertical motion at 700 mb \_\_\_\_\_



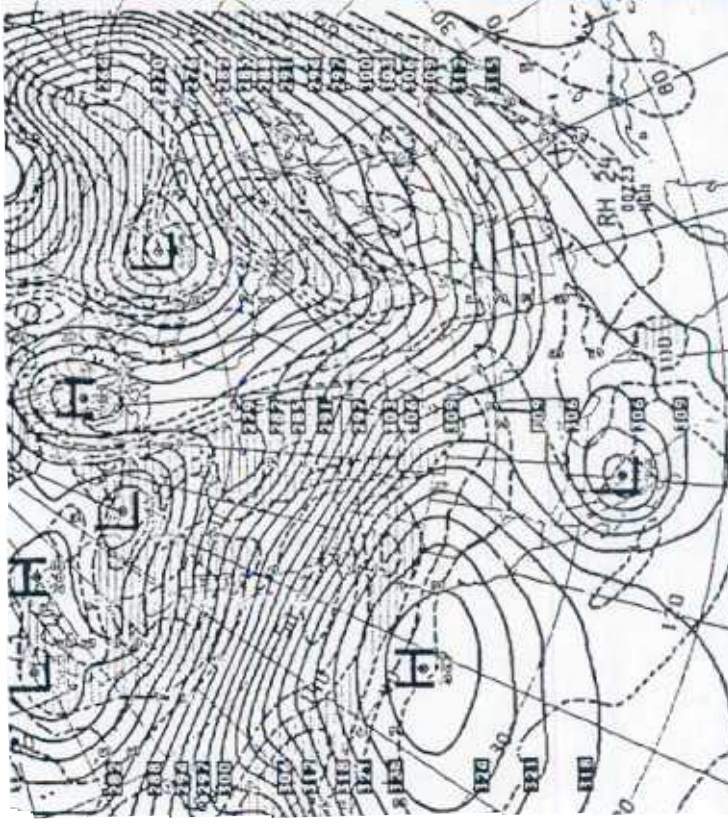
ON DEPT OF COMMERCE  
 HSL PRES/1000-500 FTK VALID 00Z SAT 23 JAN 88



ON DEPT OF COMMERCE  
 HEIGHTS/VORTICITY VALID 00Z SAT 23 JAN 88



ON DEPT OF COMMERCE  
 8039 .. 24HR FCST



ON DEPT OF COMMERCE  
 700 HEIGHT/REL HUMIDITY VALID 00Z SAT 23 JAN 88

F-114  
AT 540 FINAL EXAM

Fall 1991

*Use  $f = 10^{-4} s^{-1}$   
 $g = 10 m s^{-2}$*

1. Circle the assumptions involved in deriving the adiabatic lapse rate (5 pts).

hydrostatic relation

ideal gas law

1st law of thermodynamics

equation of motion

conservation of mass

2. Circle all 700 mb temperatures which are reasonable for Denver between April 1 to October 1 (2 pts).

10°C    5°C    0°C    -5°C    -10°C    -15°C    -20°C    -25°C  
-30°C    -35°C    -40°C    -45°C    -50°C    -55°C    -60°C    -65°C    -70°C

3. For a 500–1000 mb thickness of 5520 meters, calculate the mean temperature in °C. If the surface temperature is 5°C, calculate a linear lapse rate consistent with this thickness, and the resultant 500 mb temperature. Show your work (6 pts).

*with a surface pressure of 1000 mb*

*with height*

→  $\bar{T} =$  \_\_\_\_\_  $\partial T / \partial Z =$  \_\_\_\_\_ °C/km  $T_{500 \text{ mb}} =$  \_\_\_\_\_ °C

4. Calculate the virtual temperature for a temperature of  $20^{\circ}\text{C}$ , a dew point temperature of  $20^{\circ}\text{C}$ , and a pressure of 1000 mb. Show your work (3 pts).

$T_v$  \_\_\_\_\_  $^{\circ}\text{C}$

5. For an observed horizontal wind from  $270^{\circ}$  of  $50 \text{ m s}^{-1}$  at 500 mb, from  $305^{\circ}$  at  $20 \text{ m s}^{-1}$  at 850 mb, and a mean 850–500 mb thickness of 3000 m, calculate: (Assume a linear change of wind speed and direction with height. Show your work.) (9 pts).

(a) vertical wind shear of the horizontal wind \_\_\_\_\_  $\text{m s}^{-1} \text{ km}^{-1}$

(b) mean horizontal advection of temperature in the layer \_\_\_\_\_  $^{\circ}\text{C/hr}$

(c) mean horizontal advection of the 850 mb – 500 mb thickness \_\_\_\_\_  $^{\circ}\text{m/hr}$

6. Calculate the gradient wind speed and direction if the geostrophic wind is  $50 \text{ m s}^{-1}$  from the west for

(a) a low center with a radius of curvature of 1000 km

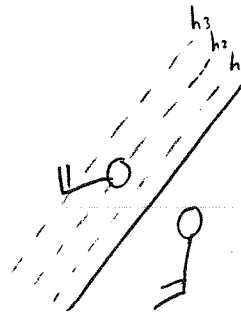
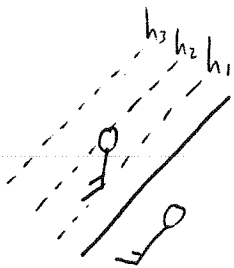
\_\_\_\_\_  $\text{m s}^{-1}$  from \_\_\_\_\_°

(b) a high center with a radius of curvature of 1000 km

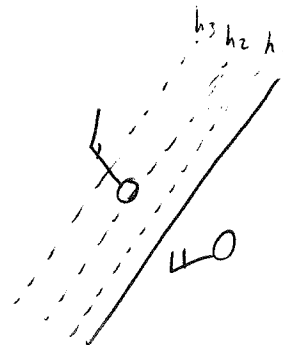
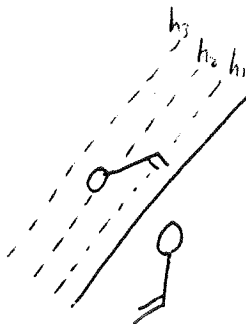
\_\_\_\_\_  $\text{m s}^{-1}$  from \_\_\_\_\_°

Show your work (5 pts).

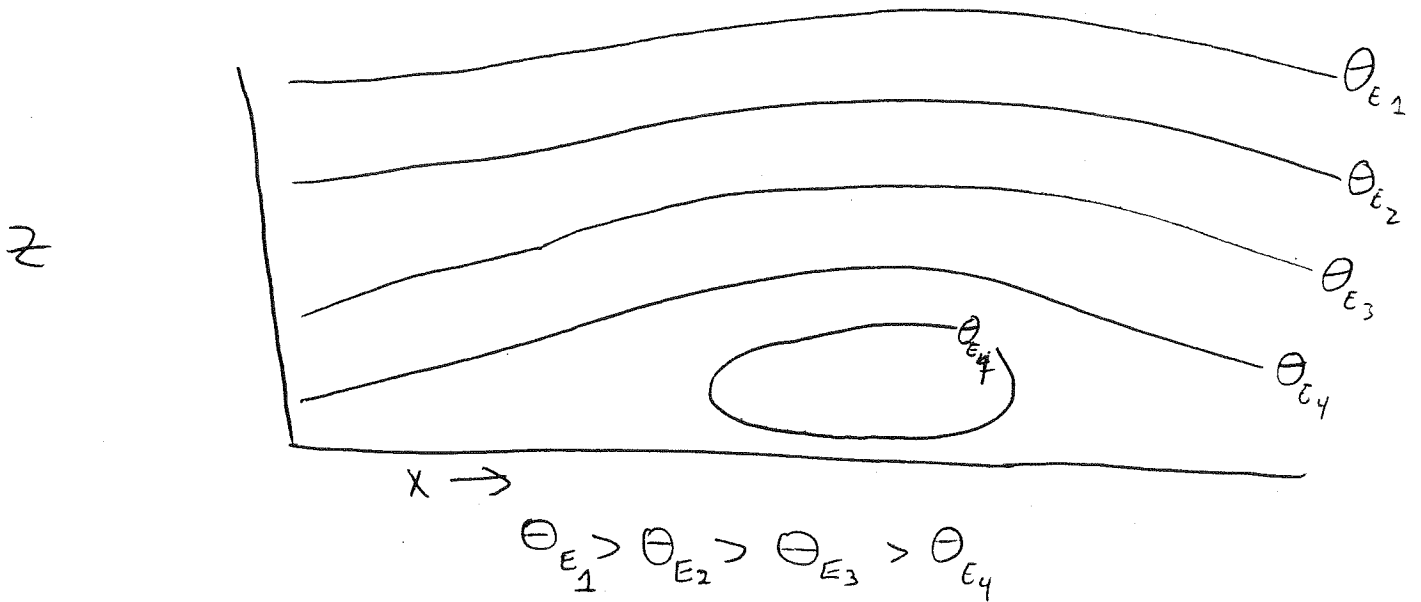
7. Given the observed surface winds and thickness gradient outlined below, indicate what type of front occurs and whether it is an 'active' or 'inactive' front. Use standard symbolism for frontal types (4 pts).



$h_1 > h_3$

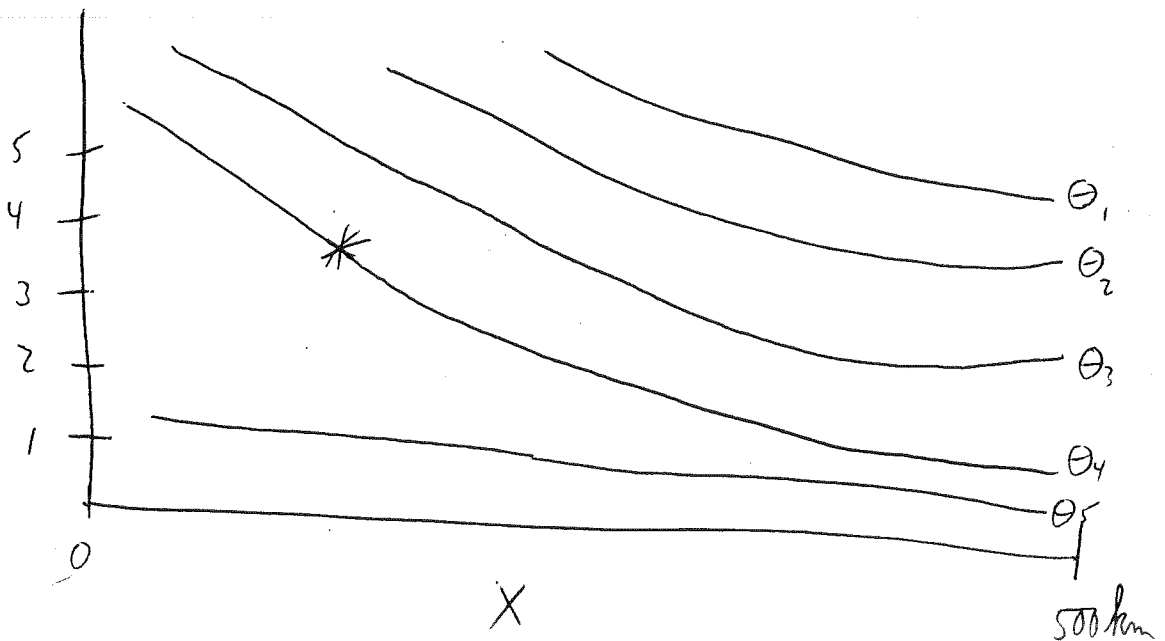


8. For the cross section of equivalent potential temperature sketched below, shade in red the regions of layer instability (5 pts).



9. For the cross section of potential temperature sketched below, estimate the magnitude and sign of vertical motion at point \*. Assume adiabatic motion and use a wind speed in the plane of the page of  $20 \text{ m s}^{-1}$ . Show calculations and formula used (5 pts).

\_\_\_\_\_  $\text{cm s}^{-1}$  \_\_\_\_\_ (formula used)



Use  $V = 10 \text{ m s}^{-1}$

$\theta_1 > \theta_5$

10. Given the attached NGM forecast model output, what are the values of the following variables at point A. Give units (7 pts).

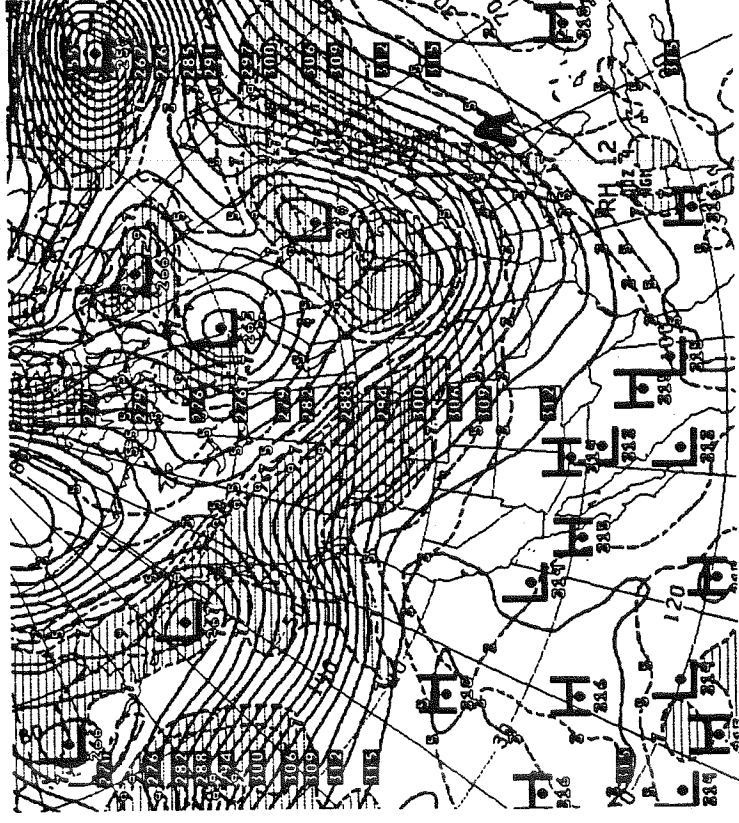
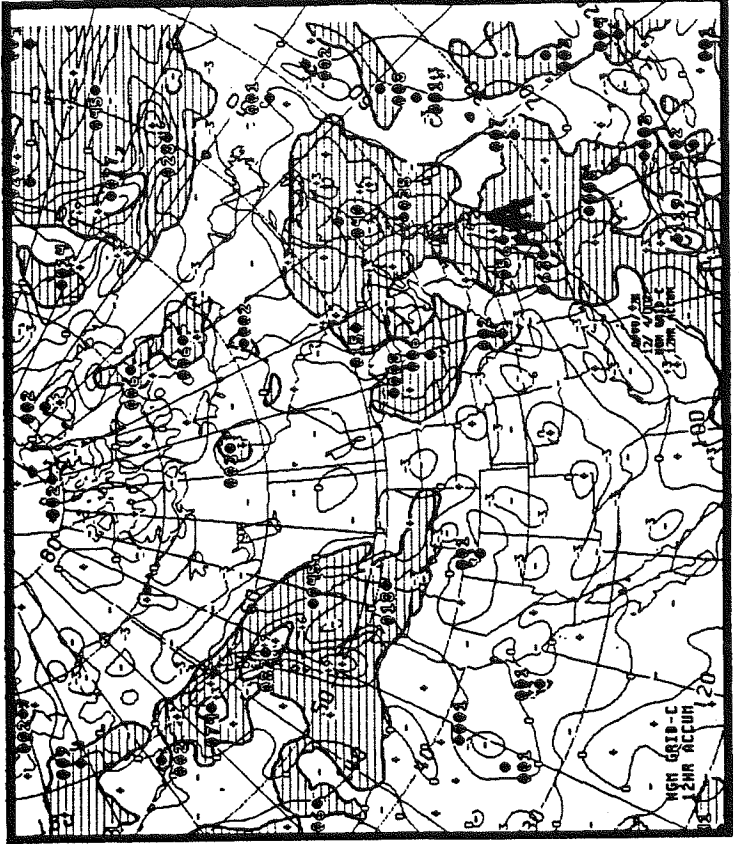
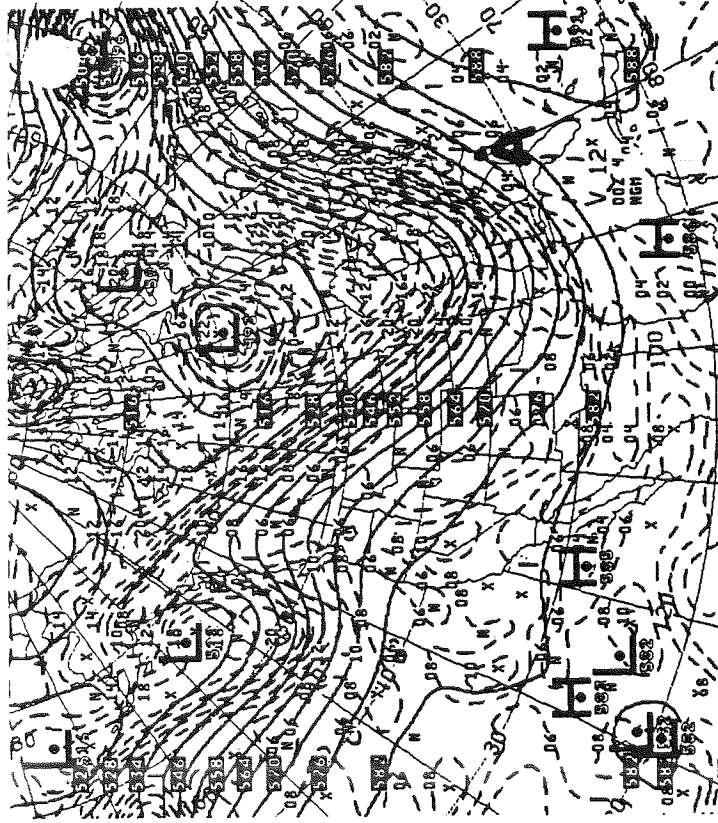
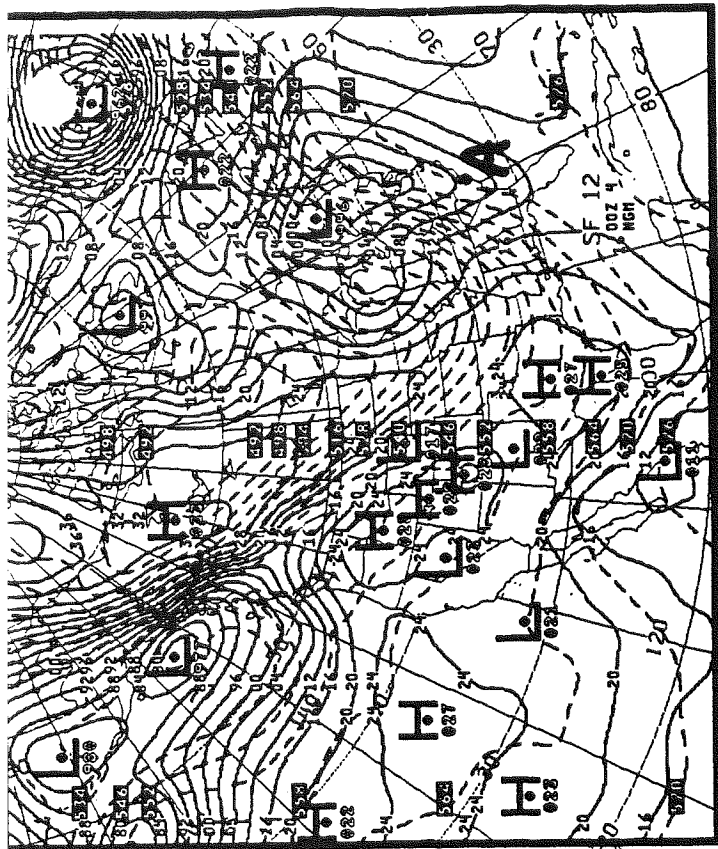
- 700 mb height \_\_\_\_\_
- 700 mb relative humidity \_\_\_\_\_
- 500 mb height \_\_\_\_\_
- 500 mb absolute vorticity \_\_\_\_\_
- surface pressure \_\_\_\_\_
- 1000 - 500 mb thickness \_\_\_\_\_
- vertical motion at 700 mb \_\_\_\_\_

11. Give the meaning of the following acronyms. For the ones that are models, also give their number of vertical levels and approximate horizontal grid intervals at 45°N (5 pts).

	Levels (if applicable)	Horizontal Grid Increments (if applicable)
NGM: _____	_____	_____
LFM _____	_____	_____
RAFS _____	_____	_____
MRF _____	_____	_____
MOS _____	_____	_____
DIFAX _____	_____	_____
ETA _____	_____	_____
WSFO _____	_____	_____
NMC _____	_____	_____
NCAR _____	_____	_____

Finally, for a 5% on top of your *course* grade, forecast the temperature on the foyer digital thermometer at 1 p.m. Friday, December 6th. If you equal or are closer to my forecast, you earn the 5%.





NO DEPT OF COMMERCE METEOROLOGICAL INFORMATION 8177 .. 12HR FCST MSL PRES/1000-500 THK VALID 00Z WED 4 DEC 91

NO DEPT OF COMMERCE METEOROLOGICAL INFORMATION 8177 .. 12HR FCST HEIGHTS/VORTICITY VALID 00Z WED 4 DEC 91

NO DEPT OF COMMERCE METEOROLOGICAL INFORMATION 8177 .. 12HR FCST PRECIP./700 VERT VEL VALID 00Z WED 4 DEC 91

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F120  
AT 540 MIDTERM  
Fall 1993

1. The subtropical jet stream is evident in satellite imagery as an anticyclonically curved cirrus band. The existence of the jet
  - (a) can be explained in terms of the topographic forcing.
  - (b) cannot be explained in terms of the thermal wind relationship.
  - (c) can be explained in terms of the thermal wind relationship.
  - (d) can be explained as an anomalously far south polar jet.
  - (e) none of the above.
  
2. Large values of thickness
  - (a) always imply relatively warm surface temperatures.
  - (b) usually imply relatively warm surface temperature but occasionally the surface can be quite cold.
  - (c) usually imply relatively cold surface temperatures but occasionally the surface can be quite warm.
  - (d) always imply relatively cold surface temperatures.
  
3. In which of the following coordinate system does the geostrophic wind inversely depend on density?
  - (a) pressure
  - (b) sigma
  - (c) isentropic
  - (d) height
  
4. Which of the following levels is defined as the level at which moisture condenses due to forced lifting of a parcel?
  - (a) level of free convection
  - (b) lifting condensation level
  - (c) mixing condensation level
  - (d) equilibrium level
  
5. Which of the following quantities (one answer) is conserved during moist ascent
  - (a) saturation mixing ratio
  - (b) mixing ratio
  - (c) potential temperature
  - (d) equivalent potential temperature
  - (e) none of the above

6. The wet bulb temperature is
  - (a) always equal to the dewpoint temperature.
  - (b) always greater than or equal to the dewpoint temperature but less than or equal to the temperature.
  - (c) always equal to or greater than the temperature.
  - (d) always equal to the potential temperature.
7. The dewpoint temperature of a parcel as it ascends
  - (a) is constant with height.
  - (b) decreases slowly with height.
  - (c) increases slowly with height.
8. A front at the surface moves in the direction of movement of
  - (a) the warm air.
  - (b) the cold air.
  - (c) the 200 mb trough axis.
  - (d) the thermal wind maximum.
9. Cold advection occurs when
  - (a) the wind speed increases with height.
  - (b) the wind veers with height.
  - (c) the wind backs with height.
  - (d) the wind speed decreases with height.
10. The symbol  $L$  represents
  - (a) light rain.
  - (b) sleet.
  - (c) hail.
  - (d) drizzle.
  - (e) graupel.
11. On an upper air analysis, a star at the base of a wind barb (or a star alone) indicates the data came from a (an)
  - (a) aircraft.
  - (b) radiosonde.
  - (c) ship.
  - (d) satellite.
12. The Omega equation is derived from the equation of motion plus (one answer)
  - (a) the conservation law for water vapor.
  - (b) the radiative flux divergence equation.
  - (c) the first law of thermodynamics.
  - (d) the incompressible continuity equation.

13. East of an upper level ridge and west of an upper level trough one generally expects to find
- (a) sinking air in the midtroposphere.
  - (b) ascending air in the midtroposphere.
  - (c) no substantial vertical motion.
14. During the occluded stage of an extratropical cyclone,
- (a) the upper low and surface system are almost vertical.
  - (b) the upper low has disappeared.
  - (c) the 500-1000 mb thickness contours are at a large angle to the height contours associated with the upper low.
  - (d) the thickness gradient has disappeared.
15. Baroclinic instability at a given latitude and static stability becomes more likely
- (a) as the geostrophic wind shear increases.
  - (b) as the geostrophic wind shear decreases.
  - (c) the wavelength of the disturbance becomes less than several hundred kilometers.
  - (d) in the spring season.
16. The geostrophic wind for a given pressure gradient as you approach the equator
- (a) increases.
  - (b) remains constant.
  - (c) decreases.
17. Vorticity is a measure of
- (a) wind strength.
  - (b) circulation.
  - (c) thermodynamic instability.
  - (d) vertical wind shear.
18. The dimensional units of vorticity is
- (a) length per second.
  - (b) per second.
  - (c) per length.
  - (d) length squared per second.
19. The vertical vorticity equation is derived by
- (a) differentiating the  $u$ -equation of motion by  $y$  and the  $v$ -equation by  $x$  and subtracting the second from the first.
  - (b) differentiating the  $u$ -equation of motion by  $x$  and the  $v$ -equation of motion by  $y$  and subtracting the second from the first.
  - (c) integrating the  $u$ -equation of motion with respect to  $y$  and the  $v$ -equation of motion with respect to  $x$  and subtracting the second from the first.
  - (d) integrating the  $u$ -equation of motion with respect to  $x$  and the  $v$ -equation of motion with respect to  $y$  and subtracting the second from the first.

20. As an air parcel moves from a ridge axis to a trof axis, its relative vorticity
- (a) becomes more cyclonic.
  - (b) becomes more anticyclonic.
  - (c) becomes more nondivergent.
  - (d) remains unchanged.
21. Cloudy, rainy (or snowy) weather on the synoptic scale occurs most frequently
- (a) east of the 500 mb ridge but west of the 500 mb trof.
  - (b) west of the 500 mb ridge but east of the 500 mb trof.
  - (c) under a 500 mb ridge.
  - (d) well removed from the polar jet stream.
22. During the development of an extratropical cyclone there is (one answer)
- (a) surface pressure rises in its center.
  - (b) midtropospheric descent east of its center ahead of the warm front.
  - (c) ageostrophic wind is convergent at low levels towards the low center.
  - (d) ageostrophic divergent upper level winds generate cyclonic relative vorticity which develops the trof downstream from the surface low center.
23. Given a temperature of 20°C, a dewpoint temperature of 10°C, and a pressure of 1000 mb, what is the relative humidity?
- (a) 10%
  - (b) 25%
  - (c) 40%
  - (d) 55%
  - (e) 70%
  - (f) 85%
  - (g) none of the above (give value)
24. For the above problem, calculate the wet bulb temperature.
- (a) 10°C
  - (b) 12°C
  - (c) 14°C
  - (d) 16°C
  - (e) 18°C
  - (f) 20°C
  - (g) none of the above (give value)

25. Which of the following atmospheric variables almost always increase with height in the middle and upper troposphere?
- (a) wet bulb temperature
  - (b) mixing ratio
  - (c) pressure
  - (d) temperature
  - (e) density
  - (f) potential temperature

26. The atmosphere is potentially unstable when

- (a)  $\gamma_d < \gamma < \gamma_m$
- (b)  $\gamma_m < \gamma < \gamma_d$
- (c)  $\frac{\partial \theta_E}{\partial z} > 0$
- (d)  $\frac{\partial \theta}{\partial z} > 0$
- (e)  $\frac{\partial \theta}{\partial z} < 0$

where  $\gamma$  is the environmental lapse rate,  $\gamma_m$  is the moist adiabatic lapse rate,  $\gamma_d$  is the dry adiabatic lapse rate,  $\theta$  is potential temperature, and  $\theta_E$  is the equivalent potential temperature.

27. Which of the following atmospheric systems decreases in intensity with height?

- (a) an extratropical cyclone.
- (b) a tropical cyclone.
- (c) a subtropical ridge.
- (d) an arctic high.
- (e) a cold front.
- (f) a warm front.
- (g) none of the above.

28. What is the dimension of  $g/C_p$  where  $g$  is the gravitational acceleration and  $C_p$  is the specific heat at constant pressure? Show work.

29. The prevailing wind direction at 20°S near the surface is from the

- (a) NE
- (b) E
- (c) SE
- (d) S
- (e) SW
- (f) W
- (g) NW
- (h) N

30. The specific heat of dry air at constant pressure is

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31. In the tropics, thunderstorms generally reach to a higher level than in midlatitudes during the summer because

- (a) the tropopause is higher.
- (b) the surface temperatures are much higher.
- (c) the wind shears are less.
- (d) the moisture values are greater.

32. The tops of cumulonimbus clouds are capable of rising higher than their level of neutral buoyancy because of

- (a) their high water content.
- (b) their excess temperature.
- (c) their low vertical wind shear.
- (d) their inertia.

33. Virga is

- (a) falling precipitation which does not reach the ground.
- (b) an optical phenomena when the sun or moon shines through an ice cloud.
- (c) drifting dry snow.
- (d) a heavy shower of graupel.

34. Clouds which have glaciated tops and anvils are called
- (a) altostratus.
  - (b) cirrocumulus.
  - (c) nimbostratus.
  - (d) stratocumulus.
  - (e) cumulonimbus.
  - (f) none of the above (give type).
35. An atmosphere in which a horizontal gradient of thickness exists is said to be
- (a) baroclinic.
  - (b) barotropic.
  - (c) conditionally unstable.
  - (d) conditionally stable.
  - (e) convectively unstable.
  - (f) hydrostatic.
  - (g) isothermal.
  - (h) none of the above.
36. If the horizontal pressure gradient near the surface is 4 mb per 200 km, the density of the air is  $1 \text{ kg m}^{-3}$  and the gravitational acceleration is estimated as  $10 \text{ m s}^{-2}$ , the horizontal gradient of the 1000 mb surface should be around
- (a) 0.4 m per 200 km.
  - (b) 1.0 m per 200 km.
  - (c) 4.0 m per 200 km.
  - (d) 10.0 m per 200 km.
  - (e) 40.0 m per 200 km.
  - (f) 100 m per 200 km.
  - (g) 400 m per 200 km.
  - (h) none of the above (give value)
37. Given that the specific humidity is 10 grams per kilogram and the temperature is  $27^\circ\text{C}$  calculate the virtual temperature.
- (a)  $23^\circ\text{C}$
  - (b)  $25^\circ\text{C}$
  - (c)  $27^\circ\text{C}$
  - (d)  $29^\circ\text{C}$
  - (e)  $31^\circ\text{C}$
  - (f) none of the above (give value)



38. Given that  $T = 10^\circ\text{C}$ ,  $p = 850$  mb, and  $T_D$  (the dewpoint)  $= 0^\circ$ , calculate  $\theta_E$ .

- (a) 290
- (b) 295
- (c) 300
- (d) 305
- (e) 310
- (f) none of the above (give value)

39. Given that the earth rotates once per day ( $2\pi/\text{day}$ ), calculate the Coriolis parameter at the equator and at the north pole.

Equator

- (a) zero  $\text{sec}^{-1}$
- (b)  $1.45 \times 10^{-6} \text{ sec}^{-1}$
- (c)  $7.25 \times 10^{-6} \text{ sec}^{-1}$
- (d)  $1.45 \times 10^{-5} \text{ sec}^{-1}$
- (e)  $7.25 \times 10^{-5} \text{ sec}^{-1}$
- (f)  $1.45 \times 10^{-4} \text{ sec}^{-1}$
- (g) none of the above (give value)

North Pole

- (a) zero  $\text{sec}^{-1}$
- (b)  $1.45 \times 10^{-6} \text{ sec}^{-1}$
- (c)  $7.25 \times 10^{-6} \text{ sec}^{-1}$
- (d)  $1.45 \times 10^{-5} \text{ sec}^{-1}$
- (e)  $7.25 \times 10^{-5} \text{ sec}^{-1}$
- (f)  $1.45 \times 10^{-4} \text{ sec}^{-1}$
- (g) none of the above (give value)

40. Given the radius of trajectory of an air parcel is 200 km, the Coriolis parameter is  $10^{-4}$ , and the wind speed is  $10 \text{ m s}^{-1}$ , calculate the centrifugal acceleration.

- (a)  $5 \times 10^{-4} \text{ m s}^{-2}$
- (b)  $5 \times 10^{-3} \text{ m s}^{-2}$
- (c)  $5 \times 10^{-2} \text{ m s}^{-2}$
- (d)  $5 \times 10^{-1} \text{ m s}^{-2}$
- (e)  $5 \text{ m s}^{-2}$
- (f) none of the above (give value)

41. Give a representative value of the sea level surface pressure in millibars and in the equivalent S.I. units.

\_\_\_\_\_ mb \_\_\_\_\_ Give units.

42. Given a surface temperature of  $5^\circ\text{C}$  and a surface dewpoint temperature of  $-5^\circ\text{C}$ , calculate the wet bulb temperature and relative humidity if the surface pressure is 950 mb.

\_\_\_\_\_  $^\circ\text{C}$  \_\_\_\_\_ %

43. Which of the following quantities are conserved with respect to the motion of dry air (i.e., air in which saturation does not occur)?

- (a)  $T$
- (b)  $T_W$
- (c) R.H.
- (d)  $T_D$
- (e)  $P$
- (f)  $\theta$
- (g)  $\theta_E$

44. Which of the following quantities are conserved with respect to the motion of saturated air.

- (a)  $T$
- (b)  $T_W$
- (c) R.H.
- (d)  $T_D$
- (e)  $P$
- (f)  $\theta$
- (g)  $\theta_E$

45. Match the name of the wind with the balance of forces which are involved in its definition.

	<u>Forces</u>
gradient	pressure gradient; Coriolis
geostrophic	pressure gradient; Coriolis, centrifugal
cyclostrophic	pressure gradient; centrifugal
friction	pressure gradient; Coriolis; centrifugal; friction

46. Convert the quantities listed below to S.I. units.

$$10 \text{ miles hour}^{-1} = \underline{\hspace{4cm}} \text{ m s}^{-1}$$

$$20^\circ\text{F} = \underline{\hspace{4cm}} ^\circ\text{C} = \underline{\hspace{4cm}} \text{ K}$$

$$80^\circ\text{F} = \underline{\hspace{4cm}} ^\circ\text{C} = \underline{\hspace{4cm}} \text{ K}$$

47. Given that you are on an airplane flying at 200 mb and the outside temperature is  $-70^\circ\text{C}$ , calculate the temperature inside the plane if this air was drawn inside and compressed to 1000 mb (show work).

$$T = \underline{\hspace{4cm}} ^\circ\text{C} = \underline{\hspace{4cm}} ^\circ\text{F}$$

48. Given the weather conditions: overcast,  $T = 32^\circ\text{F}$ ,  $T_D = 20^\circ\text{F}$ ,  $p = 986$  mb, and the wind is northeasterly at 10 knots, draw the station model.

○

49. What type of front is sketched below



- (a) active warm front  
 (b) active cold front  
 (c) active stationary front  
 (d) active warm occlusion  
 (e) active cold occlusion
50. Given a westerly geostrophic wind of  $10 \text{ m s}^{-1}$  at 1000 mb, calculate the wind at 250 mb assuming a south to north thickness gradient of  $-120 \text{ m per } 100 \text{ km}$ ,  $f = 10^{-4} \text{ s}^{-1}$  and  $g = 10 \text{ m s}^{-2}$ .

\_\_\_\_\_  $\text{m s}^{-1}$

51. You are driving a car and the temperature outside is  $4^{\circ}\text{C}$  and the dewpoint is  $-8^{\circ}\text{C}$ . It begins to rain. Should you become concerned that the rain will turn to snow or not, and if the road will become icy? You must give a brief physical explanation for credit.
52. If you are standing outside and the wind is from the northwest, in what direction relative to you do you expect the low pressure system to be?
53. To approximately what height does the troposphere extend in the tropics?
54. The thickness equation was derived using which of the following concepts (circle correct answer(s)).
- (a) the hydrostatic equation
  - (b) the cyclostrophic wind equation
  - (c) the second law of thermodynamics
  - (d) the ideal gas law
  - (e) the gradient wind equation
  - (f) the condensation equation
  - (g) the Coriolis effect
  - (h) the moist adiabatic relation
55. Circle the following properties that are not conserved during the lifting of saturated air.
- (a) potential temperature
  - (b) equivalent potential temperature
  - (c) dewpoint temperature

- (d) mixing ratio
- (e) saturation mixing ratio
- (f) relative humidity
- (g) wet bulb temperature
- (h) temperature

56. The dewpoint at 1000 mb is  $10^{\circ}\text{C}$  and the temperature is  $20^{\circ}\text{C}$ . Compute the following directly or from a thermodynamic diagram and explain how each are computed.

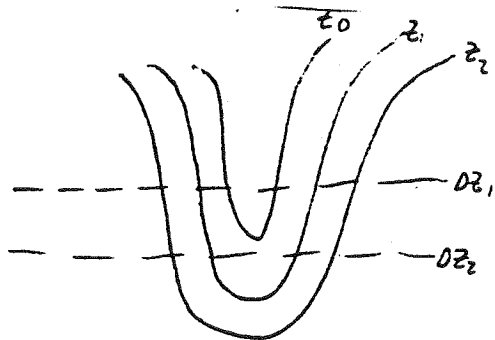
- (a) potential temperature (K)
- (b) equivalent potential temperature (K)
- (c) wet bulb temperature ( $^{\circ}\text{C}$ )
- (d) specific humidity (kg/kg)
- (e) lifting condensation level (mb)
- (f) relative humidity (percent)

57. A climber sets his altimeter to the correct reading at the beginning of a hike during which he climbs from sea level to an altitude of exactly 500 m over a 3 hr period. During this same time interval the sea level pressure drops 10 mb due to the approach of a storm. Estimate the altimeter reading at the end of the hike. Assume the mean temperature in the layer is  $0^{\circ}\text{C}$  throughout the entire time and assume the sea level pressure was 1000 mb at the start of his hike. Show your work.

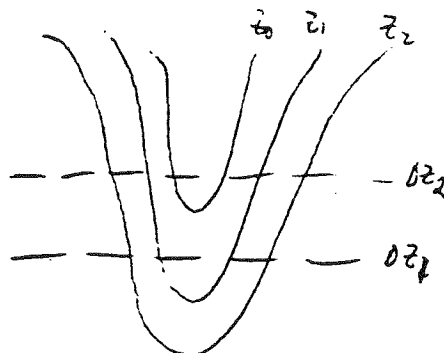
AT 540

Weather Lab - FINAL - Fall 1993

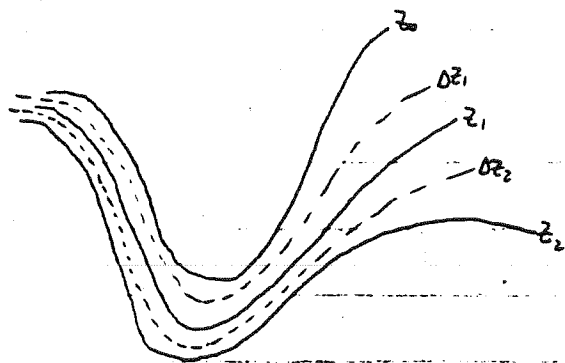
1. Which of the synoptic-scale trofs below would be expected to be deepening over time. Assume gradient wind flow. Solid lines are 700 mb height and dashed lines are 1000-500 mb thickness values.  $\Delta Z_1 < \Delta Z_2$ .  $Z_0 < Z_1$ .



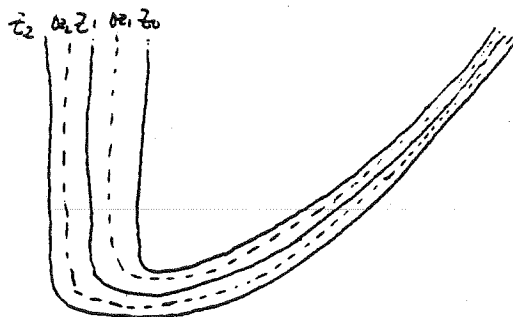
(a)



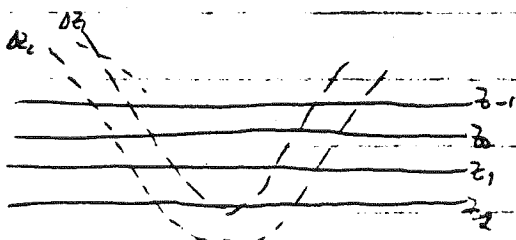
(b)



(c)



(d)



e

2. Given a 1000-500 mb rain-snow thickness of 5400 meters, the requirement that temperatures at the surface be less than  $5^{\circ}\text{C}$ , and a uniform lapse rate of (a)  $\partial T/\partial z = -1^{\circ}\text{C}/100\text{ m}$  and (b)  $\partial T/\partial z = -0.5^{\circ}\text{C}/100\text{ m}$ , calculate the elevation above sea level above which snow will occur. Assume sea level at 1000 mb. Show your work.

(a)  $z_G = \underline{\hspace{2cm}}$  meters

(b)  $z_G = \underline{\hspace{2cm}}$  meters

3. Given a westerly wind of  $20\text{ m s}^{-1}$  at 500 mb and zero winds at the top of the boundary layer (BL), compute the direction and magnitude of the top of the BL to 500 mb thickness gradient in (a) units of meters per 100 km and (b) units of  $^{\circ}\text{C}$  per 100 km. Use  $f = 10^{-4}\text{ s}^{-1}$  and assume PBL top at 1000 mb. Show your work.

(a)  $\underline{\hspace{2cm}}$  m/100 km

(b)  $\underline{\hspace{2cm}}$   $^{\circ}\text{C}/100\text{ km}$

4. Given a westerly wind speed on a potential temperature surface of  $20 \text{ m s}^{-1}$  which has a slope towards the east of 0.001, calculate the vertical velocity in  $\text{cm s}^{-1}$ . Show your work.

$$w = \underline{\hspace{2cm}} \text{ cm s}^{-1}$$

5. Circle below what satellite signature to look for to identify deep cumulonimbus convection.

a comma cloud

cold infrared image

open convective cells

sheared cloud streets

bright visible image

cyclonic vorticity advection

cold visible image

fibrous clouds

6. If you see sunglint in the satellite image it means:

(a) clouds are present and the sunlight is reflecting off of them.

(b) calm water is present and the sunlight is reflected off of it.

(c) snow is present and the sunlight is reflected off of it.

(d) bare soil is present and the sunlight is reflected off of it.

7. What is the threat score (TS) value if you observed 100 events, predicted 200 events, and correctly predicted 50 events? Show formula and work. What is the forecast bias?

(a)  $TS = \underline{\hspace{2cm}}$

(b) bias =  $\underline{\hspace{2cm}}$



8. If the temperature is  $10^{\circ}\text{C}$  and the dewpoint temperature is  $-5^{\circ}\text{C}$ , what is the wet bulb temperature at (i) 1000 mb, and (ii) at 850 mb. Also calculate the wet bulb potential temperature at these two levels.

$$T_w = \quad ^{\circ}\text{C} \text{ at } 1000 \text{ mb} \qquad \theta_w = \quad \text{K at } 1000 \text{ mb}$$

$$T_w = \quad ^{\circ}\text{C} \text{ at } 850 \text{ mb} \qquad \theta_w = \quad \text{K at } 850 \text{ mb}$$

9. Which of the atmospheric systems listed below are warm core.

extratropical cyclones

warm front

tropical cyclones

anticyclone vorticity center

subtropical ridge

thermal ridge

arctic high

jet stream

10. Circle the assumptions involved in deriving the adiabatic lapse rate.

hydrostatic relation

ideal gas law

1st law of thermodynamics

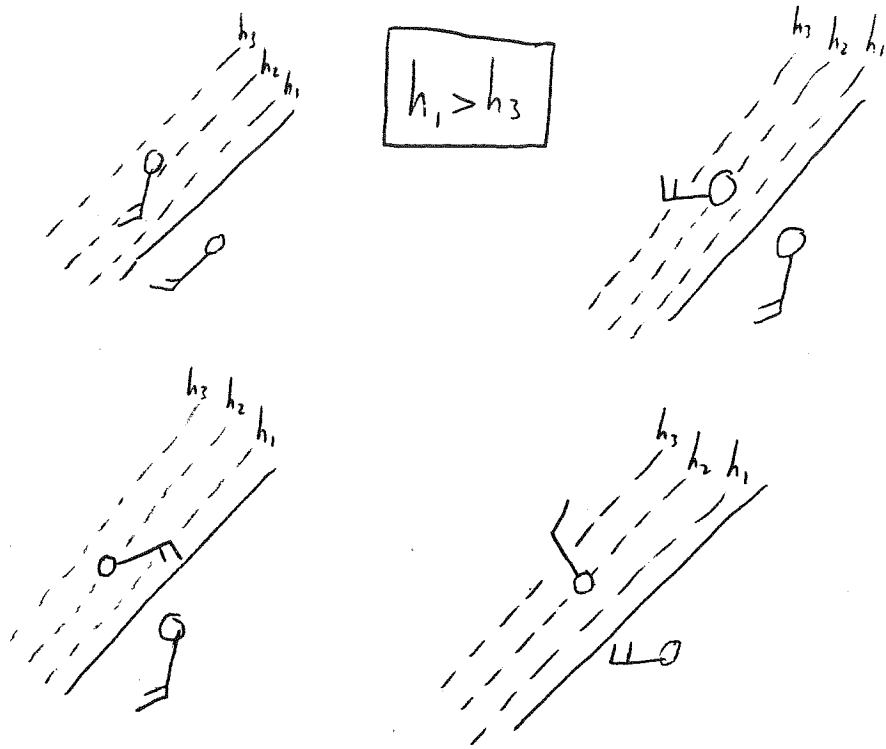
equation of motion

conservation of mass

11. Calculate the virtual temperature for a temperature of  $20^{\circ}\text{C}$ , a dewpoint temperature of  $20^{\circ}\text{C}$ , and a pressure of 1000 mb. Show your work.

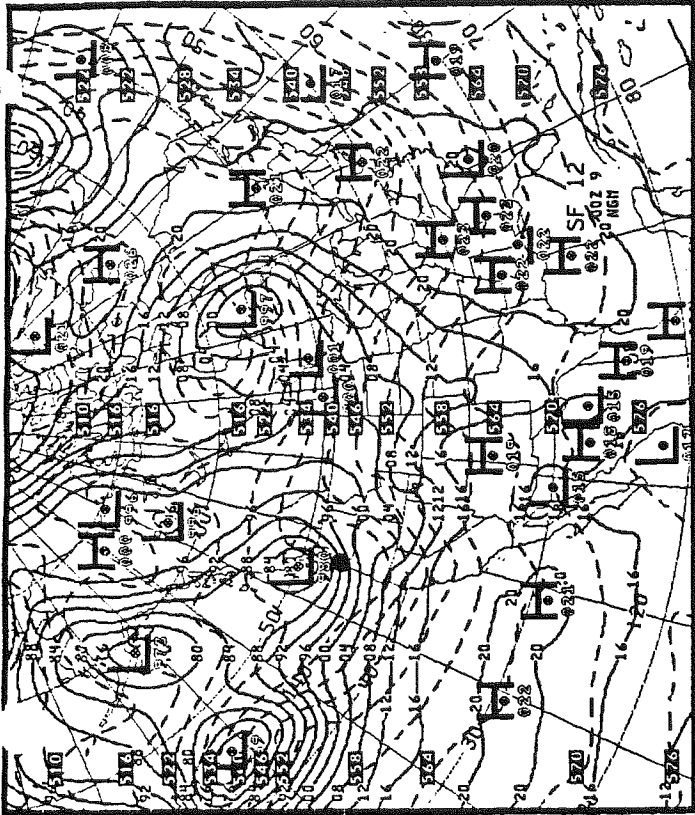
$$T_v = \underline{\hspace{2cm}}^{\circ}\text{C}$$

12. Given the observed surface winds and thickness gradient outlined below, indicate what type of front occurs and whether it is an active or inactive front. Use standard symbolism for frontal types.



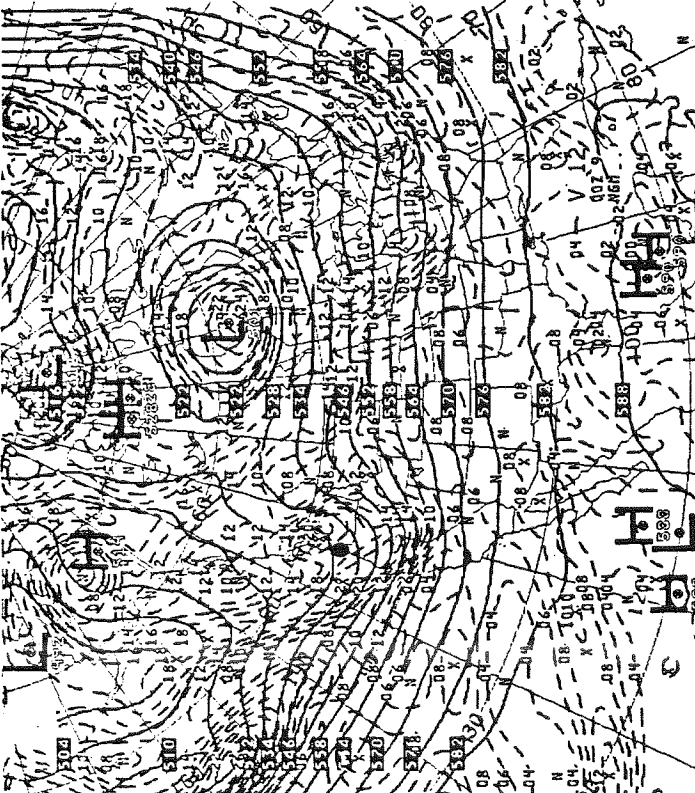
13. Given the attached NGM forecast model output, what are the values of the following variables at point A. Give units.

- 700 mb height \_\_\_\_\_
- 700 mb relative humidity \_\_\_\_\_
- 500 mb height \_\_\_\_\_
- 500 mb absolute vorticity \_\_\_\_\_
- surface pressure \_\_\_\_\_
- 1000 - 500 mb thickness \_\_\_\_\_
- vertical motion at 700 mb \_\_\_\_\_



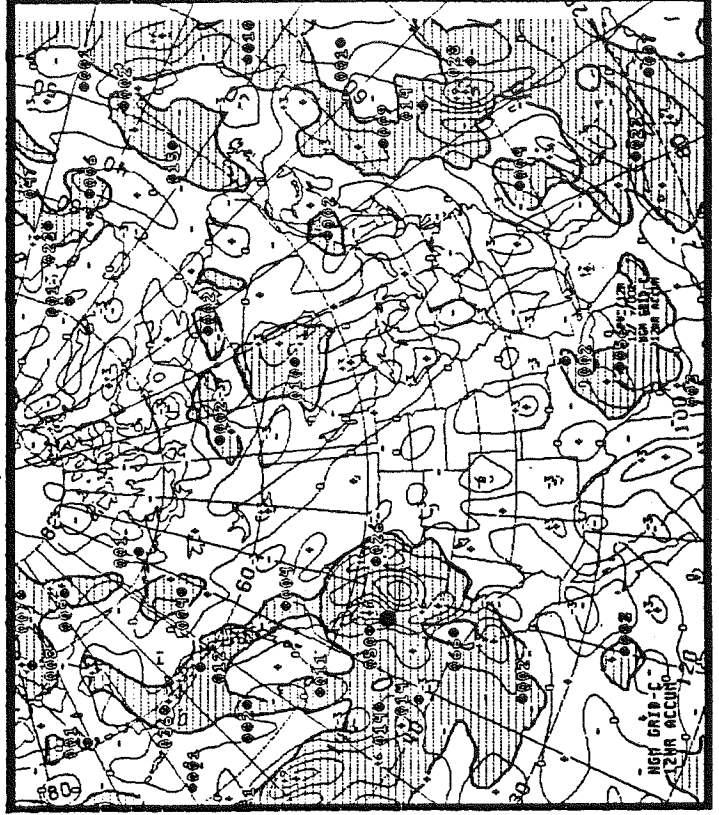
8177 .. 12HR FCST HSL PRES/1000-500 THK VALID 00Z THU 9 DEC 93

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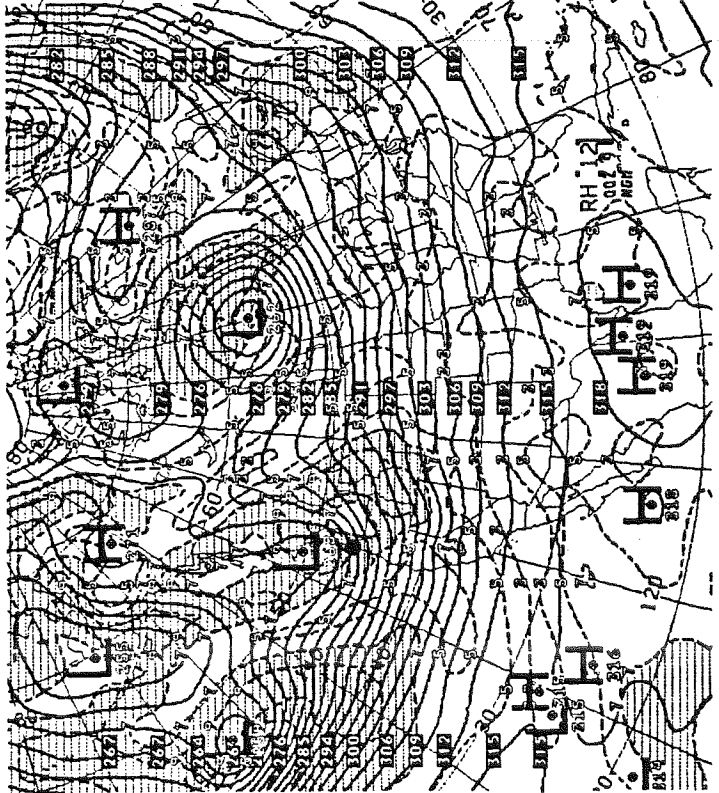
8177 .. 12HR FCST HEIGHTS/VORTICITY VALID 00Z THU 9 DEC 93

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8177 .. 12HR FCST PRECIP./700 VENT VEL VALID 00Z THU 9 DEC 93

OR DEPT OF COMMERCE NOAA/NWS/AVIATION METEOROLOGICAL CENTER



8177 .. 12HR FCST 700 HEIGHT/REL HUMIDITY VALID 00Z THU 9 DEC 93

OR DEPT OF COMMERCE NOAA/NWS/AVIATION METEOROLOGICAL CENTER

A →

14. Which of the following surface indications are useful in delineating a frontal location.
- (a) location of a pressure trof
  - (b) a wind shift line
  - (c) a horizontal dewpoint gradient
  - (d) the pressure tendencies
  - (e) horizontal temperature gradient
  - (f) none of the above
15. If the winds veer with height between 850 mb and 500 mb, but back between 500 mb and 300 mb,
- (a) the analysis must be incorrect because such a situation cannot occur.
  - (b) the jet stream must be strongest at 500 mb.
  - (c) there is cold advection in the lower level but warm advection higher up.
  - (d) there is warm advection in the lower level but cold advection higher up.
  - (e) none of the above.
16. The dewpoint temperature of a parcel as it ascends
- (a) is constant with height.
  - (b) decreases slowly with height.
  - (c) increases slowly with height.
17. The symbol  $L$  represents
- (a) light rain
  - (b) sleet
  - (c) hail
  - (d) drizzle
  - (e) graupel
18. The dimensional unit of vorticity is
- (a) length per second
  - (b) per second
  - (c) per length
  - (d) length squared per second

19. The difference between the saturation vapor pressure over a plane surface of pure water ( $e_s$ ) and over a plane surface of pure ice ( $e_{si}$ ) ( $e_s - e_{si}$ ) at  $-14^\circ\text{C}$  is
- (a) greater than zero
  - (b) zero
  - (c) less than zero
20. Which of the following geographic locations has never been observed to have a tropical cyclone development? (Note: "southern" means south of the equator; "northern" means north of the equator.)
- (a) the western, northern tropical Atlantic
  - (b) the western, southern tropical Atlantic
  - (c) the western, northern tropical Pacific
  - (d) the western, southern tropical Pacific
  - (e) the southern tropical Indian Ocean
  - (f) the northern tropical Indian Ocean
  - (g) the eastern, northern tropical Pacific
21. For an ideal gas, which of the following is the correct relationship between the specific heats at constant pressure and volume, and the gas constant?
- (a)  $R = C_v + C_p$
  - (b)  $C_v = C_p + R$
  - (c)  $0 = R + C_v + C_p$
  - (d)  $C_p = C_v + R$
  - (e)  $R = C_v \times C_p$
  - (f) none of the above

22. The type of fog which forms when air blows upslope and is cooled adiabatically is called
- (a) radiation fog
  - (b) advection fog
  - (c) arctic sea smoke
  - (d) funnel clouds
23. Most deaths in hurricanes are caused by
- (a) debris blown by strong winds
  - (b) the flooding of large rivers
  - (c) flash floods
  - (d) storm surge
  - (e) tidal waves
  - (f) other (give cause)
24. If the pressure field is curved anticyclonically (e.g., around a high pressure region) the relationship between the geostrophic wind,  $V_g$ , and the gradient wind,  $V_{gr}$ , is given by
- (a)  $V_g > V_{gr}$
  - (b)  $V_g < V_{gr}$
  - (c)  $V_g = V_{gr}$
25. Number the sequence of formation of warm rain. Leave out those components that are involved solely with cold rain processes.
- |                       |                          |
|-----------------------|--------------------------|
| condensational growth | collision-coalescence    |
| aggregation           | deposition               |
| riming                | heterogeneous nucleation |
| melting               |                          |
26. What is the value of the latent heat of condensation in S.I. units.
27. What is the most abundant gas in the earth's atmosphere (give its chemical form).

28. Order air with the least number of aerosols to that air mass with the most.

continental

marine

urban polluted

29. Blue sky occurs because

(a) blue is preferentially scattered relative to other wavelengths.

(b) blue is preferentially absorbed relative to other wavelengths.

(c) blue is preferentially emitted by the sun relative to other wavelengths.

(d) blue is preferentially reflected from the earth's surface relative to other wavelengths.

30. Properly connect the left and right sides.

ITCZ                      region of extremely low thickness

northeast trades      upper branch of Hadley cell

polar front              low-level convergence of trade winds

arctic high              demarcation between tropical and polar origin air

subtropical jet        lower branch of Hadley cell

31. Supercooled water has a temperature

(a) below 0°C

(b) 0°C

(c) between 0°C and 100°C

(d) above 100°C

32. Of the following conditions, snowflake growth is greatest
- (a) when the temperature of the air is  $0^{\circ}\text{C}$  and the mixing ratio is highly supersaturated with respect to ice.
  - (b) when the temperature of the air is  $0^{\circ}\text{C}$  and the mixing ratio slightly supersaturated with respect to ice.
  - (c) when the temperature of the air is  $-15^{\circ}\text{C}$  and the mixing ratio is highly supersaturated with respect to ice.
  - (d) when the temperature of the air is  $-15^{\circ}\text{C}$  and the mixing ratio is slightly supersaturated with respect to ice.
33. The growth of ice crystals by the freezing of supercooled water on its surface is called
- (a) deposition
  - (b) aggregation
  - (c) riming
  - (d) condensation
  - (e) other (give answer)
34. Which of the following types of electromagnetic radiation has the shortest wavelength?
- (a) X-rays
  - (b) ultraviolet
  - (c) visible
  - (d) infrared
  - (e) microwave
35. The earth primarily radiates energy in the
- (a) X-ray wavelengths
  - (b) ultraviolet wavelengths
  - (c) visible wavelengths
  - (d) infrared wavelengths



36. Blackbody irradiance is proportional to

- (a) the first power of temperature
- (b) the second power of temperature
- (c) the third power of temperature
- (d) the fourth power of temperature
- (e) the fifth power of temperature

37. The presence of a cloud cover tends to favor higher nighttime temperatures at the ground level because

- (a) it absorbs the infrared radiation from the ground and re-emits it downward.
- (b) it releases heat of condensation which is transferred to the ground.
- (c) conduction from the cloud layer to the ground cools the surface layer.
- (d) stronger winds always occur with a cloud layer.

38. Order the following forms of electromagnetic radiation in order from the short wavelength to longest.

radio

visible

infrared

X-ray

ultraviolet

39. Order the following depths, in a given layer of soil, as to which has the larger diurnal temperature variation. Label 1 for the largest variation; 4 for the least.

1 cm

10 cm

100 cm

1000 cm

40. The "greenhouse" effect is an incorrect analogy to the manner in which longwave radiation tends to be trapped by the earth's atmosphere. Greenhouses are relatively hot compared to areas outside it primarily because
- (a) the glass is heated by electricity.
  - (b) the glass lets in solar heating but prevents heated air from rising and leaving the enclosure.
  - (c) the glass is made opaque to visible light.
  - (d) the glass is heated substantially by the sun and this heat is conducted into the greenhouse.
41. The earth is closer to the sun in
- (a) July
  - (b) September
  - (c) January
  - (d) March
  - (e) it is equidistant at all times.
42. Sleet occurs
- (a) when rain falls through a subfreezing layer near the ground and freezes into ice pellets.
  - (b) when wet snow, which is almost melted, strikes the ground.
  - (c) when rain is being converted into snowflakes.
  - (d) most frequently in thunderstorms.
  - (e) none of the above (state when it occurs).
43. The majority of carbon near the earth's surface is in
- (a) the atmosphere
  - (b) the ocean
  - (c) the biosphere
  - (d) rocks
44. Fronts move
- (a) in the direction of the thermal wind.
  - (b) in the direction of the cold air only.
  - (c) in the direction of the warm air only.
  - (d) in the direction of cold air for cold fronts and in the direction of warm air for warm fronts.

45. When you emerge from a filled swimming pool, the temperature at your skin surface is approximately equal to the
- (a) dewpoint temperature
  - (b) frost point temperature
  - (c) wet bulb temperature
  - (d) dry bulb temperature
46. Green plants have that color because they
- (a) reflect visible colors but green.
  - (b) absorb visible colors but green.
  - (c) absorb as a blackbody.
  - (d) radiate as a blackbody.
  - (e) radiate with green the wavelength of maximum radiative energy.

BONUS: Forecast the temperature at 1 pm tomorrow at Fort Collins. If you are equal or are closer than my forecast you earn 5% on top of your grade.

I enjoyed teaching you this semester. I wish you success during the rest of your college career.

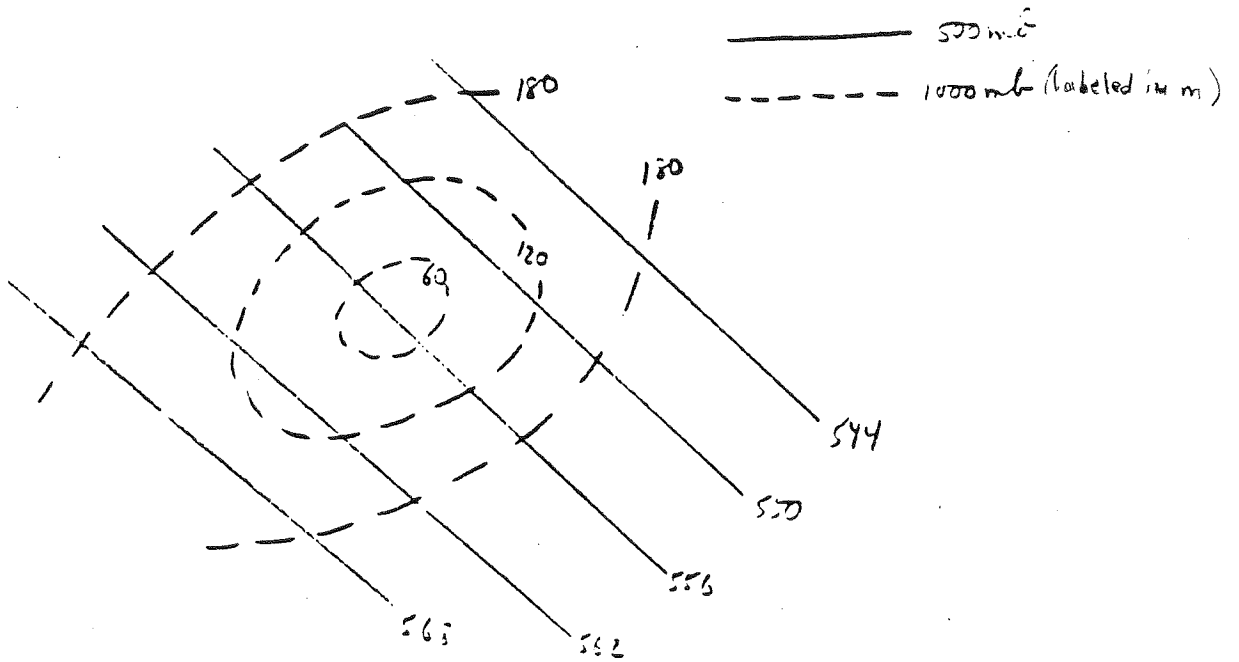
R. Pielke

## MID TERM EXAM - AT 540

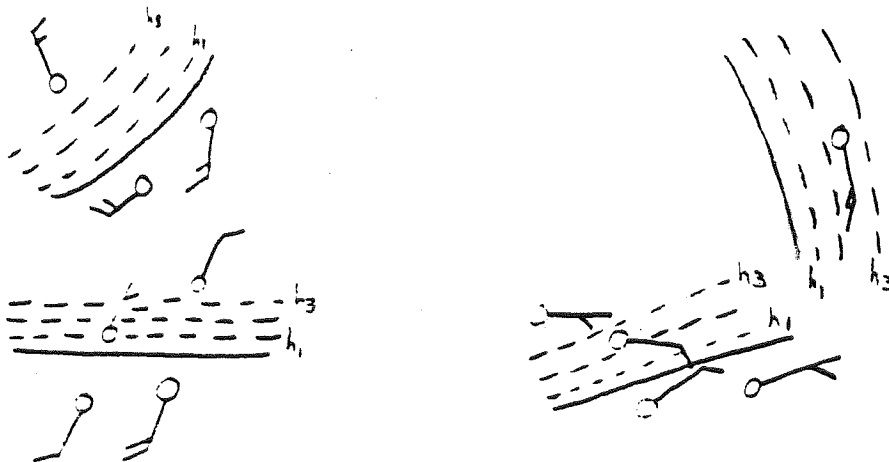
Fall 1994

1. Indicate which of the following are correct expressions of the geostrophic wind relation (could be more than one answer).
- (a)  $\vec{V}_g = \vec{k} \times \frac{1}{f\rho} \nabla_z p$
  - (b)  $\vec{V}_g = \vec{k} \times \frac{g}{f} \nabla_p z$
  - (c)  $\vec{V}_g = \vec{k} \times \frac{1}{f} \nabla_\theta (C_p T + gz)$
  - (d)  $\vec{V}_g = \vec{k} \times \frac{\rho}{p} \nabla_H f$
  - (e) none of the above
2. Which of the following values of precipitable water are reasonable in an arctic high.
- (a) 2.00 inches
  - (b) 1.00 inches
  - (c) .20 inches
  - (d) .0001 inches
  - (e) none of the above
3. A necessary condition to define a synoptic front is
- (a) the existence of a horizontal surface temperature gradient
  - (b) the existence of a gradient of percent of cloud cover
  - (c) the existence of a horizontal thickness gradient in the lower troposphere
  - (d) the presence of precipitation
  - (e) winds in the cold air normal to the front
4. Assume that the layer between 500 and 1000 mb is isothermal.  $R = 287 \text{ J kg}^{-1} \text{ K}^{-1}$  while  $g = 10 \text{ m s}^{-2}$  and  $\ln 2 = .69$ . What is the thickness if the temperature of the layer is  $0^\circ\text{C}$  (1st column) and if the temperature layer is  $25^\circ\text{C}$  (2nd column)? Show work.
- |                                |                                |
|--------------------------------|--------------------------------|
| 4260 m                         | 4172 m                         |
| 4780 m                         | 4830 m                         |
| 5430 m                         | 5420 m                         |
| 5820 m                         | 5928 m                         |
| 6130 m                         | 6520 m                         |
| none of the above (give value) | none of the above (give value) |

5. Sketched below are the heights of a 1000 mb and a 500 mb pressure surface. Draw in and label in decameters the values of the thickness (contours at 60 m intervals).

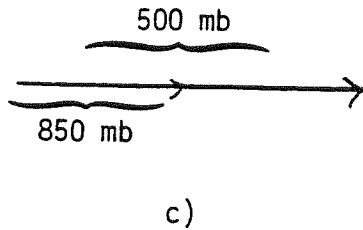
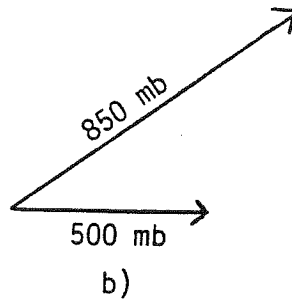
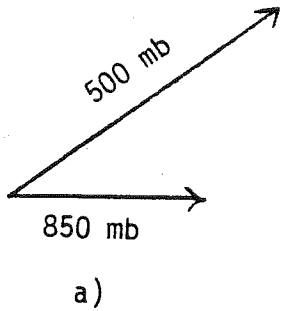


6. Indicate by an arrow the direction towards which the front would be expected to move given the surface wind pattern indicated by the station model. Indicate the type of front. The values  $h_1, h_2, \dots$  are lines of constant thickness where  $h_1 > h_2 > h_3$  etc.



7. Give representative (i.e., realistic) values of the following quantities. You must provide the correct dimensional units.
- (a) relative vorticity on the synoptic scale \_\_\_\_\_.
  - (b) Coriolis parameter at  $40^{\circ}\text{N}$  \_\_\_\_\_.
  - (c) 1000 - 500 mb thickness at  $30^{\circ}\text{N}$  in the summer \_\_\_\_\_.
  - (d) 200 mb wind speed in the center of the jet stream \_\_\_\_\_.
  - (e) sea level maximum pressure associated with a cP high \_\_\_\_\_.

8. Given the 850 mb to 500 mb geostrophic wind changes drawn below, calculate the thickness gradient, and equivalent layer-mean temperature gradients. Draw the orientation of the lines of constant thickness. Indicate whether cold, neutral, or warm advection is occurring and indicate the direction of the horizontal temperature gradient. To simplify the number of computations that you need to make, assume the magnitude of the wind difference between 850 mb and 500 mb for (b) and (c) is the same as that in (a). Use  $1 \text{ cm} = 25 \text{ m s}^{-1}$  with respect to the wind vectors.



- |    |                      |                    |
|----|----------------------|--------------------|
|    | $\nabla_p(\Delta z)$ | $\nabla_p \bar{T}$ |
| a) | <u>          </u>    | <u>          </u>  |
| b) | <u>          </u>    | <u>          </u>  |
| c) | <u>          </u>    | <u>          </u>  |

9. Of the following, circle only the lapse rates (between 1000 mb to 900 mb and with a 1000 mb temperature of 30°C) which are convectively neutral or unstable.

$$\frac{\partial \theta}{\partial Z} = 1^\circ \text{C}/\text{km}$$

$$\frac{\partial \theta_w}{\partial Z} = 1^\circ \text{C}/\text{km}$$

$$\frac{\partial T}{\partial Z} = -1^\circ \text{C}/\text{km}$$

$$\frac{\partial \theta_E}{\partial Z} = -1^\circ \text{C}/\text{km}$$

10. Calculate the virtual temperature for a temperature of 35°C, a dewpoint temperature of 25°C and a pressure of 1000 mb. Show your work.

$$T_v \underline{\hspace{10em}}^\circ \text{C}$$

11. Calculate the gradient wind speed and direction (show your work) if the geostrophic wind is 30 m s<sup>-1</sup> from the west for

(a) a low center with a radius of curvature of 1000 km  
 \_\_\_\_\_ m s<sup>-1</sup> from \_\_\_\_\_°

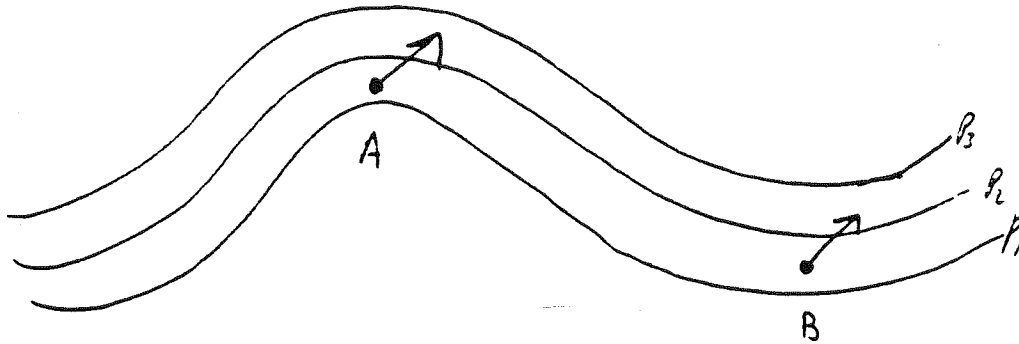
(b) a high center with a radius of curvature of 1000 km \_\_\_\_\_ m s<sup>-1</sup> from  
 \_\_\_\_\_°



12. Circle the assumptions involved in deriving the adiabatic lapse rate.

- hydrostatic relation
- 1st law of thermodynamics
- conservation of mass
- ideal gas law
- equation of motion

13. Given the pressure distribution below, draw a balance of forces that would result in a non-accelerating wind velocity at points A and B.



$$P_3 < P_1$$

14. Properly connect the left and right sides.

ITCZ	region of extremely low thickness
northeast trades	upper branch of Hadley cell
polar front	low-level convergence of trade winds
arctic high	demarcation between tropical and polar origin air
subtropical jet	lower branch of Hadley cell

15. Give representative values of temperature and dewpoint temperature for the following air mass types in the summer.

Summer

*mT*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

*mP*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

*cP*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

*cA*     $T =$  \_\_\_\_\_     $T_D =$  \_\_\_\_\_

16. Plot the 500 mb station model for the following observations at a location at 40°N. Temperature = -25°C; dewpoint temperature = -29°C; wind = 35 knots from the south; a height of 5320 meters; and a 12 hour height change of minus 120 meters.

17. In which of the following coordinate system does the geostrophic wind inversely depend on density?
- (a) pressure
  - (b) sigma
  - (c) isentropic
  - (d) height
18. Which of the following levels is defined as the level at which moisture condenses due to forced lifting of a parcel?
- (a) level of free convection
  - (b) lifting condensation level
  - (c) mixing condensation level
  - (d) equilibrium level
19. Which of the following quantities (one answer) is conserved during moist ascent?
- (a) saturation mixing ratio
  - (b) mixing ratio
  - (c) potential temperature
  - (d) equivalent potential temperature
  - (e) none of the above
20. The wet bulb temperature is
- (a) always equal to the dewpoint temperature.
  - (b) always greater than or equal to the dewpoint temperature but less than or equal to the temperature.
  - (c) always equal to or greater than the temperature.
  - (d) always equal to the potential temperature.
21. The dewpoint temperature of a parcel as it ascends
- (a) is constant with height.
  - (b) decreases slowly with height.
  - (c) increases slowly with height.

22. A front at the surface moves in the direction of movement of
- (a) the warm air.
  - (b) the cold air.
  - (c) the 200 mb trof axis.
  - (d) the thermal wind maximum.
23. The symbol  $L$  represents
- (a) light rain.
  - (b) sleet.
  - (c) hail.
  - (d) drizzle.
  - (e) graupel.
24. The Omega equation is derived from the equation of motion plus (one answer)
- (a) the conservation law for water vapor.
  - (b) the radiative flux divergence equation.
  - (c) the first law of thermodynamics.
  - (d) the incompressible continuity equation.
25. East of an upper-level ridge and west of an upper-level trof, one generally expects to find
- (a) sinking air in the mid-troposphere.
  - (b) ascending air in the mid-troposphere.
  - (c) no substantial vertical motion.
26. The geostrophic wind for a given pressure gradient as you approach the equator
- (a) increases.
  - (b) remains constant.
  - (c) decreases.
27. The dimensional unit of vorticity is
- (a) length per second.
  - (b) per second.
  - (c) per length.
  - (d) length squared per second.

28. As an air parcel moves from a ridge axis to a trough axis, its relative vorticity
- (a) becomes more cyclonic.
  - (b) becomes more anticyclonic.
  - (c) becomes more nondivergent.
  - (d) remains unchanged.
29. Given a temperature of  $20^{\circ}\text{C}$ , a dewpoint temperature of  $10^{\circ}\text{C}$ , and a pressure of 1000 mb, what is the relative humidity?
- (a) 10%
  - (b) 24%
  - (c) 40%
  - (d) 55%
  - (e) 70%
  - (f) 85%
  - (g) none of the above (give value)
30. For the above problem, calculate the wet bulb temperature.
- (a)  $10^{\circ}\text{C}$
  - (b)  $12^{\circ}\text{C}$
  - (c)  $14^{\circ}\text{C}$
  - (d)  $16^{\circ}\text{C}$
  - (e)  $18^{\circ}\text{C}$
  - (f)  $20^{\circ}\text{C}$
  - (g) none of the above (give value)
31. Which of the following atmospheric variables almost always increase with height in the middle and upper troposphere?
- (a) wet bulb temperature
  - (b) mixing ratio
  - (c) pressure
  - (d) temperature
  - (e) density
  - (f) potential temperature

32. The atmosphere is potentially unstable when

- (a)  $\gamma_d < \gamma < \gamma_m$
- (b)  $\gamma_m < \gamma < \gamma_d$
- (c)  $\frac{\partial \theta_E}{\partial z} > 0$
- (d)  $\frac{\partial \theta}{\partial z} > 0$
- (e)  $\frac{\partial \theta}{\partial z} < 0$

where  $\gamma$  is the environmental lapse rate,  $\gamma_m$  is the moist adiabat lapse rate,  $\gamma_d$  is the dry adiabat lapse rate,  $\theta$  is potential temperature, and  $\theta_E$  is the equivalent potential temperature.

33. The tops of cumulonimbus clouds are capable of rising higher than their level of neutral buoyancy because of

- (a) their high water content.
- (b) their excess temperature.
- (c) their low vertical wind shear.
- (d) their updraft inertia.

34. Virga is

- (a) falling precipitation which does not reach the ground.
- (b) an optical phenomena when the sun or moon shines through an ice cloud.
- (c) drifting dry snow.
- (d) a heavy shower of graupel.

35. Clouds which have glaciated tops and anvils and form when  $\partial \theta_E / \partial Z$  is less than zero are called

- (a) altostratus.
- (b) cirrocumulus.
- (c) nimbostratus.
- (d) stratocumulus.
- (e) cumulonimbus.
- (f) none of the above (give type).

36. An atmosphere in which a horizontal gradient of thickness exists is said to be
- (a) baroclinic.
  - (b) barotropic.
  - (c) conditionally unstable.
  - (d) conditionally stable.
  - (e) convectively unstable.
  - (f) hydrostatic.
  - (g) isothermal.
  - (h) none of the above.
37. If the horizontal pressure gradient near the surface is 4 mb per 200 km, the density of the air is  $1 \text{ kg m}^{-3}$  and the gravitational acceleration is estimated as  $10 \text{ m s}^{-2}$ , the horizontal gradient of the 1000 mb surface should be around
- (a) 0.4 m per 200 km.
  - (b) 1.0 m per 200 km.
  - (c) 4.0 m per 200 km.
  - (d) 10.0 m per 200 km.
  - (e) 40.0 m per 200 km.
  - (f) 100 m per 200 km.
  - (g) 400 m per 200 km.
  - (h) none of the above (give value).
38. Given that  $T = 10^\circ\text{C}$ ,  $p = 850 \text{ mb}$ , and  $T_D$  (the dewpoint) =  $0^\circ$ , calculate  $\theta_E$ .
- (a) 290 K
  - (b) 295 K
  - (c) 300 K
  - (d) 305 K
  - (e) 310 K
  - (f) none of the above (give value)

39. Given that the earth rotates once per day ( $2\pi/\text{day}$ ), calculate the Coriolis parameter at the equator and at the North Pole.

Equator

- (a) zero  $\text{sec}^{-1}$
- (b)  $1.45 \times 10^{-6} \text{ sec}^{-1}$
- (c)  $7.25 \times 10^{-6} \text{ sec}^{-1}$
- (d)  $1.45 \times 10^{-5} \text{ sec}^{-1}$
- (e)  $7.25 \times 10^{-5} \text{ sec}^{-1}$
- (f)  $1.45 \times 10^{-4} \text{ sec}^{-1}$
- (g) none of the above (give value)

North Pole

- (a) zero  $\text{sec}^{-1}$
- (b)  $1.45 \times 10^{-6} \text{ sec}^{-1}$
- (c)  $7.25 \times 10^{-6} \text{ sec}^{-1}$
- (d)  $1.45 \times 10^{-5} \text{ sec}^{-1}$
- (e)  $7.25 \times 10^{-5} \text{ sec}^{-1}$
- (f)  $1.45 \times 10^{-4} \text{ sec}^{-1}$
- (g) none of the above (give value)

40. Given that you are on an airplane flying at 200 mb and the outside temperature is  $-70^\circ\text{C}$ , calculate the temperature inside the plane if this air was drawn inside and compressed to 1000 mb.

T = \_\_\_\_\_  $^\circ\text{C}$  = \_\_\_\_\_  $^\circ\text{F}$



41. Given a westerly geostrophic wind of  $10 \text{ m s}^{-1}$  at 1000 mb, calculate the wind at 250 mb assuming a south to north 1000 mb - 250 mb thickness gradient of  $-120 \text{ m}$  per 100 km,  $f = 10^{-4} \text{ s}^{-1}$  and  $g = 10 \text{ m s}^{-2}$  (show work).

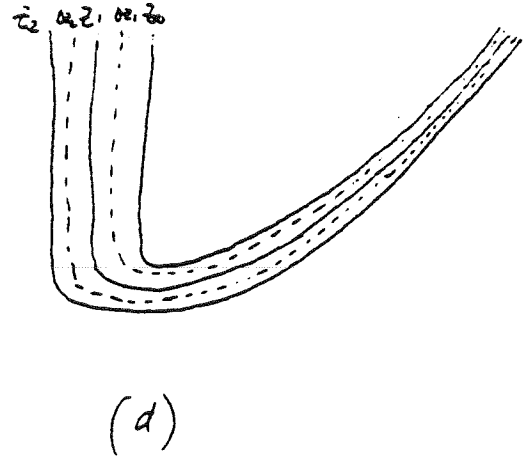
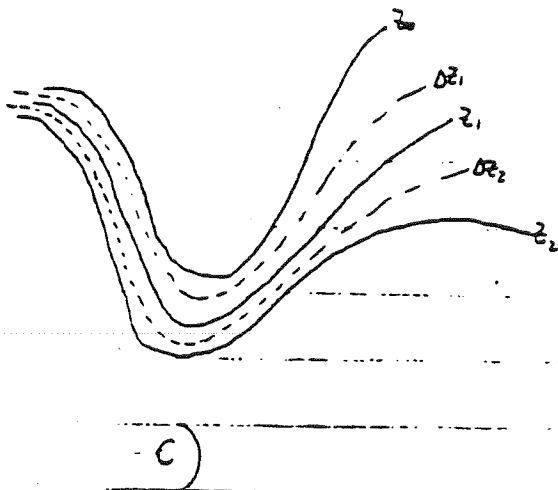
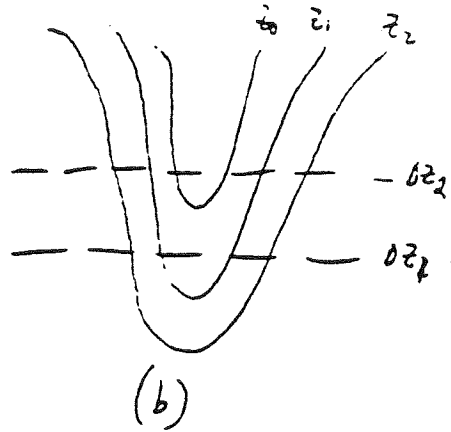
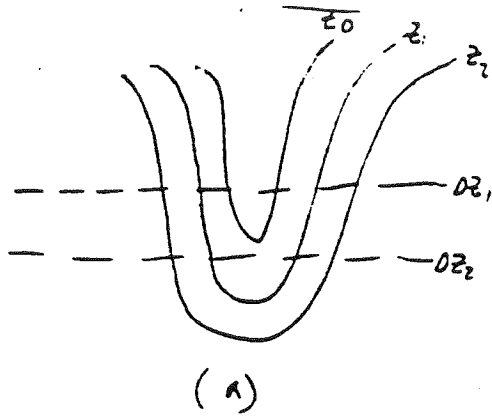
\_\_\_\_\_  $\text{m s}^{-1}$

42. You are driving a car in Fort Collins and the temperature outside is  $4^\circ\text{C}$  and the dewpoint is  $-8^\circ\text{C}$ . It begins to rain. Should you become concerned that the rain will turn to snow or not, and if the road will become icy? You must give a brief physical explanation for credit.

43. If you are standing outside and the wind is from the northwest, in what direction relative to you do you expect the low pressure system to be?

44. To approximately what height does the troposphere extend in the tropics?

45. Which of the synoptic-scale trofs below would be expected to be deepening over time. Assume gradient wind flow. Solid lines are 700 mb height and dashed lines are 1000-500 mb thickness values ( $\Delta z_2 > \Delta z_1$ ).



46. Given a 1000-500 mb rain-snow thickness of 5400 meters, the requirement that temperatures at the surface be less than  $5^{\circ}\text{C}$ , and a uniform lapse rate of (a)  $\partial T/\partial z = -1^{\circ}\text{C}/100\text{ m}$  and (b)  $\partial T/\partial z = -0.5^{\circ}\text{C}/100\text{ m}$ , calculate the elevation above sea level above which snow will occur. Assume a surface pressure of 1000 mb. Show your work.

(a)  $z_G = \underline{\hspace{10em}}$  meters

(b)  $z_G = \underline{\hspace{10em}}$  meters

47. Which of the following geographic locations has never been observed to have a tropical cyclone development? (Note: "southern" means south of the equator; "northern" means north of the equator.)

- (a) the western, northern tropical Atlantic
- (b) the western, southern tropical Atlantic
- (c) the western, northern tropical Pacific
- (d) the western, southern tropical Pacific
- (e) the southern tropical Indian Ocean
- (f) the northern tropical Indian Ocean
- (g) the eastern, northern tropical Pacific

48. Blackbody irradiance is proportional to

- (a) the first power of temperature.
- (b) the second power of temperature.
- (c) the third power of temperature.
- (d) the fourth power of temperature.
- (e) the fifth power of temperature.

49. The presence of a cloud cover tends to favor higher nighttime temperatures at the ground level because
- (a) it absorbs the infrared radiation from the ground and re-emits it downward.
  - (b) it releases heat of condensation which is transferred to the ground.
  - (c) conduction from the cloud layer to the ground cools the surface layer.
  - (d) stronger winds always occur with a cloud layer.
50. The "greenhouse" effect is an incorrect analogy to the manner in which longwave radiation tends to be trapped by the earth's atmosphere. Greenhouses are relatively hot compared to areas outside it primarily because
- (a) the glass is heated by electricity.
  - (b) the glass lets in solar heating but prevents heated air from rising and leaving the enclosure.
  - (c) the glass is made opaque to visible light.
  - (d) the glass is heated substantially by the sun and this heat is conducted into the greenhouse.
51. The earth is closer to the sun in
- (a) July
  - (b) September
  - (c) January
  - (d) March
  - (e) it is equidistant at all times.
52. Sleet occurs
- (a) when rain falls through a subfreezing layer near the ground and freezes into ice pellets.
  - (b) when wet snow, which is almost melted, strikes the ground.
  - (c) when rain is being converted into snowflakes.
  - (d) most frequently in thunderstorms.
  - (e) none of the above (state when it occurs).
53. The majority of carbon near the earth's surface is in
- (a) the atmosphere.
  - (b) the ocean.
  - (c) the biosphere.
  - (d) rocks.

54. When you emerge from a filled swimming pool, the temperature at your skin surface is approximately equal to the
- (a) dewpoint temperature.
  - (b) frost point temperature.
  - (c) wet bulb temperature.
  - (d) dry bulb temperature.
55. Green plants have that color because they
- (a) reflect visible colors but green.
  - (b) absorb visible colors but green.
  - (c) absorb as a blackbody.
  - (d) radiate as a blackbody.
  - (e) radiate with green the wavelength of maximum radiative energy.
56. Most deaths globally in hurricanes are caused by
- (a) debris blown by strong winds.
  - (b) the flooding of large rivers.
  - (c) flash floods.
  - (d) storm surge.
  - (e) tsunamis.
  - (f) other (give cause).
57. Number the sequence of formation of warm rain. Leave out those components that are involved solely with cold rain processes.
- condensational growth
  - aggregation
  - riming
  - melting
  - collision-coalescence
  - deposition
  - heterogeneous nucleation

58. What is the value of the latent heat of condensation in S.I. units?

59. What is the most abundant gas in the earth's atmosphere (give its chemical formula)?

60. Order air with the least number of aerosols to that air mass with the most.

continental

marine

urban polluted

61. Blue sky occurs because

(a) blue is preferentially scattered relative to other wavelengths.

(b) blue is preferentially absorbed relative to other wavelengths.

(c) blue is preferentially emitted by the sun relative to other wavelengths.

(d) blue is preferentially reflected from the earth's surface relative to other wavelengths.

62. Supercooled water has a temperature

(a) below  $0^{\circ}\text{C}$

(b)  $0^{\circ}\text{C}$

(c) between  $0^{\circ}$  and  $100^{\circ}\text{C}$

(d) above  $100^{\circ}\text{C}$

63. Of the following conditions, snowflake growth is greatest
- (a) when the temperature of the air is  $0^{\circ}\text{C}$  and the mixing ratio is highly supersaturated with respect to ice.
  - (b) when the temperature of the air is  $0^{\circ}\text{C}$  and the mixing ratio slightly supersaturated with respect to ice.
  - (c) when the temperature of the air is  $-15^{\circ}\text{C}$  and the mixing ratio is highly supersaturated with respect to ice.
  - (d) when the temperature of the air is  $-15^{\circ}\text{C}$  and the mixing ratio is slightly supersaturated with respect to ice.
64. The growth of ice crystals by the freezing of supercooled water on its surface is called
- (a) deposition.
  - (b) aggregation.
  - (c) riming.
  - (d) condensation.
  - (e) other (give answer).
65. Which of the following types of electromagnetic radiation has the shortest wavelength?
- (a) X-rays
  - (b) ultraviolet
  - (c) visible
  - (d) infrared
  - (e) microwave
66. The earth primarily radiates energy in the
- (a) X-rays wavelengths.
  - (b) ultraviolet wavelengths.
  - (c) visible wavelengths.
  - (d) infrared wavelengths.



**FINAL EXAM - AT 540 (Open Book)**

Fall 1994

For all questions that apply, assume  $1 \text{ knot} = 0.5 \text{ m s}^{-1}$ . If you find a question that you do not understand, just explain how you interpret it and then answer it that way.

**1. Define the acronyms listed below (11.5 pts)**

- (a) MRF
- (b) NGM
- (c) NMC
- (d) LFC
- (e) LCL
- (f) NWP
- (g) CCN
- (h) IN
- (i) AVN
- (j) CAT
- (k) RASS
- (l) CLASS
- (m) NOAA
- (n) NASA
- (o) GMT
- (p) ITCZ
- (q) QBO
- (r) RAFS
- (s) RDAS
- (t) MOS
- (u) PVA
- (v) L.I.
- (w) cP

**2. Given a 1000-500 mb thickness of 5520 m, calculate the mean layer temperature in degrees C. Show your work (5 points).**

3. Given a thermal wind in the 1000-500 mb layer of 100 knots, calculate the horizontal thickness gradient in units of meters per 100 kilometers. Assume a latitude of  $40^{\circ}\text{N}$ . Show your work (5 points).

For this problem, what is the horizontal gradient of the 100-500 mb layer mean temperature in units of  $^{\circ}\text{C}$  per 100 km? Show your work (3 points).

4. For a latitude of  $40^{\circ}\text{N}$  and east-west flow (without any north-south component), what is the absolute vertical vorticity associated with a 50 knot per 500 km horizontal wind shear. Show your work (5 points).

5. Given a pressure of 850 mb, a temperature of 30°C and a dewpoint temperature of 0°C, determine the following (4.5 points).
- the wet bulb temperature =
  - the saturation mixing ratio =
  - the mixing ratio =
  - the relative humidity =
  - $\theta$  =
  - $\theta_E$  =
  - $\theta_W$  =
  - the saturation vapor pressure =
  - the vapor pressure =
6. Which of the following journals are published by the American Meteorological Society (1 point).
- Boundary Layer Meteorology
  - Weather and Forecasting
  - Monthly Weather Review
  - Journal of Atmospheric Science
  - Atmospheric Environment
  - Quarterly Journal of the Royal Meteorological Society
7. An ensemble set of model output predictions is (give the one best answer based on current NMC NWP application) (2 points).
- a suite of predictive results in which slight changes to initial conditions are made.
  - a collection of model results which were initialized at different times.
  - a group of model results that have used different spatial resolution but the same starting time.
  - a selection of model results that use slightly different representations of topography.
8. Dynamic cloud seeding involves (2 points)
- the deliberate conversion of supercooled water to ice in a cumulus cloud using limited quantities of silver iodide in order to create a few large snow crystal which will precipitate.
  - the deliberate conversion of supercooled water to ice in a cumulus cloud, using large quantities of silver iodide, in order to release large quantities of latent heat of fusion from the numerous small ice crystals so as to enhance the buoyancy of the cloud.
  - same as (i) but for a stratiform cloud.
  - same as (ii) but for a stratiform cloud.
9. What is the 50% rain-snow 1000-500 mb thickness for Denver, Colorado (1 point).

10. At what electromagnetic wavelength is the atmosphere most opaque to radiation? Values are in microns (2 points).
- (a) 50 - 100
  - (b) 20 - 50
  - (c) 12.5 - 20
  - (d) 10 - 12.5
  - (e) 8 - 10
  - (f) 5 - 8
11. What is a realistic value for the albedo (for short-wave radiation) of fresh snow? (2 points)
- (a) 0.05
  - (b) 0.25
  - (c) 0.55
  - (d) 0.75
  - (e) 0.95
12. The adiabatic lapse rate is equal to \_\_\_\_\_( $^{\circ}\text{C}/\text{km}$ ). (2 points)
13. In units of  $10^{12}$  grams per year, the biological fixation of nitrogen between the atmosphere, and the ocean and land is about (2 points)
- (a) 30
  - (b) 110
  - (c) 190
  - (d) 270
  - (e) 350
14. The flux of carbon dioxide into the atmosphere due to fossil fuel combustion and deforestation is estimated to be (in units of  $10^{15}$  grams of carbon per year) about (2 points).
- (a) 7
  - (b) 14
  - (c) 21
  - (d) 28
  - (e) 35
15. The mesopause is at a height of around (1 point).
- (a) 20 km
  - (b) 40 km
  - (c) 60 km
  - (d) 80 km
  - (e) 100 km

16. Which of the following meteorological systems are active sensors? (2 points)
- (a) radar
  - (b) lidar
  - (c) RASS
  - (d) satellite IR images
  - (e) satellite visible images
17. The earth is closest to the sun in (1 point)
- (a) January
  - (b) March
  - (c) June
  - (d) September
18. In the Southern Hemisphere, the Coriolis "force" is (1 point)
- (a) at a 90° angle to the left of the wind.
  - (b) at a 90° angle to the right of the wind.
  - (c) in the same direction as the wind.
  - (d) in the direct opposite direction as the wind.
19. Snow that melts while falling but then refreezes in the subfreezing stable layer near the surface is called (1 point)
- (a) hail
  - (b) snow grains
  - (c) graupel
  - (d) sleet
20. At a supersaturation of 1%, the number of cloud condensation nuclei in non-urban continental air is on the order of (2 points)
- (a) 0.5 per  $\text{cm}^3$
  - (b) 5 per  $\text{cm}^3$
  - (c) 50 per  $\text{cm}^3$
  - (d) 500 per  $\text{cm}^3$
  - (e) 5000 per  $\text{cm}^3$
21. The collection of snowflakes as they fall is referred to as (1 point)
- (a) riming
  - (b) aggregation
  - (c) deposition
  - (d) contact nucleation
  - (e) graupel growth

22. The growth of an ice crystal at the expense of evaporation from water droplets is greatest at (2 points)
- (a)  $0^{\circ}\text{C}$
  - (b)  $-5^{\circ}\text{C}$
  - (c)  $-15^{\circ}\text{C}$
  - (d)  $-25^{\circ}\text{C}$
  - (e)  $-35^{\circ}\text{C}$
23. At a temperature of  $-10^{\circ}\text{C}$  and an ice supersaturation of 15%, the type of ice crystal that results is (2 points)
- (a) dendrites
  - (b) columns
  - (c) plates
  - (d) prisms
  - (e) needles
24. The passage of lightning through the air heats the atmosphere to values on the order of (1 point)
- (a) 300 K
  - (b) 3,000 K
  - (c) 30,000 K
  - (d) 300,000 K
  - (e) 3,000,000 K
25. The current value of the eccentricity of the earth's orbit is (1 point)
- (a) 0
  - (b) 0.008
  - (c) 0.016
  - (d) 0.024
  - (e) 0.032
  - (f) 0.040
26. According to the Trewartha and Horn climate categories, Colorado has what type of climate? (2 points)

27. Which of the following are units in the S.I system? (2 points)
- (a) meters
  - (b) joules
  - (c) ergs
  - (d) watts
  - (e) calories
  - (f) knots
  - (g) miles
  - (h) seconds
  - (i) °C
  - (j) newton
28. The new version of the Eta model has how many vertical levels operational in 1994? (1 point)
29. A T126 NMC spectral global model corresponds to what approximate equivalent spatial resolution? (2 points)
- \_\_\_\_\_ km
30. If a correctly forecast area of precipitation greater than 1 cm is 1000 km<sup>2</sup>, the forecast area of this amount is 2000 km<sup>2</sup> while the observed area is 3000 km<sup>2</sup>, what is the Threat Score? Show your work (2 points).
31. What is the bias in the last question? Show your work (2 points).

32. What type of cloud out of the following list would you expect if  $\partial\theta_E/\partial z > 0$ ?
- (a) cumulonimbus
  - (b) stratus
  - (c) cumulus congestus
  - (d) cumulus humulus
  - (e) altocumulus
33. If  $\Delta p = 10$  mb per 1000 kilometers, the latitude is  $40^\circ\text{S}$ , and the surface pressure is 1000 mb, what is the magnitude of the geostrophic wind? Show your work (2 points).
34. Which of the following are warm core atmospheric features? (2 points)
- (a) hurricane
  - (b) typhoon
  - (c) subtropical ridge
  - (d) polar high
  - (e) extratropical low
  - (f) warm front
  - (g) jet streaks
35. Extratropical cyclone development is described using what theoretical concept (choose the best answer)? (2 points)
- (a) Richardson number instability
  - (b) Kelvin-Helmholtz instability
  - (c) Baroclinic instability
  - (d) Barotropic instability
  - (e) Inertial instability
36. If the mean mixing ratio between the surface ( $z = 0$ ) and 5000 meters is  $2 \text{ g kg}^{-1}$ , and there is negligible water higher up, what is the precipitable water in cm? Assume a reasonable mean density for the layer between the surface and 5000 meters. Show your work (3 points).



37. Fort Collins is in what Colorado Zone Forecast Area (1 point)?

Good luck on the test and the remainder of your graduate work.

Roger A. Pielke, Fall 1994

**Exercise #7**  
**AT 540 WEATHER LAB**  
Fall 1995

Readings

1. Facsimile Products, pgs. 1-1 to 1-7, 2-1 to 2-24, and 8-43 to 8-75.
2. Anthes, R.A., 1983: Regional models of the atmosphere in middle latitudes (Review). *Mon. Wea. Rev.*, 1306-1335.
3. Guaraldi, J. and L.F. Bosart, 1985: An assessment of the skill of the NMC 6-10 temperature and precipitation outlook. *Bull. Amer. Meteor. Soc.*, **66**, 831-839.
4. Klein, W.H., 1982: Statistical weather forecasting on different time scales. *Bull. Amer. Meteor. Soc.*, 170-177.
5. Policy Statement of the American Meteorological Society on Weather Forecasting. *Bull. Amer. Meteor. Soc.*, August 1991 issue, 1273.

Assignment

1. Using GMPACK, obtain the surface, 700 mb, and 500 mb analyses for a specific time period. Contour the surface map for isobars at 4 mb intervals and insert fronts. Contour the 700 mb and 500 mb analyses at 30 m and 60 m intervals, respectively.
2. Obtain the Eta and NGM 12 hour, 24 hour, 36 hour, and 48 hour forecasts corresponding to the time analyzed in #1 for the surface, 700 mb, and 500 mb levels. Discuss the degree of agreement between the predictions and your analyses.
3. Obtain the MRF 72 and 84 hour 500 mb simulation corresponding to the time in your analysis. Discuss the degree of agreement between the predictions and your analysis.

Exercise #1 (Due Thursday September 7th)

AT 540 WEATHER LAB

Fall 1995

Reference Material (can be obtained from Dallas, Room 220)

1. Lecture notes – REQUIRED
2. “The use of the Skew T, Log P Diagram in Analysis and Forecasting.” Air Weather Service, pgs. 1-1 to 3-2 – Recommended (on reserve in library).

Exercise

1. Using the data provided to you, plot the Denver sounding for August 24th, 12z (0500 MST). Tabulate  $T$ ,  $T_D$ , wind speed and direction as a function of  $p$  and  $z$  as appropriate. Then plot on the thermodynamic diagram provided to you.

## MID-TERM EXAM - AT 540 (Open Book) Fall 1995

\*Note: If any question is unclear, write in your interpretation and then answer. Questions 1-37 are worth one point each. The remaining questions are as indicated.

1. In the Southern Hemisphere, the Coriolis "force" is
  - (a) at a  $90^\circ$  angle to the left of the wind.
  - (b) at a  $90^\circ$  angle to the right of the wind.
  - (c) in the same direction as the wind.
  - (d) in the direct opposite direction as the wind.
2. Snow that melts completely while falling but then refreezes in the subfreezing stable layer near the surface is called
  - (a) hail
  - (b) snow grains
  - (c) graupel
  - (d) sleet
3. The earth is closer to the sun in
  - (a) July
  - (b) September
  - (c) January
  - (d) March
  - (e) it is equidistant at all times
4. For an ideal gas, which of the following is the correct relationship between the specific heats at constant pressure and volume, and the gas constant?
  - (a)  $R = C_v + C_p$
  - (b)  $C_v = C_p + R$
  - (c)  $0 = R + C_v + C_p$
  - (d)  $C_p = C_v + R$
  - (e)  $R = C_v \times C_p$
  - (f) none of the above
5. Which of the atmospheric systems listed below are warm core.
  - (a) extratropical cyclones
  - (b) tropical cyclones
  - (c) subtropical ridge
  - (d) arctic high
  - (e) warm front
  - (f) anticyclone vorticity center
  - (g) thermal ridge
  - (h) jet stream

6. The dewpoint temperature of a parcel as it ascends

- (a) is constant with height
- (b) decreases slowly with height
- (c) increases slowly with height

7. Given that  $T = 10^\circ\text{C}$ ,  $p = 850$  mb, and  $T_D$  (the dewpoint)  $= 0^\circ$ , calculate  $\theta_E$ .

- (a) 290
- (b) 295
- (c) 300
- (d) 305
- (e) 310
- (f) none of the above (give value)

8. Given that the earth rotates once per day ( $2\pi/\text{day}$ ), calculate the Coriolis parameter at the equator and at the north pole.

Equator

- (a) zero  $\text{sec}^{-1}$
- (b)  $1.45 \times 10^{-6} \text{ sec}^{-1}$
- (c)  $7.255 \times 10^{-6} \text{ sec}^{-1}$
- (d)  $1.45 \times 10^{-5} \text{ sec}^{-1}$
- (e)  $7.25 \times 10^{-5} \text{ sec}^{-1}$
- (f)  $1.45 \times 10^{-4} \text{ sec}^{-1}$
- (g) none of the above (give value)

North Pole

- (a) zero  $\text{sec}^{-1}$
- (b)  $1.45 \times 10^{-6} \text{ sec}^{-1}$
- (c)  $7.25 \times 10^{-6} \text{ sec}^{-1}$
- (d)  $1.45 \times 10^{-5} \text{ sec}^{-1}$
- (e)  $7.25 \times 10^{-5} \text{ sec}^{-1}$
- (f)  $1.45 \times 10^{-4} \text{ sec}^{-1}$
- (g) none of the above (give value)

9. Given the radius of trajectory of an air parcel is 200 km, the Coriolis parameter is  $10^{-4}$ , and the wind speed is  $10 \text{ m s}^{-1}$ , calculate the centrifugal acceleration.

- (a)  $5 \times 10^{-4} \text{ m s}^{-2}$
- (b)  $5 \times 10^{-3} \text{ m s}^{-2}$
- (c)  $5 \times 10^{-2} \text{ m s}^{-2}$
- (d)  $5 \times 10^{-1} \text{ m s}^{-2}$
- (e)  $5 \text{ m s}^{-2}$
- (f) none of the above (give value)

10. Which of the following quantities are conserved with respect to the motion of dry air (i.e., air in which saturation does not occur)?
- (a)  $T$
  - (b)  $T_W$
  - (c) R.H.
  - (d)  $T_D$
  - (e)  $P$
  - (f)  $\theta$
  - (g)  $\theta_E$
11. Which of the following quantities are conserved with respect to the motion of saturated air.
- (a)  $T$
  - (b)  $T_W$
  - (c) R.H.
  - (d)  $T_D$
  - (e)  $P$
  - (f)  $\theta$
  - (g)  $\theta_E$
12. The tops of cumulonimbus clouds are capable of rising higher than their level of neutral buoyancy because of
- (a) their high water content
  - (b) their excess temperature
  - (c) their low vertical wind shear
  - (d) their inertia
13. Virga is
- (a) falling precipitation which does not reach the ground
  - (b) an optical phenomena when the sun or moon shines through an ice cloud
  - (c) drifting dry snow
  - (d) a heavy shower of graupel
14. An atmosphere in which a horizontal gradient of thickness exists is said to be
- (a) baroclinic
  - (b) barotropic
  - (c) conditionally unstable
  - (d) conditionally stable
  - (e) convectively unstable
  - (f) hydrostatic
  - (g) isothermal
  - (h) none of the above

15. As an air parcel moves from a ridge axis to a trough axis, its relative vorticity
- (a) becomes more cyclonic
  - (b) becomes more anticyclonic
  - (c) becomes more nondivergent
  - (d) remains unchanged
16. During the development of an extratropical cyclone, (one answer)
- (a) surface pressure rises in its center.
  - (b) there is midtropospheric descent east of its center ahead of the warm front.
  - (c) ageostrophic wind is convergent at low levels towards the low center.
  - (d) ageostrophic divergent upper level winds generate cyclonic relative vorticity which develops the trough downstream from the surface low center.
17. Given a temperature of  $20^{\circ}\text{C}$ , a dewpoint temperature of  $10^{\circ}\text{C}$ , and a pressure of 1000 mb, what is the relative humidity?
- (a) 10%
  - (b) 25%
  - (c) 40%
  - (d) 55%
  - (e) 70%
  - (f) 85%
  - (g) none of the above (give value)
18. For the above problem, calculate the wet bulb temperature.
- (a)  $10^{\circ}\text{C}$
  - (b)  $12^{\circ}\text{C}$
  - (c)  $14^{\circ}\text{C}$
  - (d)  $16^{\circ}\text{C}$
  - (e)  $18^{\circ}\text{C}$
  - (f)  $20^{\circ}\text{C}$
  - (g) none of the above (give value)
19. Which of the following atmospheric variables almost always increase with height in the middle and upper troposphere?
- (a) wet bulb temperature
  - (b) mixing ratio
  - (c) pressure
  - (d) temperature
  - (e) density
  - (f) potential temperature

20. The atmosphere is potentially unstable when

- (a)  $\gamma_d < \gamma < \gamma_m$
- (b)  $\gamma_m < \gamma < \gamma_d$
- (c)  $\frac{\partial \theta_E}{\partial z} > 0$
- (d)  $\frac{\partial \theta}{\partial z} > 0$
- (e)  $\frac{\partial \theta}{\partial z} < 0$

where  $\gamma$  is the environmental lapse rate,  $\gamma_m$  is the moist adiabatic lapse rate,  $\gamma_d$  is the dry adiabatic lapse rate,  $\theta$  is potential temperature, and  $\theta_E$  is the equivalent potential temperature.

21. The wet bulb temperature is

- (a) always equal to the dewpoint temperature
- (b) always greater than or equal to the dewpoint temperature but less than or equal to the temperature
- (c) always equal to or greater than the temperature
- (d) always equal to the potential temperature

22. A front at the surface moves in the direction of movement of

- (a) the warm air
- (b) the cold air
- (c) the 200 mb trough axis
- (d) the thermal wind maximum

23. Cold advection occurs when

- (a) the wind speed increases with height
- (b) the wind veers with height
- (c) the wind backs with height
- (d) the wind speed decreases with height

24. The symbol  $L$  represents

- (a) light rain
- (b) sleet
- (c) hail
- (d) drizzle
- (e) graupel

25. On an upper air analysis, a star at the base of a wind barb (or a star alone) indicates the data came from a (an)

- (a) aircraft
- (b) radiosonde
- (c) ship
- (d) satellite



26. The Omega equation is derived from the equation of motion plus (one answer)
- (a) the conservation law for water vapor
  - (b) the radiative flux divergence equation
  - (c) the first law of thermodynamics
  - (d) the incompressible continuity equation
27. East of an upper level ridge and west of an upper level trough one generally expects to find
- (a) sinking air in the midtroposphere
  - (b) ascending air in the midtroposphere
  - (c) no substantial vertical motion
28. Baroclinic instability at a given latitude and static stability becomes more likely
- (a) as the geostrophic wind shear increases
  - (b) as the geostrophic wind shear decreases
  - (c) the wavelength of the disturbance becomes less than several hundred kilometers
  - (d) in the spring season
29. The geostrophic wind for a given pressure gradient as you approach the equator
- (a) increases
  - (b) remains constant
  - (c) decreases
30. Vorticity is a measure of
- (a) wind strength
  - (b) circulation
  - (c) thermodynamic instability
  - (d) vertical wind shear
31. The dimensional units of vorticity is
- (a) length per second
  - (b) per second
  - (c) per length
  - (d) length squared per second
32. The vertical vorticity equation is derived by
- (a) differentiating the  $u$ -equation of motion by  $y$  and the  $v$ -equation by  $x$  and subtracting the second from the first.
  - (b) differentiating the  $u$ -equation of motion by  $x$  and the  $v$ -equation of motion by  $y$  and subtracting the second from the first.
  - (c) integrating the  $u$ -equation of motion with respect to  $y$  and the  $v$ -equation of motion with respect to  $x$  and subtracting the second from the first.
  - (d) integrating the  $u$ -equation of motion with respect to  $x$  and the  $v$ -equation of motion with respect to  $y$  and subtracting the second from the first.

33. Of the following, circle only the lapse rates (between 1000 mb to 900 mb and with a 1000 mb temperature of 30°C) which are convectively neutral or unstable.
- (a)  $\frac{\partial \theta}{\partial z} = 1^\circ\text{C}/1 \text{ km}$
  - (b)  $\frac{\partial \theta_w}{\partial z} = 1^\circ\text{C}/1 \text{ km}$
  - (c)  $\frac{\partial T}{\partial z} = -1^\circ\text{C}/\text{km}$
  - (d)  $\frac{\partial \theta_E}{\partial z} = -1^\circ\text{C}/1 \text{ km}$
34. Circle the assumptions involved in deriving the adiabatic lapse rate
- (a) hydrostatic relation
  - (b) 1st law of thermodynamics
  - (c) conservation of mass
  - (d) ideal gas law
  - (e) equation of motion
35. Which of the following cloud types is indicative of strong vertical mixing in the lower troposphere
- (a) cirrus
  - (b) cirrostratus
  - (c) altocumulus
  - (d) stratus
  - (e) cumulonimbus
  - (f) none of the above
36. The intensity of a front is most closely related to
- (a) the horizontal dew point gradient
  - (b) the intensity of the surface wind shift at frontal passage
  - (c) the vertical shear of the horizontal wind
  - (d) the magnitude of the pressure
  - (e) the strength of surface winds in the cold air behind the front
  - (f) none of the above
37. Assume that the layer between 500 and 1000 mb is isothermal.  $R$  is  $.287 \times 10^7 \text{ ergs g}^{-1} \text{ K}^{-1}$  while  $g = 10^3 \text{ cm s}^{-2}$  and  $\ln 2 = .69$ . What is the thickness if the temperature of the layer is 0°C (1st column) and if the temperature of the layer is 25°C (2nd column)?

4260 m	4172 m
4780 m	4830 m
5430 m	5420 m
5820 m	5928 m
6130 m	6520 m
none of the above	none of the above

38. What is the mathematical criterion for dynamic instability in straight line flow on the anticyclonic side of a jet stream? (2 pts)

39. Give representative (i.e., realistic) values of the following quantities. You must provide the correct dimensional units. (2 pts)

(a) relative vorticity on the synoptic scale \_\_\_\_\_

(b) Coriolis parameter at 40°N \_\_\_\_\_

(c) 1000-500 mb thickness at 30°N in the summer \_\_\_\_\_

(d) 200 mb wind speed in the center of the jet stream \_\_\_\_\_

(e) sea level maximum pressure associated with a *cP* high \_\_\_\_\_

40. Calculate the virtual temperature for a temperature of 35°C, a dewpoint temperature of 25°C, and a pressure of 1000 mb. Show your work. (1 pt)

$T_V$  \_\_\_\_\_ °C

41. If you are standing outside and the wind is from the northwest, in what direction relative to you do you expect the low pressure system to be? (1 pt)

42. You are driving a car and the temperature outside is  $4^{\circ}\text{C}$  and the dewpoint is  $-8^{\circ}\text{C}$ . It begins to rain. Should you become concerned that the rain will turn to snow or not, and if the road will become icy? You must give a brief physical explanation for credit. (2 pts)

43. Calculate the gradient wind speed and direction if the geostrophic wind is  $30\text{ m s}^{-1}$  from the west for

(a) a low center with a radius of curvature of 500 km

\_\_\_\_\_  $\text{m s}^{-1}$  from \_\_\_\_\_ $^{\circ}$

(b) a high center with a radius of curvature of 500 km

\_\_\_\_\_  $\text{m s}^{-1}$  from \_\_\_\_\_ $^{\circ}$

Show your work (2 pts)

44. For a 500-1000 mb thickness of 5700 meters, calculate the mean temperature in °C. If the surface temperature is 30°C, calculate a linear lapse rate consistent with this thickness, and the resultant 500 mb temperature. Show your work. (4 pts)

$$T = \underline{\hspace{2cm}} = \underline{\hspace{2cm}} \text{ } ^\circ\text{C}/\text{km} \quad T_{500 \text{ mb}} = \underline{\hspace{2cm}} \text{ } ^\circ\text{C}$$

45. Properly connect the left and right sides. (2 pts)

ITCZ	region of extremely low thickness
northeast trades	upper branch of Hadley cell
polar front	low level convergence of trade winds
arctic high	demarcation between tropical and polar origin air
subtropical jet	lower branch of Hadley cell

46. Given a parcel moving southward at  $10 \text{ m s}^{-1}$  with constant horizontal velocity shear and curvature of trajectory, calculate the change of the lapse rate as the parcel moves from  $50^\circ\text{N}$  to  $40^\circ\text{N}$ . Assume a beta-plane centered at  $40^\circ\text{N}$ , and an initial lapse rate of  $\left. \frac{\partial\theta}{\partial p} \right|_{50^\circ\text{N}} = 10^\circ\text{C}/100 \text{ mb}$ .

$$\left. \frac{\partial\theta}{\partial p} \right|_{40^\circ\text{N}} = \underline{\hspace{2cm}} \text{ } ^\circ\text{C}/\text{km}$$

Using this information, assuming  $w = 0$  at the ground, and the wind is a constant up to 100 mb above the surface, estimate vertical motion in  $\text{cm s}^{-1}$  at 300 mb above the surface.

$$w = \underline{\hspace{2cm}} \text{ cm s}^{-1} \text{ (4 pts)}$$

47. Relative geostrophic vorticity. Show that on a constant pressure surface with  $f$  being constant that:  
(4 pts)

$$\zeta_g = \hat{k} \cdot \nabla \times \vec{v}_g = \frac{g}{f} \nabla_p^2 z = \frac{g}{f} \left( \frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2} \right).$$

48. What is the dimension of  $g/C_p$  where  $g$  is the gravitational acceleration and  $C_p$  is the specific heat at constant pressure? Show work. (1 pt)

49. Match the name of the wind with the balance of forces which are involved in its definition. (2 pts)

- |               |  |
|---------------|--|
| gradient      | pressure gradient; Coriolis                        |
| geostrophic   | pressure gradient; Coriolis, centrifugal           |
| cyclostrophic | pressure gradient; centrifugal                     |
| friction      | pressure gradient; Coriolis; centrifugal; friction |

50. Convert the quantities listed below to S.I. units (1 pt)

10 miles hour<sup>-1</sup> = \_\_\_\_\_ m s<sup>-1</sup>

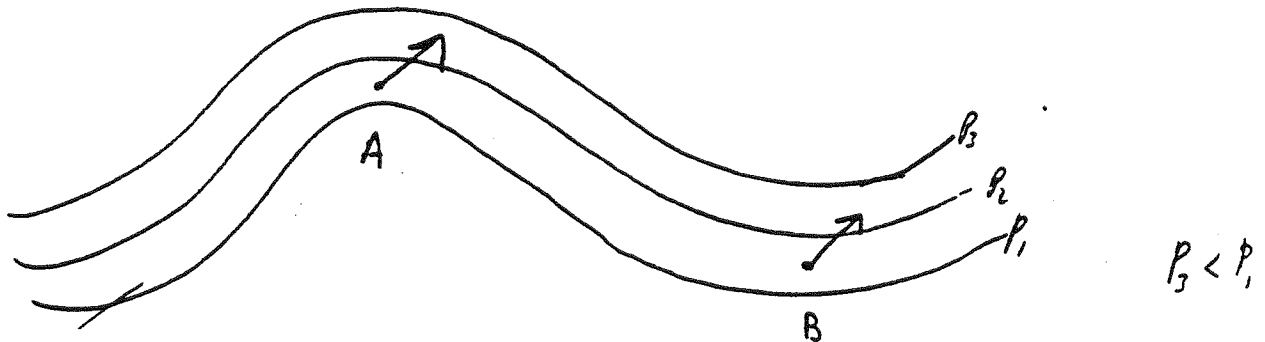
20°F = \_\_\_\_\_ °C = \_\_\_\_\_ K

80°F = \_\_\_\_\_ °C = \_\_\_\_\_ K

51. Given that you are on an airplane flying at 200 mb and the outside temperature is -70°C, calculate the temperature inside the plane if this air was drawn inside and compressed to 1000 mb (show work). (1 pt)

T = \_\_\_\_\_ °C = \_\_\_\_\_ °F

52. Given the pressure distribution below, draw a balance of forces that would result in a non-accelerating wind velocity at points A and B. (4 pts)

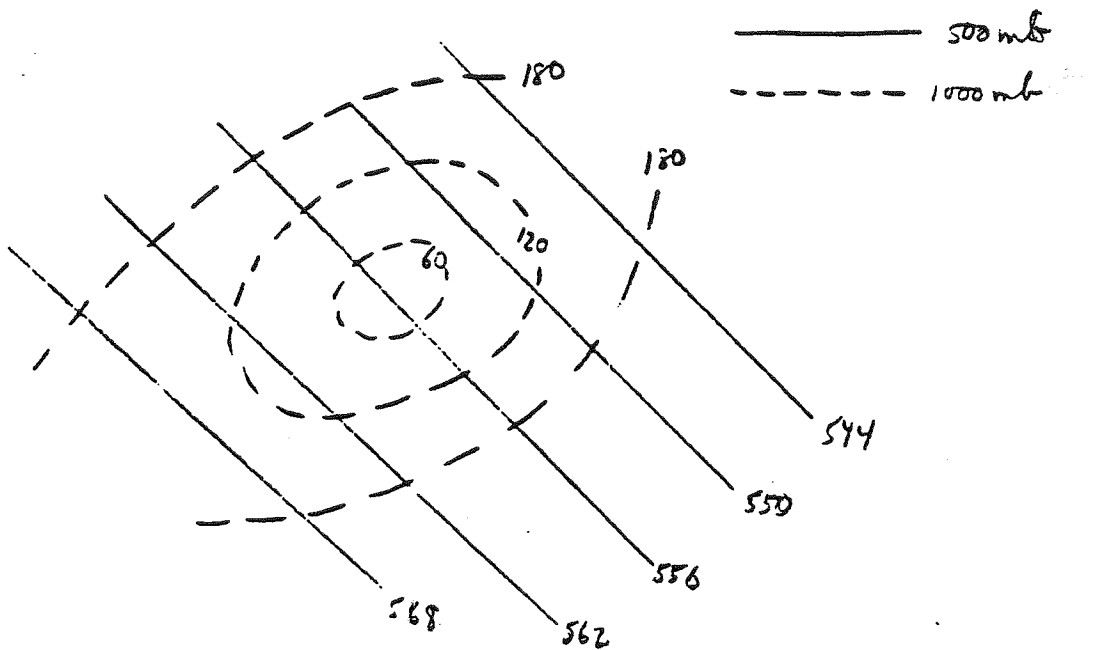


53. Plot the 500 mb station model for the following observations at a location of  $40^{\circ}\text{N}$ . Temperature =  $-25^{\circ}\text{C}$ ; dew point temperature =  $-29^{\circ}\text{C}$ ; wind = 35 knots from the south; a height of 5320 meters; and a 12 hour height change of minus 120 meters. (1 pt)

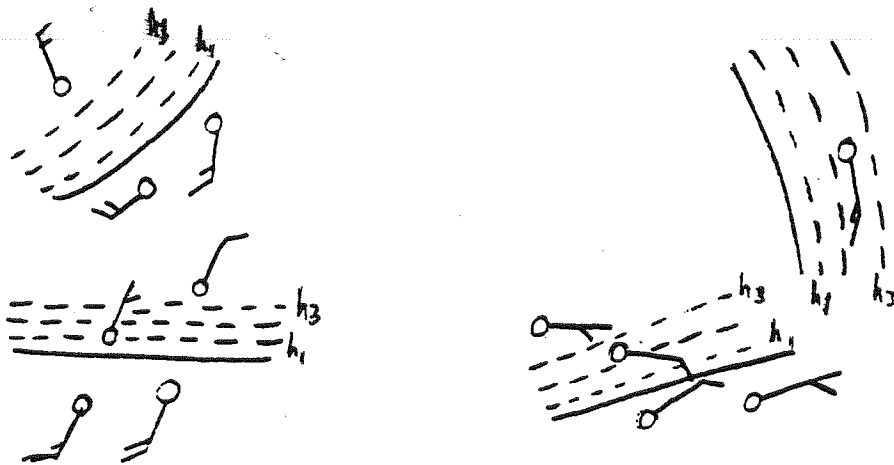
54. Plot the surface station model for the following observations at a location at  $40^{\circ}\text{N}$ . Temperature =  $80^{\circ}\text{F}$ ; dew point temperature =  $70^{\circ}\text{F}$ ; visibility = 5 miles; wind = 10 knots from the southeast; obscured, light thunderstorms; mean sea level pressure = 1020 mb; pressure falling and then steady over the past 3 hours; pressure change is minus 0.3 mb. (1 pt)



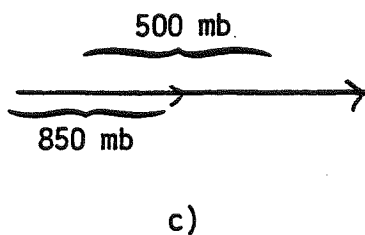
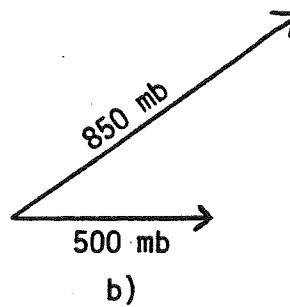
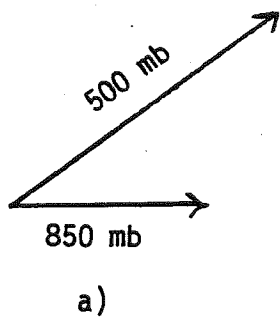
55. Sketched below are the heights of a 1000 mb and 500 mb pressure surface. Draw in and label in decameters the values of the thickness (contours at 60 m intervals). (2 pts)



56. Indicate by an arrow the direction towards which the front would be expected to move given the surface wind pattern indicated by the station model. Indicate the type of front. The values  $h_1, h_2, \dots$  are lines of constant thickness where  $h_1 > h_2 > h_3$  etc. (2 pts)



57. Given the 850 mb to 500 mb geostrophic wind changes drawn below, calculate the thickness gradient, and equivalent layer-mean temperature gradients. Draw the orientation of the lines of constant thickness. Indicate whether cold, neutral, or warm advection is occurring and indicate the direction of the horizontal temperature gradient. The magnitude of the wind at 850 mb in a) is  $20 \text{ m s}^{-1}$  (this provides you the scale of the vectors). (6 pts)



- a)  $\frac{\nabla_p(\Delta z)}{\quad}$   $\frac{\nabla_p \bar{T}}{\quad}$
- b)
- c)

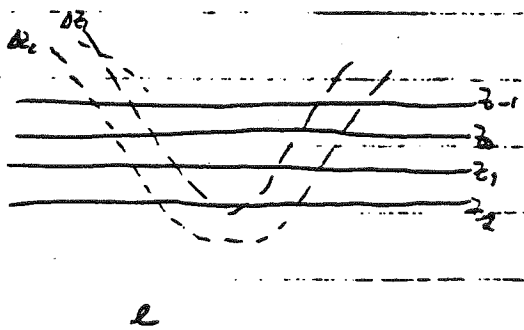
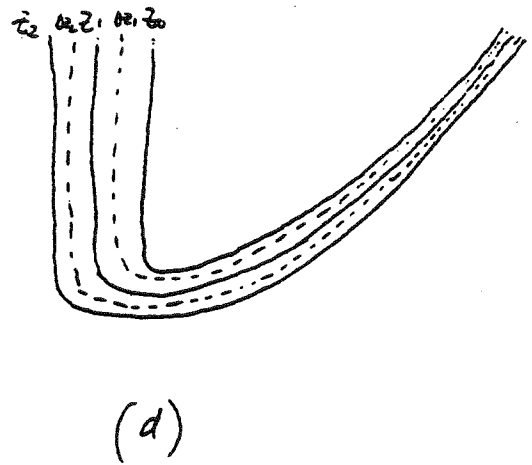
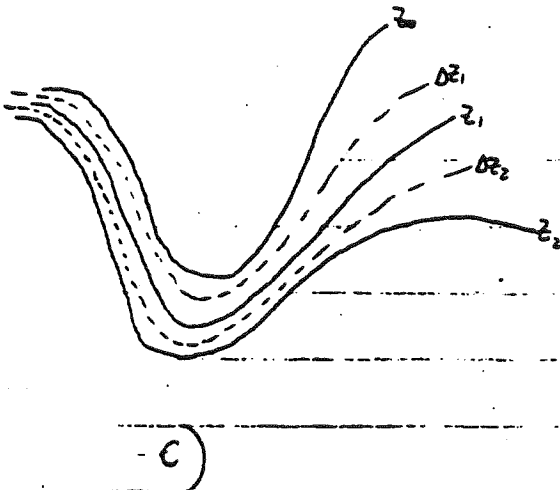
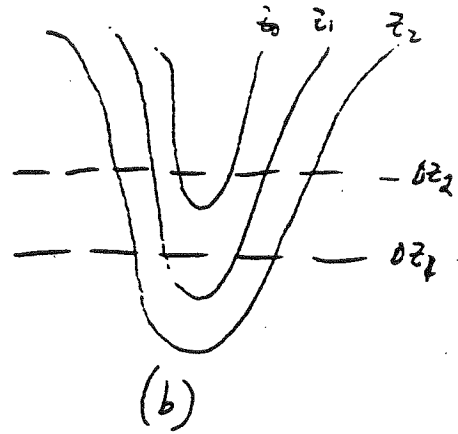
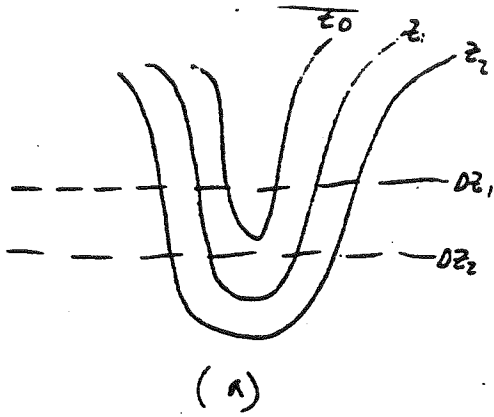
58. Given the attached 700 mb analysis, calculate the following at point  $\oplus$  B. Show work. (2 pts)

geostrophic wind speed

geostrophic wind direction

temperature advection (use geostrophic wind)

59. Which of the synoptic-scale trofs below would be expected to be deepening over time. Assume gradient wind flow. Solid lines are 700 mb height and dashed lines are 1000-500 mb thickness values.  $\Delta Z_1 < \Delta Z_2$ .  $Z_0 < Z_1$ . (2 pts)



60. Given the figures below, write in the letter of the definition which most closely relates the two. (2 pts)

inactive cold front

active cold front

cold occlusion

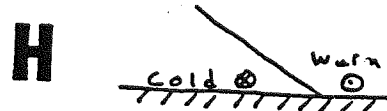
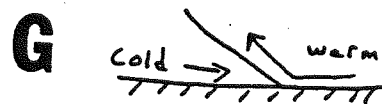
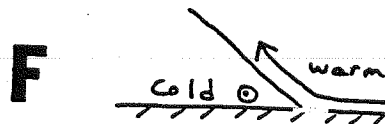
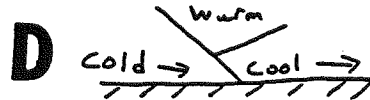
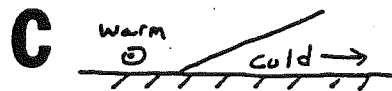
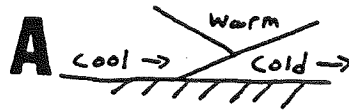
warm occlusion

inactive warm front

active warm front

inactive stationary front

active stationary front



AT 540 Final Exam - Open Book

Fall 1995

Answers should be concise. Points will be taken off for poorly written (i.e., verbose) answers. Total points - 68

1. If the mean 1000-500 mb temperature was  $0^{\circ}\text{C}$ , what is the thickness of the 1000-500 mb layer (show work)?  
\_\_\_\_\_meters

What assumptions were used in obtaining this answer (i.e., in the derivation of the thickness equation and in the calculation of the thickness) (4 pts).

2. What is the thermodynamic condition for a potentially unstable lapse rate? (1 pt)

3. Describe the synoptic situation in which the gradient wind is less than the geostrophic wind (2 pts).

4. Write out the definition of the geostrophic wind in the coordinate system where potential temperature is the vertical coordinate (2 pts).

5. What is the mathematical criteria for inertial instability? Where does this concept apply in synoptic meteorology? (2 pts)
  
6. What is a necessary condition for a synoptic-scale front? (2 pts)
  
7. Briefly describe the concept of baroclinic instability and how this is relevant in synoptic meteorology (2 pts).
  
8. What is a realistic height above sea level of the tropopause over Fort Collins in the fall? (1 pt)
  
9. For a wind along a surface of potential temperature of  $50 \text{ m s}^{-1}$  and a slope of that surface in the direction of the wind of 100 meters per 100 kilometers, what is the vertical motion? (1 pt)
  
10. What is the reason that virtual temperature has been defined? (1 pt)
  
11. Write out the expression for horizontal water vapor flux in the layer from the ground surface to the tropopause (4 pts).

12. Write out the meaning of the acronyms and abbreviations listed below (4 pts).

(a) MOS

(b) NGM

(c) NMC

(d) LFM

(e) MRF

(f) ASOS

(g) ACARS



(h) WSR-88D

(i) WSFO

(j) CYS

(k) FAI

(l) GTJ

(m) MSL

(n) PVA

(o) mT

(p) GEMPAK

(q) NWS

(r) NOAA

(s) LCL

(t) LFC

(u) MCL

(v) PV

(w) ECMWF

(x) CAPE

13. What is the 50% chance rain-snow thickness for Denver? (1 pt)
  
14. In words, describe what an occluded front is (2 pts).
  
15. Discuss briefly what cold air damming is, and why it is relevant for weather along the Colorado Front Range (2 pts).
  
16. What is meant by model resolution? What is the resolution of the ETA model and the MRF model? (4 pts)
  
17. Why is pressure used as the vertical coordinate in a synoptic analyses (e.g., the 850 mb; 700 mb; etc.)? (2 pts)
  
18. What is the mathematical definition of warm advection? (define terms; 1 pt)

19. What is the mathematical definition of positive vorticity advection? (define terms; 1 pt)
20. What is the mathematical definition of (i) curvature vorticity and (ii) shear vorticity? (define terms; 1 pt)
21. What is the mathematical relation between geostrophic vorticity and the height field? (define terms; 1 pt)
22. What is the isallobaric wind? (1 pt)
- 
23. What is the thermal wind? What assumptions are used in its derivation? How is the thermal wind related to the thickness between pressure surfaces? (4 pts)
24. What is the distance in kilometers of one degree of latitude? (1 pt)
25. What is the difference between a streamline and a trajectory? (1 pt)

26. What is meant by a warm core synoptic feature? Give two examples of a synoptic warm core system ( 1 pt).
27. On the synoptic scale, which surface better represents the movement of an air parcel? Why? When would this better representation be inaccurate? [coordinate surface:  $Z$ ,  $p$ ,  $\theta$ ,  $\sigma_p$ ] (4 pts)
28. What is the moist adiabatic lapse rate at 850 mb for a temperature of 25°C? (2 pts)
29. What is the dewpoint temperature? How is it related to the wet bulb temperature? (2 pt)
30. Provide typical (i.e., normal) values for Fort Collins in the fall of the following: (Use S.I. Units; 3 pts).
- (a) 500 mb temperature
  - (b) 700 mb temperature
  - (c) 1000-500 mb thickness

(d) 200 mb wind speed and direction

(e) 500 mb height

(f) 700 mb height

31. Define (i) potential vorticity, (ii) absolute vorticity, and (iii) relative vorticity (1 pt).

32. Define diabatic heating (1 pt).

33. What Colorado zone (for the NWS) is Fort Collins in? (1 pt)

34. List out 5 places on the World Wide Web that you have accessed weather information (4 pts).

35. Briefly discuss Q-vectors and how they are used in synoptic meteorology (1 pt).

BONUS: Forecast the 1 p.m. temperature at DIA on Friday, December 15th. If you are equal or closer than my forecast, you will receive 5% added to your final exam grade.

## Exercise #1

AT 540

Fall 1997

### Reference Material (due Sept. 9, 1997)

1. Lecture notes – REQUIRED
2. “The use of the Skew T, Log P Diagram in Analysis and Forecasting.” Air Weather Service, pgs. 1-1 to 3-2. Recommended

Exercise Plot the Denver, Grand Junction and Tampa, Florida thermodynamic soundings on the thermodynamic paper that is provided. This includes temperature and dew point temperature as a function of pressure, and wind speed and direction as a function of height. Use the plotting wind barb format described in the notes. Use solid red lines to connect the temperature points and dashed red lines to connect the dew point temperatures.



Exercise #2  
AT 540  
(due September 23rd)  
Fall 1997

Recommended "The Use of the Skew T, Log P Diagram in Analysis and Forecasting." Air Weather Service. Pgs. 4-1 to 4-19; Required Lecture notes. Assignment

1. Using each of the sounding plotted in Lab Exercise #1, compute:
  - (a) mixing ration -  $w$
  - (b) saturation mixing ration -  $w_s$
  - (c) relative humidity -  $R.H.$
  - (d) vapor pressure -  $e$
  - (e) saturation vapor pressure -  $e_s$
  - (f) potential temperature -  $\theta$
  - (g) wet-bulb potential temperature -  $\theta_w$
  - (h) equivalent temperature -  $T_e$
  - (i) virtual temperature -  $T_v$
  - (j) tropopause at 1000 mb for Tampa, 800 mb, 700 mb, 500 mb, 200 mb
2. Compute from surface values, or other values as necessary.
  - (a) convection condensation level -  $CCL$
  - (b) convection temperature -  $T_c$
  - (c) lifting condensation level -  $LCL$
  - (d) mixing condensation level -  $MCL$
  - (e) level of free convection -  $LFC$
  - (f) equilibrium level -  $EL$
  - (g) heights and pressure depth of layers of positive buoyancy -  $p_i, p_i + 1, \Delta p$
  - (h) K index -  $KI$
  - (i) Lifted Index -  $LI$

### Exercise #3

AT 540

Due +3 weeks

Fall 1997

Recommend Facsimile Products. National Weather Service, pgs. 6-39 to 6-55.

Required Lecture notes, Chapter 3.

#### Assignment

1. Using the three soundings that you obtained for the Lab Exercise #1
  - (a) obtain the reported 700 mb, 500 mb, 300 mb and 200 mb heights
  - (b) use the temperatures in the sounding information to calculate the 500 mb, 300 mb and 200 mb heights starting from the 700 mb is known. Compare with heights given in the sounding.
2. Use the appropriate station model and plot on a blank sheet of paper the surface, 700 mb, 500 mb, 300 mb and 200 mb observation for each of the three soundings in #1.
3. Use the map with station information provided to you to plot the 700 mb, 500 mb and 200 mb fields over the United States
  - (a) contour by hand the
    - i. heights (60 m intervals)
    - ii. temperature (5° C intervals)
    - iii. dew point temperature (5°C intervals)
  - (b) use graphical subtraction to obtain the 700 mb - 500 mb thickness at 60 m intervals.
  - (c) use the plotted 700 mb - 500 mb thickness, and contour this field and compare with (b).
4. On your 700 mb analyses, color in red areas of temperature advection greater than 10°/hour; color in blue areas of temperature advection less than -10°/hour.
5. Draw the 500 mb and 700 mb winds in a vector format. Superimpose the winds and calculate the wind shear between these two layers. Contour the wind shear by drawing lines parallel to the wind shear vectors. Compare this result with the thickness calculation performed in #3(b). For Denver and Seattle, compute the thickness gradient from this analysis and from the thickness analysis in #3.

You will need tracing paper to perform these analyses.

## Exercise #4

AT 540

Due +4 weeks

Fall 1997

Required Lecture Notes (Chapter 5)

### Assignment

1. Obtain the plotted surface observations over the contiguous U.S.
  2. Analyze the
    - (a) isobaric field at 4 mb intervals
    - (b) temperature field at 10°C intervals
    - (c) dew point temperature field at 10°C intervals
    - (d) frontal locations (justify on a separate sheet of paper)
  3. Calculate the geostrophic and gradient winds at Denver. Compare with the observed surface and 700 mb winds. Also calculate the 500-700 mb thermal wind for Denver. Compare with the horizontal near temperature gradient in the 500-700 mb layer over Denver, and compare to the horizontal gradient calculated using the thermal wind.
  4. Use the surface field to infer what the vorticity and temperature advection patterns and diabatic heating terms are at Washington, D.C.
  5. Label synoptic categories on your surface map (use tracing paper if you wish).
-

## Exercise #5

AT 540

Due +5 weeks

Fall 1997

Recommended Cahir, J.J. *et al.*, 1976: New tools for forecasters: real-time cross sections produced in field. *BAMS*, 1426-1433.

Required Lecture notes (Chapter 3).

### Assignment

Obtain sounding analyses for the cross section given in class which are

- parallel to the general flow
- perpendicular to the general flow

Using the stations along each cross section, your thermodynamic diagrams and tracing paper:

- plot and contour  $\theta$  and  $\theta_E$  at 5° C intervals for each cross section. Use separate sheets for  $\theta$  and  $\theta_E$ .
- calculate and contour relative humidity intervals of 10%, 30%, 50%, 70%, and 90%. Shade in green, values of relative humidity greater than 70%.
- use your  $\theta$  analysis where R.H. < 70%, and your  $\theta_e$  analysis where R.H.  $\geq$  70% to compute trajectory lines on a separate sheet of tracing paper.
- superimpose the observed winds on your analysis and evaluate vertical velocity at those locations using the adiabatic method. Contour in red, areas of vertical motion greater than 1 cm s<sup>-1</sup> and in blue areas less than -1 cm s<sup>-1</sup>.

## Exercise #6

AT 540

Due December 2, 1997

Fall 1997

### Readings(on reserve)

- Bader et al., 1995: *Images in Weather Forecasting*, University Press, Cambridge, 499 pgs.

#### 1. Recommended

Assignment Select from the World Wide Web, and hard copy output

1. a hemispheric image
2. a western U.S. sector
3. a Colorado image

of your choice and interpret the major cloud and clear air features in terms of our discussion of weather patterns in class. Write up your discussion and attach relevant synoptic analyses.

**Exercise #7**  
(Revised)

**AT 540**  
NWP Models and MOS  
Due December 4th

Fall 1997

Additional Readings; see also previous reading assignments on models

1. Guaraldi, J. and L.F. Bosart, 1985: An assessment of the skill of the NMC 6-10 temperature and precipitation outlook. *Bull. Amer. Meteor. Soc.*, 66, 831-839.
2. Klein, W.H., 1982: Statistical weather forecasting on different time scales. *Bull. Amer. Meteor. Soc.*, 170-177.
3. Bosart, L.F., 1981: A preliminary assessment of the state of the art of thunderstorm probability forecasting. *Bull. Amer. Meteor. Soc.*, 62, 790-792.
4. Charba, J.P. and W.H. Klein, 1980: Skill in precipitation forecasting in the National Weather Service. *Bull. Amer. Meteor. Soc.*, 61, 1546-1555.
5. Policy Statement of the American Meteorological Society on Weather Forecasting. *Bull. Amer. Meteor. Soc.*, 1385-1387. Also see <http://www.ametsoc.org/AMS/policy/weaforc.html>.

Assignment

1. Obtain xeroxes of the surface, 700 mb, and 500 mb analyses for a specific time period from the map board.
2. Obtain the Eta or NGM 12 hour, 24 hour, 36 hour, and 48 hour forecasts corresponding to the time analyzed in #1 for the surface, 700 mb, and 500 mb levels. Discuss the degree of agreement between the predictions and your analyses.
3. Obtain the MRF 72 hour, 84 hour, and 10 day 500 mb simulation corresponding time in your analysis. Discuss the degree of agreement between the predictions and your analysis.

If you use the Web, and complete this exercise for upcoming weather, it may be easier for you to obtain the needed data.

## Exercise #8

Revised

AT 540

Fall 1997

Due December 4th

### Readings

1. <http://geowww.gcn.uoknor.edu/WWW/Mesonet/Mesonet.html>
2. Browning, K.A., 1982: *Nowcasting*, pgs. 149-166 and 207-221.

### Assignment

- Obtain the Grand Junction (GTJ) Sounding for a situation with westerly 700 mb flow. Lift the GTJ sounding to 2.7 km above GTJ. Assume that the entire sounding lifts uniformly. Then descend the sound assuming:
  1. 0% rainout
  2. 20% rainout
  3. 50% rainout
  4. 100% rainout

and compare with the Denver sounding (DEN). If the precipitation is dropped out uniformly over a 100 km distance, what would be the amount of precipitation at the surface per unit area?

**AT 540 Midterm**

Fall 1997

(open book)

(2 hour time period)

1. Given a westerly geostrophic wind of  $10 \text{ m s}^{-1}$  at 700 mb, a 700 mb height of 3000 meters, a westerly geostrophic wind of  $30 \text{ m s}^{-1}$  at 500 mb, a 500 mb height of 5700 meters, compute (showing work):

(a) the horizontal gradient of 500-700 mb mean temperature (magnitude and direction)

(b) the 500-700 mb mean temperature

(c) the horizontal mean temperature advection in this layer



2. Given a temperature of  $20^{\circ}\text{C}$ , a dewpoint temperature of  $15^{\circ}\text{C}$ , and an atmospheric pressure of 850 mb, what is the virtual temperature (show work).

3. Which of the trofs plotted below would deepen as a result of westerly momentum input/output. Plotted are 500 mb heights.

4. What determines the differences between cumuliform and stratiform clouds?

5. Plot on the surface station model:  $T = 5^{\circ}\text{C}$ ,  $T_D = 2^{\circ}\text{C}$ ,  $p = 1000$  mb, winds 10 knots from the southeast, the pressure change over the last 6 hours was  $-3$  mb, the sky is overcast and light rain is falling.

6. Plot the station model at 500 mb for  $T = -10^{\circ}\text{C}$ ,  $T_D = -14^{\circ}\text{C}$ , a wind of 50 knots from the southwest, a height of 5810 meters with a change of  $-30$  meters over the last 12 hours.

7. Define the following acronyms

- CAPE

- LCL

- MCL

- PVA

- $\omega$

- CIN

- NGM

- MRF

- LFC

8. Discuss briefly what is the jet streak entrance and exit region, and what can be inferred related to vertical motion. Sketch if you would like.

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9. If the north-south velocity gradient is  $10 \text{ m s}^{-1}$  per 100 km, what is the absolute vorticity at  $40^\circ\text{N}$ ?

10. Show mathematically how geostrophic vorticity can be expressed as a curvature of the height field. What curvature in the height field and what horizontal shear in the geostrophic wind is required to produce a relative vorticity of  $10^{-4}\text{s}^{-1}$ ?

11. If  $T = 20^\circ\text{C}$ ,  $T_D = 10^\circ\text{C}$ , and  $p = 700 \text{ mb}$ , what are

- $\theta$

- $\theta_E$

- $\theta_w$

- $T_w$

- $w$

- $w_s$

- R.H.

- LCL (from this height)

12. Provide realistic (October) values for Fort Collins for the following.

- 500 mb height

- 500 mb temperature
- 500 mb wind
- 1000-500 mb thickness
- 1000-500 mb thickness gradient
- tropopause height
- absolute vorticity

BONUS: Forecast the 1 p.m. temperature at DIA tomorrow. If you are equal or closer than my forecast, you will receive 5% added to your midterm grade.

Good Luck!

R.A. Pielke

FINAL EXAM - AT540  
FALL 1997 (Open Book - 39 pts)

1. Of the plots of 500 mb heights and 1000-500 mb thickness, which example would be most likely to result in strongest surface cyclogenesis (4 pts)?

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2. Of the contours of 500 mb heights drawn below, which example has the largest relative vorticity (4 pts)?

3. Of the soundings schematically illustrated below, which has the greatest CAPE (4 pts)?

4. Of the following values of temperature ( $T$ ), pressure ( $P$ ), and dewpoint temperature ( $T_D$ ), which one has the highest value of  $\theta_e$  (2 pts)?

	$T(^{\circ}\text{C})$	$P$ (mb)	$T_D$ ( $^{\circ}\text{C}$ )
(i)	20	850 mb	0
(ii)	10	700 mb	0
(iii)	25	850 mb	5
(iv)	15	700 mb	5
(v)	5	500 mb	5

5. Write a mathematical expression for how the geostrophic wind changes as a function of latitude assuming the same gradient of height on a pressure surface (hint -  $f = 2\Omega \sin \theta$ ) (2 pts).



6. Define the following (1/6 pt each).

(a) CIN

(b) NOGAPS

(c) MRF

(d) CAPE

(e) 12 GMT (also give what this corresponds to in terms of Colorado time)

(f) ECMWF

(g) NGM

(h) PVA

(i)  $w$

(j)  $\Omega$

(k) Eta

(l) tephigram

7. Give representative values of the following for Fort Collins (1/8 pt each).

(a)  $f$

(b) absolute vorticity

(c) maximum wind speed at 200 mb

(d) maximum temperature at 500 mb

(e) maximum value of CAPE

(f) tropopause

(g) rain-snow 1000-500 mb thickness

(h) maximum value of precipitable water

8. Given the schematic surface weather map drawn below, identify (4 pts).
- (a) with an "A" where the greatest PVA and warm advection would be expected.
  - (b) with a "B" where NVA but warm advection is likely to result in cloudy, but non-precipitating weather.
  - (c) with a "C" where clear, cool skies with light winds are expected.
  - (d) with a "D" where atmospheric dispersion is best.

9. On the cross section shown below, assume all wind is in the plane of the figure, and is constant everywhere in the figure. Assume the air is unsaturated. Circle where the strongest ascent would be. With a uniform wind of  $50 \text{ m s}^{-1}$ , what is the value of the ascent (4 pts)?

10. Use the equations in the notes to show why the thermal wind is parallel to the thickness contours (2 pts).
11. Given the satellite image shown in class, what weather feature have I asked you to identify (2 pts)?
12. What are your two most useful weather web sites (2 pts)?
13. Which of the following weather features are warm-core? Circle all that apply (2 pts).
- hurricane
  - thermal low
  - nor'easter
  - subtropical ridge
  - polar high

14. Draw a cross section of an active warm front (4 pts).

Bonus: Forecast the temperature for 1 p.m. tomorrow at DIA; (If you are equal or are better than my forecast, I will add 5% to your exam grade!)

Good luck on the test!

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