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NUMERICAL MODEL EVALUATION OF THE EXTENSION OF THE CRITICAL DIVIDING STREAMLINE HYPOTHESIS TO MESOSCALE TWO-DIMENSIONAL TERRAIN

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Abstract—A two-dimensional nonlinear numerical model is used to study the extension of the critical dividing streamline hypothesis to larger scale terrain than considered in most previous observational studies. Upstream blocking in the absence of thermal forcing is found to be reasonably well described for air quality assessment purposes by the critical dividing streamline hypothesis. The effect of rotation (i.e. the Coriolis force) is to decrease the extent of blocking in marginal cases. Influence of the Coriolis force is expected to increase as the length scale of the topography increases.

It is also found that thermally induced nocturnal slope winds may compromise the dividing streamline hypothesis as a result of their entrainment mass flux. We suggest that slope flows have not played a substantial role in previous tracer studies over small-scale terrain due to the dependence of slope flows on length scale and ambient thermal stratification. Tracer studies around mesoscale terrain would help to clarify the importance of rotational and diabatic effects.

Key word index: Air pollution, dividing streamline, mountain meteorology, numerical modeling, upwind stagnation.

1. INTRODUCTION

The need for air quality models appropriate for use in complex terrain is increasingly recognized. The Complex Terrain Model Development program of the U.S. Environmental Protection Agency is pursuing the development of these models as next-generation air quality assessment tools (Schiermeier, 1984; Egan, 1984). Such models typically do not integrate the time-dependent equations of motion, but instead rely on analytic parameterizations of topographic effects. The critical dividing streamline hypothesis is an example of one such representation for the effects of topography which is being considered for use in statutory air quality models. This formulation (described in section 2) proposes a simple guide for determining whether upwind stagnation occurs for stably stratified flow over terrain, and allows the depth of the stagnant layer to be estimated.

The critical dividing streamline hypothesis has been validated in laboratory experiments (e.g. Hunt and Snyder, 1980; Lee *et al.*, 1984) and atmospheric tracer studies (e.g. Rowe, 1980; Strimaitis *et al.*, 1983). The atmospheric tracer studies have mainly been conducted around small-scale terrain. An example is Cinder Cone Butte, a site used in the CTMD program (Strimaitis *et al.*, 1983, 1985). This is a nearly conical hill rising about 100 m above the surrounding terrain and having a radius of about 350 m.

There is concern as to whether the dividing streamline hypothesis can be transferred from the laboratory and small-scale field studies to mesoscale terrain (e.g. Hovind *et al.*, 1979). In this paper, we use a mesoscale numerical model to examine the application of the critical dividing streamline hypothesis to two-dimensional terrain which is an order of magnitude larger than that considered in most previous dispersion studies. A numerical model provides a suitable apparatus for such an investigation, as it permits the selective activation of physical processes.

We begin by altering the numerical model so that it reflects the simplifications of the critical dividing streamline hypothesis, and compare the numerical model results to the predictions of the dividing streamline hypothesis. Next, we add turbulence and the Coriolis force to the numerical model formulation, and compare the results with these processes to the previous model results in which they were omitted. Finally, we also activate the numerical model's radiation parameterization and surface energy balance, so that the effects of nocturnal drainage winds may be examined.

2. THE CRITICAL DIVIDING STREAMLINE HYPOTHESIS

The fundamental assumption of the dividing streamline hypothesis is that when the potential energy gained by lifting a parcel from its original elevation h_c to a higher elevation h_2 exactly balances the kinetic energy originally possessed by the parcel at h_c, no further ascent can occur. This assumption leads to the determination of a critical dividing streamline height h_c, expressed as

$$h_c = H(1 - Fr). \quad (1)$$

[See Sheppard (1956) and Ryan and Lamb (1984) for derivations.] In (1), H is the obstacle height, and Fr is a Froude number defined as

$$Fr = \frac{U}{NH} \quad (2)$$

where U is the ambient flow velocity and N is ambient Brunt–Vaisala frequency. A finite depth of upwind stagnation ($0 < h_c < H$) is predicted by (1) for $Fr < 1$.

This simple energetic argument neglects a number of physical processes, such as the Coriolis force, thermally induced accelerations, wave and buoyancy phenomena, and turbulent fluxes. Several of these processes, most notably the Coriolis force and thermally induced circulations, are known to be dependent on the horizontal length scale. This implies that the success of the critical dividing streamline hypothesis in describing flow around small-scale terrain (e.g. Rowe, 1980; Strimaitis *et al.*, 1983; Ryan *et al.*, 1984) may not necessarily extend to larger scale terrain.

3. THE NUMERICAL MODEL

3.1. *Model formulation*

The numerical model used in these experiments has been described in detail by Mahrer and Pielke (1977, 1978) and McNider and Pielke (1981). It is a nonlinear, time-dependent atmospheric model based on the primitive equations as simplified by the incompressible and hydrostatic approximations. Airflow over nonuniform terrain is considered using a terrain-following vertical coordinate (Pielke and Martin, 1981).

A viscous layer of the form described by Durran and Klemp (1983) is used in the upper portions of the model to inhibit the downward reflection of wave energy into the interior of the domain. (See Klemp and Lilly, 1978 for discussion of the properties of absorbing layers.) Lateral boundary conditions are zero-gradient. Turbulent transfer is parameterized using first-order closure. Surface fluxes are diagnosed according to the relationships formulated by Businger *et al.* (1971). Above the surface layer, exchange coefficients are determined by a profile approach in the unstable regime (Pielke and Mahrer, 1975) and elsewhere by a local Richardson number dependent formulation (McNider and Pielke, 1981). Diabatic forcing is represented using a surface energy balance and parameterizations of short- and long-wave radiative heating in the atmosphere (Mahrer and Pielke, 1977).

Numerical solution of the equations is by forward time differencing on all prognostic terms except for vertical diffusion, which uses a future-weighted version of the Crank–Nicholson scheme as described by Paegle *et al.* (1976). Spatial differencing is centered for all terms except advection, which uses upstream interpolation on cubic splines (Mahrer and Pielke, 1978). Other details of the numerical procedures used in the model are discussed by Mahrer and Pielke (1978).

3.2. *Model validation*

The ability of the numerical model to predict diabatic flows and flow over complex terrain has been established in previous studies. Mahrer and Pielke (1978) showed that the numerical solutions for weakly nonlinear flow over complex terrain compare favorably to linear theory. Recent comparisons to observational data include Segal *et al.* (1982a, b), Abbs (1986) and Abbs and Pielke (1986). In the present study, the interaction of ambient winds with thermally forced drainage flows is of particular importance. The model's ability to account for these interactions will thus be examined before proceeding with sensitivity studies.

We have evaluated model predictions relative to observations taken as part of the U.S. Dept. of Energy Atmospheric Studies in Complex Terrain (ASCOT) program. The observational site was Rattlesnake Mountain, a nearly two-dimensional ridge located in central Washington State, U.S.A. Detailed observations at this site have been compiled by Horst and Doran (1982). The ridge rises to a crest height of about 600 m MSL from the surrounding elevation of about 300 m MSL. For a more complete description of the site, see Horst and Doran (1982) or Doran and Horst (1983).

The two-dimensional model was initialized at 1900 local time, 1 July 1980. Initial wind and thermodynamic profiles, surface temperature and roughness, and other input data were obtained from Horst and Doran (1982). Integration continued until midnight.

The predictions at midnight are compared to the observations taken at Tower B in Fig. 1. Correspondence between the two is generally good, with minor tendencies toward overprediction of the slope wind velocity (by about 0.8 m s^{-1}) and underprediction of the potential temperature (by about 1 K). The overall shape of the wind profile agrees with the observations, and in particular the height of the slope

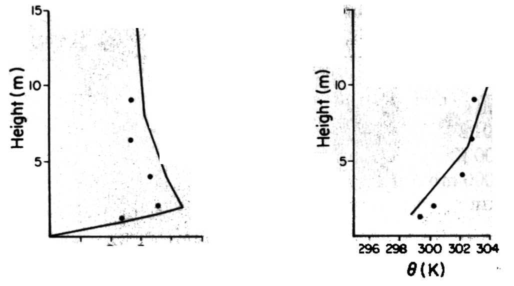

Fig. 1. Profiles of (a) downslope wind component and (b) potential temperature at Rattlesnake Mountain Tower B, 0000 local time, 2 July 1980. Solid curves are model predictions; darkened circles are observations.

flow velocity maximum (4 m) is accurately predicted. The model potential temperature profile differs from the observed profile mainly in that the predicted near-surface inversion is less sharp than observed.

We conclude that the model is able to replicate the observed features of nocturnal slope flows with reasonable accuracy. This will allow us to examine the effect of nocturnal thermally forced slope flows on the predictions of the critical dividing streamline hypothesis.

4. SIMULATIONS WITH NO DIABATIC FORCING

4.1. *Experimental design*

A useful feature of numerical models is that they can allow selective activation of physical processes. This permits the effect of different processes to be examined in a systematic manner. In this section, we describe two sets of numerical experiments. The first set (termed the 'free slip' experiments) uses a simplified version of the model which reflects most of the assumptions of the dividing streamline hypothesis. The second set (the 'no slip' experiments) introduces surface friction and the Coriolis force. Effects of diabatic forcing are deferred to section 5.

The model was executed with values of $Fr = 0.25$, 0.5, 0.75 and 1 in each set of experiments. There are several ways to produce such a range of Fr, since there are three parameters (U, N and H) which may be varied to yield a given Froude number. We chose to hold U and N constant and to vary H for two reasons. First, this approach has the advantage of maintaining a constant vertical wavelength, given by (Smith, 1979):

$$\lambda_z = \frac{2\pi U}{N}. \tag{3}$$

A constant vertical wavelength allowed the use of exactly the same computational domain for each Fr. This gave confidence that differences for simulations with different Fr in fact reflected the effects of Fr, since the numerical procedures did not vary. Second, holding the width of the topography constant kept the same value of r_λ, the ratio of the vertical to horizontal wavelengths:

$$r_\lambda = \frac{\lambda_z}{\lambda_x} = \frac{U}{N a} \tag{4}$$

where a is the half-width of the topography. Holding r_λ constant also permits a more focused evaluation of the effects of varying Fr.

The ambient Brunt–Vaisala frequency was specified as constant in space with a value $N = 0.01\ \mathrm{s}^{-1}$, which corresponds to the ICAO standard atmosphere lapse rate. The ambient wind (i.e. the approach flow) was also spatially constant, with a value $U = 3\ \mathrm{m\,s}^{-1}$ reflecting the low wind speed regimes typically of concern for poor air quality. We defined the Froude number using the ambient flow velocity and ambient Brunt–Vaisala frequency. This represents an external Froude number, as opposed to an internal Froude number which is based on the local stability and flow velocity. The topography height could then be solved by Equation (2) for each value of Fr, and ranged from 1200 m for $Fr = 0.25$ to 300 m for $Fr = 1$.

We specified the topography shape as a two-dimensional triangular ridge with a base width of 16 km. This width represents approximately an order of magnitude increase compared to the small-scale topography used in most field investigations of dividing streamlines. The triangular cross-section produces well-defined topography with homogeneous surroundings, so that the approach flow is unperturbed until it reaches the ridge. Other shapes such as a Gaussian and the bell-shaped Witch of Agnesi have been used by other investigators; however, both the Gaussian and Witch of Agnesi extend infinitely far from the ridge crest, and thus do not allow unperturbed approach flows.

The ridge was contained in a 70-km wide computational domain (Table 1). The grid spacing was 1 km in the main portion of the domain so that the ridge would be well resolved. Total depth of the domain was 6500 m encompassing 3.45 vertical wavelengths ($\lambda_z = 1885$ m), with the upper 2000 m making up the absorbing layer (section 3.1).

4.2. *Free-slip experiments*

As discussed in section 2, the dividing streamline hypothesis neglects a number of physical processes such as the Coriolis force, diabatic heating, surface frictional stress and turbulent transfer. Therefore we begin by altering the mesoscale model to omit most of these processes. Although this is not physically realistic, comparison of simulations with and without these phenomena permits a systematic evaluation of their effect on upstream blocking.

Complete elimination of turbulent transfer in the model was not possible due to the presence of breaking waves. As shown for example by Huppert and Miles (1969), breaking waves occur for $Fr \lesssim 1$, which also encompasses the Froude number regime where block-

Table 1. Initial conditions and numerical specifications for dividing streamline simulations

Initial and boundary conditions	
Ambient wind	$U = 3\ \mathrm{m\,s^{-1}}$
Ambient Brunt–Vaisala frequency	$N = 0.01\ \mathrm{s^{-1}}$
Surface potential temperature	$\theta_0 = 300\ \mathrm{K}$
Surface pressure	$p_0 = 1000\ \mathrm{mb}$
Topography half-height width	$a = 4\ \mathrm{km}$
Numerical specifications	
Time step	$\Delta t = 7\ \mathrm{s}$
Horizontal grid	60 gridpoints; $\Delta x = 1$ km ($\Delta x = 2$ km for five gridpoints nearest each boundary); topography centered at gridpoint 29.
Vertical grid	'telescoping' grid with 30 levels at 5, 10, 17.5, 27.5, 40, 60, 100, 150, 250, 400, 600 . . . (constant $\Delta z = 300$ m) . . . 6000, 6500 m
Horizontal filter coefficient	$\delta = 0.05$
Absorbing layer	Upper seven levels (4500–6500 m), e-folding time scale 667 s

ing is expected. Breaking waves produce superadiabatic layers aloft which are both physically unrealistic and computationally troublesome. Accordingly, the turbulence parameterization was activated for negative values of the local Richardson number.

Initial and boundary conditions for the simulations are presented in Table 1. The simulations were executed to steady state, which was defined by horizontal velocity changes of $0.1\ \mathrm{m\,s^{-1}}$ or less from one hour to the next in the lower levels. Horizontal velocity fields for the steady-state solutions are presented in Fig. 2. Regions of weak reversed flow were produced for $Fr \leqslant 0.75$, with a critical value for blocking estimated as $Fr \approx 0.8$. Observations by Tan and Leverson (1981) for a blocking situation in Colorado and by Kitabayashi (1977) for a case in Japan have also noted reversed flow in the blocked region. The threshold of Fr for upstream blocking is comparable to Pierrehumbert and Wyman's (1985; hereafter PW85) critical value for blocking of $Fr \leqslant 0.67$. Figure 2(c) shows that the stagnant region for $Fr = 0.75$ is confined to a limited area near the base of the ridge, suggesting that the small discrepancy between the present results and those of PW85 may be due to the difference in obstacle shape.

The steady-state results were then used to evaluate streamlines for particles released 12 km upwind (in the sense of the imposed ambient flow) from the ridge crests. In these evaluations, particles were released from several heights near the critical height predicted by the dividing streamline hypothesis at intervals of 120 s. As the flow fields were essentially in steady state, particle trajectories could be equated to streamlines. Blocking was defined by the failure of particles to cross over the ridge within 3 h. Since the unperturbed ambient wind would carry the particles 12 km in about 1 h, the failure of the particles to surmount the ridge in 3 h represents a substantial accumulation on the windward side of the topography. This definition of blocking recognizes that the wind need not be slowed to zero in order to have a negative impact on pollutant dispersion. (Preliminary evaluations indicated that a period < 3 h was too close to the free-stream transit time, while the sensitivity on the long end of the time scale was much less.)

The results of the numerical streamline evaluations are compared to the predictions of the dividing streamline hypothesis in Fig. 3. The results show that while the general trend reflects the dividing streamline hypothesis in that the blocked region decreases in depth with increasing Fr, the numerical results tend to predict blocking to a lower height than indicated by the dividing streamline hypothesis. This suggests that the simple parcel arguments upon which the dividing streamline is based may not take complete account of the relevant physics involved in mesoscale airflow over two-dimensional terrain. The discrepancy may also be due in part to inaccuracies in the numerical formulation.

4.3. *No-slip numerical experiments*

The simulations were repeated with the addition of surface frictional stress and with the turbulent parameterization described by McNider and Pielke (1981), with the treatment of turbulence not restricted to superadiabatic layers. The Coriolis force was also included. The value of the Rossby number, defined as

$$Ro = \frac{U}{fa} \tag{5}$$

(where f is the Coriolis parameter), was 7.5 for these cases. This value suggests that the Coriolis force will be of relatively minor importance, though perhaps not altogether negligible. The initial and boundary conditions and the numerical specifications were identical to those for the free-slip experiments (Table 1) except as required by the inclusion of turbulence and the Coriolis force. The roughness length z_0 was taken as 0.1 m, and the latitude is typical of the coterminous United States.

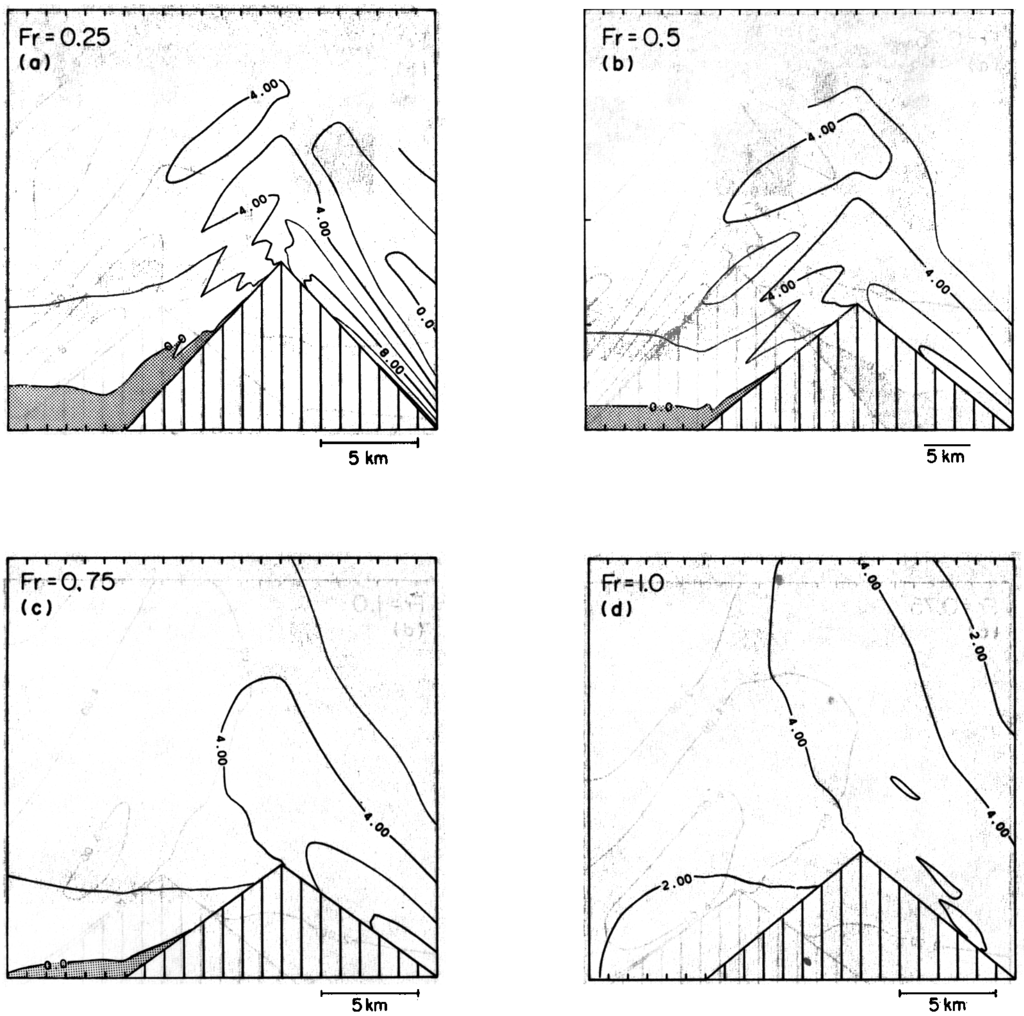

Fig. 2. Steady-state horizontal velocity fields for free-slip simulations with (a) *Fr* = 0.25, (b) *Fr* = 0.5, (c) *Fr* = 0.75, and (d) *Fr* = 1. Stagnant regions (velocity ≤ 0) are shaded. Vertical scale differs from figure to figure for clarity.

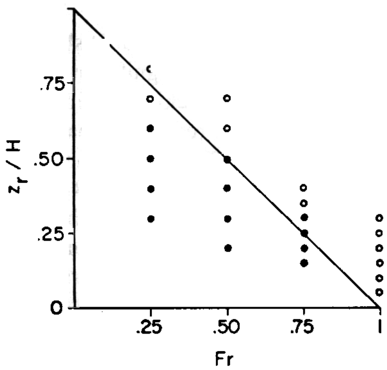

Fig. 3. Comparison of free-slip streamline evaluations with prediction of critical dividing streamline hypothesis. Closed circles denote release heights for streamlines which failed to surmount the ridge crest within 3 h; open circles otherwise. Diagonal line is separation of these regimes as predicted by dividing streamline hypothesis.

As with the free-slip simulations, the model was executed until steady states were achieved. The resulting horizontal velocity fields are shown in Fig. 4. A significant difference between these results and those of the free-slip experiments (Fig. 2) is that the stagnant region is absent for $Fr = 0.75$, and for $Fr = 0.5$ is slightly shallower than in the free-slip case. The free-slip and no-slip solutions for $Fr = 0.25$ are quite similar. The addition of turbulence and the Coriolis force thus acts to decrease the extent of blocking in marginal cases ($Fr = 0.75$ and 0.50) but has relatively little influence when the blocking is strongly established ($Fr = 0.25$).

Streamline evaluations were performed by the same technique used for the free-slip simulations. The results are compared to the predictions of the critical dividing streamline hypothesis in Fig. 5. The main difference between the no-slip and free-slip streamlines is the decrease in the depth of blocking for the simulations with $Fr \leqslant 0.75$. Since the two sets of

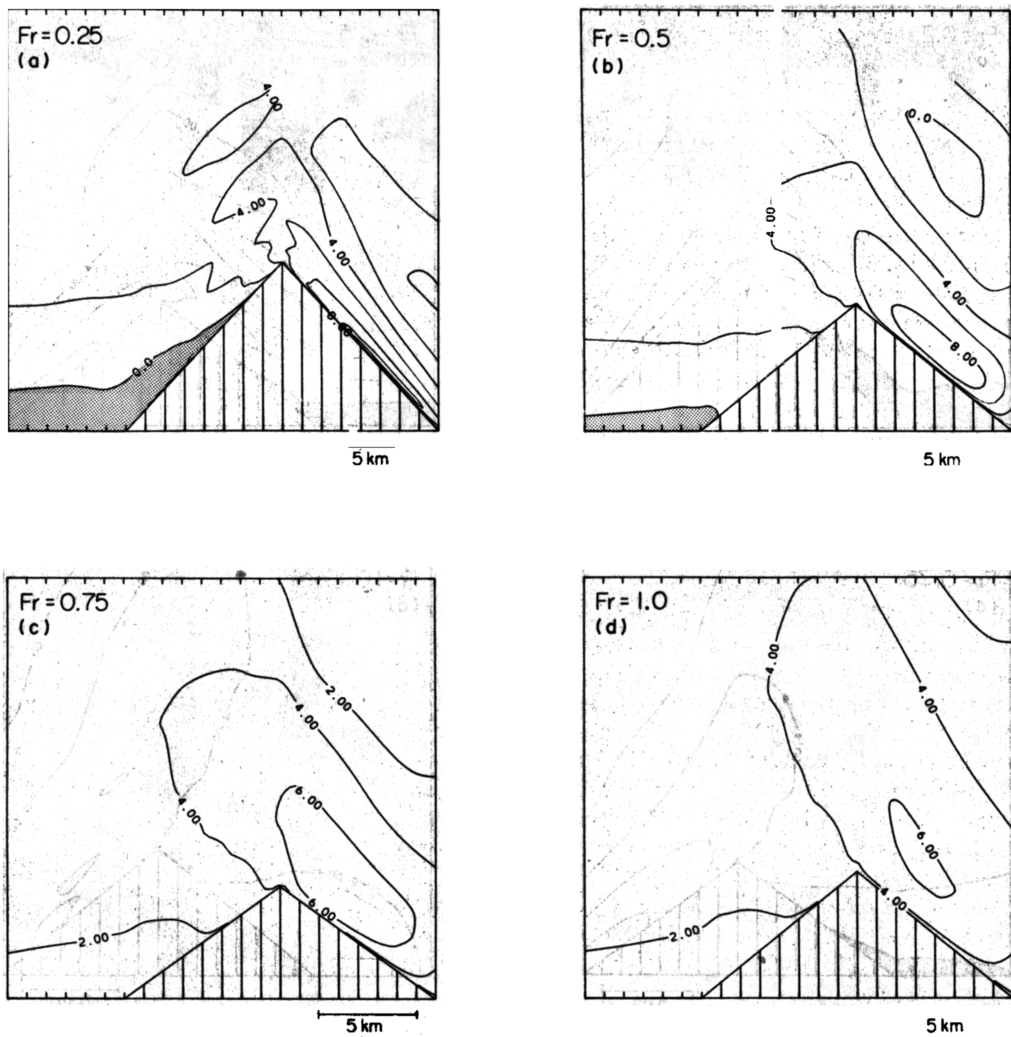

Fig. 4. As Fig. 2, except for no-slip simulations (i.e. including friction and the Coriolis force).

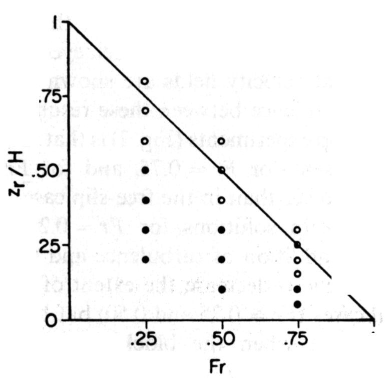

Fig. 5. As Fig. 3, except for no-slip simulations.

simulations were performed identically except for the inclusion of turbulence and the Coriolis force, the differences must be due to one or both of these processes.

Pierrehumbert and Wyman (1985) showed that the Coriolis force can have a significant effect on the generation of upwind blocking, acting to decrease the extent of the blocked region compared to the case of no Coriolis force. They also showed that the relevant scaling parameter is the Rossby number divided by the Froude number, such that the effect of rotation is expected to be greatest for large Froude numbers and small Rossby numbers. The results presented here, in which the influence of the Coriolis force was greatest for the marginal blocking case (larger Fr) and fairly insignificant for the more well-established blocking (smaller Fr), agree with the scaling presented by PW85. The tendency for the Coriolis force to decrease the extent of blocking indicates that while the critical dividing streamline hypothesis does not give a complete description of the physics for mesoscale and larger scale (small Rossby number) flows, it at least is 'conservative' when used for the evaluation of pollutant dispersion, in that it tends to overpredict the extent of upwind stagnation.

5. INFLUENCE OF NOCTURNAL SLOPE FLOWS ON THE DIVIDING STREAMLINE HYPOTHESIS

5.1. *Numerical simulations*

We now turn to the effect of nocturnal slope flows on the critical dividing streamline hypothesis. For this purpose, diabatic forcing is allowed by activating the numerical model's surface energy balance and radiative parameterization. A Froude number of 1.5 was specified in this simulation; otherwise, all input parameters were as in Table 1. The simulation began with a 4-h period with no diabatic forcing, during which the flow adjusted to the underlying terrain. Following this dynamic initialization, the radiation parameterization was activated at 45 min before sunset in order to approximate the time at which the surface heat flux changed from upward to downward.

Figure 6(a) shows the streamlines produced at the end of the dynamic initialization, before the imposition of radiative cooling. As expected from the results in the previous section, the particles surmount the ridge with no evidence of upstream blocking. The particles remain at nearly the same height above the topography at which they originated. Since the Froude number of 1.5 is above the theoretical critical value of unity, these results agree with the predictions of the critical dividing streamline hypothesis.

The streamlines obtained in the presence of thermal forcing are considerably different from those produced with purely mechanical forcing. Fig. 6(b) illustrates the streamlines resulting from particle releases at the same positions as Fig. 6(a), but after 4 h of radiative cooling. The low level releases stagnate or pass close to the surface as a result of the development of the drainage wind and its entrainment mass flux. Although the dividing streamline hypothesis would take account of changes in the Froude number due to the development of slope flows, the entrainment mass flux would not be considered in the energetic arguments upon which the dividing streamline hypothesis is based.

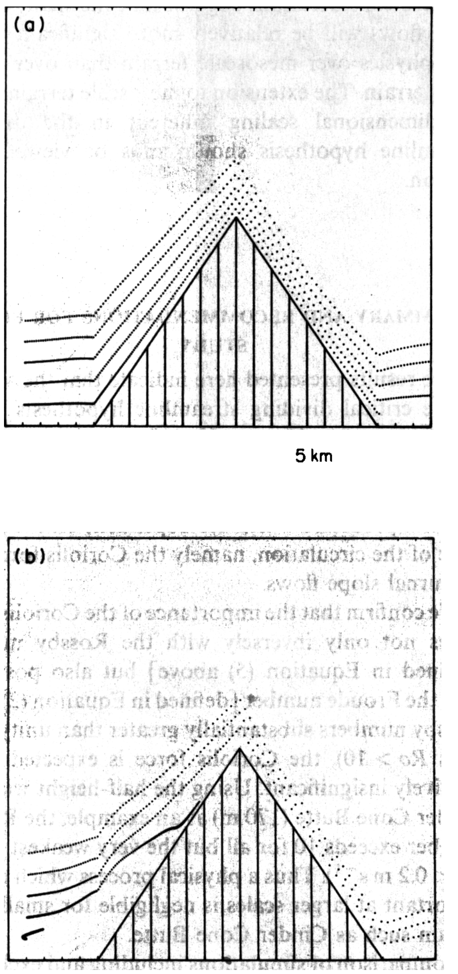

Fig. 6. Streamline evaluations for simulation with $Fr = 1.5$ (a) after dynamic initialization but before onset of cooling and (b) after 4 h of cooling.

5.2. *Scaling of the influence of drainage flows*

Analytical studies provide some insight as to the scaling of nocturnal slope flows in mesoscale and local scale terrain. In particular, there are two factors which suggest that slope flows are more important for mesoscale terrain than for smaller scale terrain:

(i) The slope flow mass flux is dependent on the length of the slope. Manins and Sawford (1979) use analytical scaling to show that slope flow velocity varies with the 1/3 power of slope length. Also, as discussed for example by Horst and Doran (1986), the depth of the slope flow layer varies approximately linearly with downslope distance. The slope flow mass flux, which is the product of the flow velocity and the flow depth, is therefore strongly dependent on slope length. Mesoscale slope flows will generally have much greater entrainment mass flux than flows over small-scale terrain such as Cinder Cone Butte.

(ii) Small-scale terrain lies mostly within the nocturnal surface-based inversion, substantially inhibiting the development of slope flows. Nocturnal surface inversions are typically of order 100 m in depth and can have potential temperature stratifications of $100\,\mathrm{K\,km^{-1}}$ or greater. According to the analytical solution of Prandtl (as discussed by Rao and Snodgrass, 1981), slope flow velocity is inversely proportional to the square root of the potential temperature lapse rate, while the slope flow depth is inversely proportional to the fourth root of the lapse rate. Slope flows over terrain lying totally within the nocturnal surface based inversion thus have a much smaller mass flux than flows over higher terrain which is exposed to a lapse rate closer to the free atmosphere value.

These considerations suggest that thermally forced slope flows will be relatively more significant to the flow physics over mesoscale terrain than over small-scale terrain. The extension to mesoscale terrain of the non-dimensional scaling inherent in the dividing streamline hypothesis should thus be viewed with caution.

6. SUMMARY AND RECOMMENDATIONS FOR FUTURE STUDY

The results presented here indicate that the success of the critical dividing streamline hypothesis in the assessment of stably stratified flow over small-scale topography (length scale < 1 km) may not extend to flow around mesoscale terrain. This is due to two physical processes which are dependent on the length scale of the circulation, namely the Coriolis force and nocturnal slope flows.

We confirm that the importance of the Coriolis force scales not only inversely with the Rossby number [defined in Equation (5) above] but also positively with the Froude number [defined in Equation (2)]. For Rossby numbers substantially greater than unity (perhaps $Ro > 10$), the Coriolis force is expected to be relatively insignificant. Using the half-height width of Cinder Cone Butte (170 m) as an example, the Rossby number exceeds 10 for all but the very weakest winds ($U < 0.2\ \mathrm{m\,s^{-1}}$). Thus a physical process which can be important at larger scales is negligible for small-scale terrain such as Cinder Cone Butte.

Comparison of simulations including and excluding diabatic forcing suggests that the dividing streamline hypothesis is an accurate predictor of pollutant dispersion only in the absence of significant thermally forced circulations. As discussed in section 5, the influence of nocturnal slope flows is expected to increase with both the height and the length of the terrain. While slope flows are expected to be nearly always too weak to have significant impacts on dispersion over small-scale terrain, they may have important effects on flow characteristics over mesoscale terrain.

There is a clear need for more observational dispersion studies around terrain with length scales of order 2–20 km. Most previous observational programs have been conducted around either small-scale terrain such as Cinder Cone Butte (Strimaitis *et al.*, 1983, 1985) or much larger scale terrain such as the Appalachian mountain range in the CAPTEX study. It appears that the dynamics of airflow over intermediate terrain are distinct from both smaller scale and larger scale (meso-α) terrain. Tracer studies in these intermediate-scale regions would help to establish the physical processes which are relevant to dispersion on this scale. As noted by a reviewer, many other phenomena such as the interaction of multiple scales of terrain, the influence of plume buoyancy, and three-dimensionality vs two-dimensionality could also be profitably studied.

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