MESOSCALE MODELLING OF WIND ENERGY OVER NON-HOMOGENEOUS TERRAIN

(Review Article)

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Abstract. The use of numerical mesoscale models for the evaluation of wind energy potential over non-homogeneous terrain is outlined, focusing on the following: (i) an overview of modelling investigations of relevance to wind energy; and (ii) a discussion of the optimal implementation of mesoscale models in wind energy studies.

1. Introduction

Common methodologies for the evaluation of regional wind energy potential involve the use of either observational or modelling approaches. As will be discussed in the concluding section of the paper, each methodology has advantages and shortcomings, although, fortunately, both are complementary to each other. It is the purpose of the current paper to discuss various aspects in the application of numerical mesoscale models for wind energy potential assessments over non-homogeneous terrain. However, as an introduction it is worth summarizing briefly the main features of both methodologies.

1.1. Observational Approaches

Evaluations of wind energy based on wind observations (usually surface winds) at well-exposed sites provide an accurate representation of the wind in the immediate vicinity of the measuring site. Upper winds may be extrapolated with a certain degree of accuracy from the surface data. However, the resolution of the wind energy pattern throughout an extended area by this methodology requires a large number of observational sites (this requirement is most essential when complex terrain is considered). Since such observational networks, generally, are not established for wind energy assessments, the existing observational data are not optimal for such evaluations. In addition, wind data are not always available within local subregions which may have a reasonable potential for wind energy. Examples of regional observational wind energy

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studies include those of Baker *et al.* (1978), Martner and Marwitz (1982) and Wendland (1982), among others.

1.2. Diagnostic models

In recent years diagnostic models have been widely used in evaluations of flow patterns over complex terrain. Generally, these models consider mass conservation or other simplifications of the equations of motion while optimizing toward a minimal error between the computed and observed wind (usually due to the lack of upper level data, an extrapolation based on available surface winds for the initial wind profile with height is adopted). Objective analysis is used to interpolate those profiles to the horizontal grid locations in order to provide the initial guess for the wind field. Examples of diagnostic models include those of Dickerson (1978), Sherman (1978) and Endlich *et al.* (1982) among others.

1.3. Prognostic mesoscale models

Prognostic mesoscale models predict the meteorological fields based on a mathematical representation of the relevant physical processes. It is expected that when more realistic representations of the dominant physical processes are included, the overall prediction should be improved. A detailed discussion relating to various aspects of these models can be found for example, in Pielke (1984). It is worth noting that prognostic models can be combined with existing data at various time periods in order to produce a generalized quasi-prognostic model (i.e., the model equations are nudged toward the observations when the simulation and observation times are coincident, but the model solutions at all times are consistent with the fundamental physical relations).

In the next section we shall discuss the utilization of prognostic models for wind energy assessments in non-homogeneous terrain. Selective types of situations of possible relatively high wind energy potential will be considered while emphasizing the prognostic mesoscale modelling approach. Use of these models in a generalized dynamic mode and quasi-predictive mode will also be discussed.

2. Prognostic Modelling of Wind Energy

2.1. Flat onshore coastal areas

In flat coastal areas, the sea breeze when interacting with a supportive synoptic flow may result in a reasonable potential for wind energy. In the absence of synoptic flow, the sea breeze is not likely to have a significant wind energy potential as implied for example by previous model studies (e.g., Estoque, 1961; Neumann and Mahrer, 1971).

Wind energy studies by Garstang *et al.* (1980) and Snow (1981) focused on coastal locations along the eastern and Gulf coasts of the U.S. where the mesoscale flow was often strongly supported by the prevailing synoptic flow. In these latter two publications, regions of substantial usable wind energy were reported in certain coastal areas of the United States, but not in others. By relating the prognostic mesoscale model simulations to the more common synoptic patterns in three selected coastal locations, a climatology of wind energy potential was created which agreed closely with the existing observations of wind energy where they were available. Over the Delmarva peninsula coasts, for instance, a substantial region of persistent large wind energy was found during cold, arctic outbreaks – a period when electrical demand is expected to be high. This higher region of wind energy occurred because the land area was narrow and the air had accelerated upwind over the Chesapeake Bay.

2.2. Offshore wind energy

The reduced roughness of the sea surface results in a gradient in the cross-shore flow intensity between the onshore and the offshore sections. Hsu (1981) suggests for example that surface-layer flows over the water are larger by a factor of one to two as compared to those over the adjacent land. Intensification of the flow over the water was found by Snow (1981) to be significant for winter outbreaks of continental cold air over the offshore water in the eastern U.S. In such situations, if the flow is vertically sheared as expected in a strong baroclinic winter-time cold outbreak, a deepening of the planetary boundary layer over the relatively warm water (e.g., see Chou and Atlas, 1982) results in the downward transport of momentum and consequently an intensification of the surface-layer flow. Low-level, coast-parallel jets can also develop because of a persistent horizontal temperature gradient between land and water (e.g., Mizzi and Pielke, 1984) as discussed in Section 2.5.

The routine availability of offshore wind data is rare. Also, previous prognostic model studies in coastal areas, with the exception of studies such as Snow (1981), and Tag

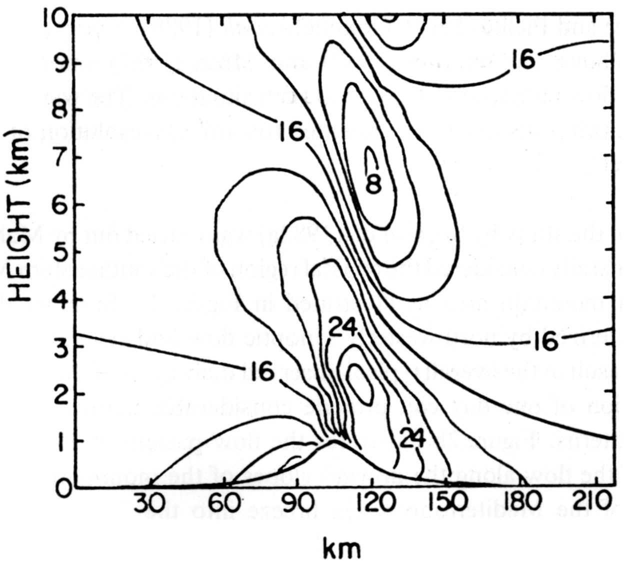

Fig. 1. The cross-ridge wind component (m s^{-1}) for a 1 km ridge height as simulated with a 2-D numerical mesoscale model for a cross-ridge geostrophic flow of 20 m s^{-1}. Contour interval 2 m s^{-1}. (From Mahrer and Pielke, 1978.)

and Fett (1983) (in which the offshore penetration of the sea breeze in Florida was evaluated), generally do not emphasize the analysis of flows over the water.

2.3. Mountainous terrain

Mountainous terrain frequently is associated with high wind energy potential and therefore is attractive for wind energy surveys and modelling. Generally, modelling of the flow patterns in such locations has been oriented toward meteorological aspects rather than specific evaluations of wind energy. However, the information provided by such studies can be projected to the needs of wind energy assessments. Numerical studies such as Mahrer and Pielke (1975), Klemp and Lilly (1978), and Anthes and Warner (1978) provided model evaluation as to the location and character of the peak value of the wind velocity along a mountain ridge during strong downslope wind events (i.e., chinooks). Figure 1 which is adopted from Mahrer and Pielke (1978) illustrates the spatial distribution of wind speed over an idealized mountain barrier under the influence of strong synoptic flow in a stratified atmosphere.

Thermally induced flows in mountain areas, namely, daytime upslope induced flows and nocturnal drainage, may interact with the synoptic flow to enhance or detract from the wind energy potential. Simulation results given in Segal *et al.* (1982a) illustrate such situations.

2.4. Mountainous coastal area

The combination of synoptic flow interacting with a variety of mesoscale-induced flows may provide an opportunity for significantly increased wind energy potential. Model studies by Mahrer and Pielke (1977), Ookouchi *et al.* (1979), Alpert *et al.* (1982), Segal *et al.* (1982b), Schultz and Warner (1982) and Mizzi (1982) among others provide examinations for flow patterns involved with such situations. The wind energy study by Segal *et al.* (1982a), for instance, was oriented toward the resolution of wind patterns over central Israel.

An extension of the study by Segal *et al.* (1982a) was carried out by Mahrer and Segal (1984). This latter study considered the coastal region of the southeastern Mediterranean and the adjacent mountain area as illustrated in Figure 2a. Summer day situations, which are characterized by northwesterly synoptic flow and several interacting mesoscale processes, result in the overall typical observed daily cycle of the flow in this region. Hence a simulation of one day can provide considerable information regarding the seasonal flow patterns. Figure 2b illustrates the flow pattern at 1900 LST. Dynamic intensification of the flow along the upwind slopes of the mountains is evident. Also, the penetration of the Mediterranean sea breeze into the Jordan Rift Valley is an important factor in the intensification of the westerly component of the flow. The relatively high wind energy at that location around this hour is illustrated in Figure 2c. The supportive daytime sea breeze and nocturnal drainage in this area provide relatively high daily wind energy potential (Figure 2d).

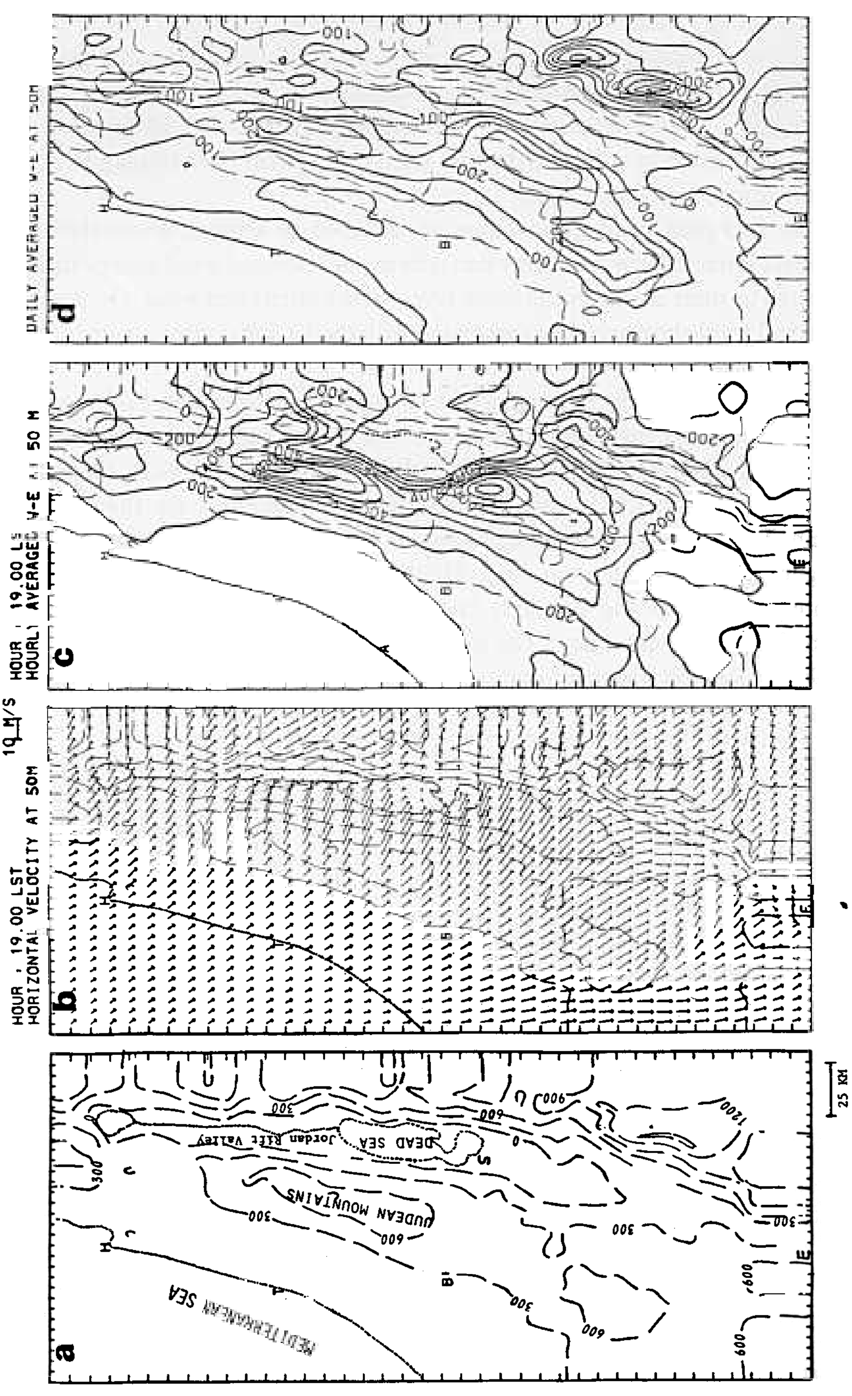

Fig. 2. (a) Schematic illustration of the terrain of the southeastern Mediterranean coastal area; (b) simulated typical summer flow at 50 m height at 1900 LST; (c) hourly averaged wind energy (W m^{-2}) for 1800–1900 LST; (d) daily averaged wind energy (W m^{-2}). (From Mahrer and Segal, 1984.)

2.5. Low level jet

The low level jet (LLJ) which is often observed in the nocturnal period can be caused by the diurnal spatial variation in thermal forcing associated with land-water contrasts and sloping terrain. The thermal forcing can contribute to the LLJ development through two mechanisms: (i) time-dependent variations in the eddy diffusion within the boundary layer, (ii) production of a diurnal thermal wind component over sloping terrain or other diurnally forced baroclinic zone.

Although the LLJ peak wind speed values are attained, in general, above the height which is of direct interest for wind energy considerations, elevated wind energy turbines could be affected to some extent by the lower levels of the intensified wind. On the other hand, the vertical wind shear which is associated with the LLJ may provide undesirable engineering problems.

Bonner (1968) evaluated the frequency of LLJ over the eastern and midwest areas of the U.S., and found the highest frequency over the Great Plains and along the south Texas coast. McNider and Pielke (1981) and McNider *et al.* (1982) carried out simulations involved with LLJ's and provided model evaluations for the LLJ over sloping terrain. The results showed resemblance to the observed features involved with the LLJ. Figure 3 which is adopted from McNider and Pielke (1981) illustrates the nocturnal intensification of the southerly component of the wind within a simulated cross-section along the Great Plains. The simulated feature resembles that suggested by Hoecker (1963) based on observed data.

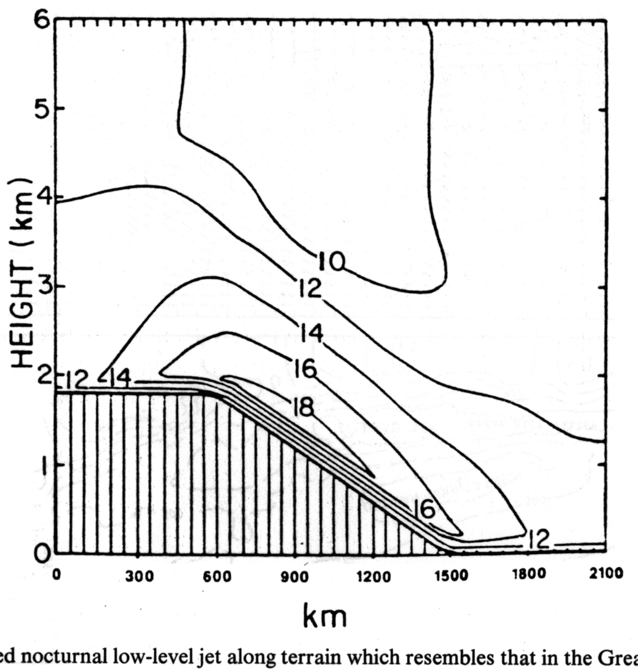

Fig. 3. Simulated nocturnal low-level jet along terrain which resembles that in the Great Plains. Contours are of the southerly velocity component. Contour intervals are $2\ m\ s^{-1}$. (From McNider and Pielke, 1981.)

2.6. ADDITIONAL SITUATIONS

The aforementioned discussion has been focused on major forcings over irregular terrain in relation to wind energy. Over such terrain, however, there are other related conditions leading to an enhancement of wind.energy potential. Several of these conditions are attractive for mesoscale prognostic model simulations, but there has, of yet, been little systematic attention to the resolution of their impact. It is worth mentioning some of these as candidates for future model studies:

(i) Topographical configurations which are likely to enhance flow. For example, wide and deep passages in mountainous areas are expected to cause dynamical intensification of the flow. This is the reason that wind energy turbines were placed in the Columbia Gorge in Washington State – a location that was selected using wind-induced tree growth deformation, and existing synoptic observations in the Gorge.

(ii) Terrain or coastline geometrical configurations which may affect the intensity of flow induced by differential heating, (e.g., a convex shore line if bulging seaward will generally intensify the sea breeze as compared to an equivalent case with a straight shore line).

(iii) The existence of an upper-level synoptic subsidence inversion over mountainous terrain may be considered as a 'lid' to mesoscale flows passing the terrain and therefore leading to its intensification.

(iv) Penetration of the daytime planetary boundary layer into vertically sheared wind will result in downward fluxes of momentum which will intensify the surface flow.

3. Non-Prognostic Modelling of Wind Energy

3. DYNAMIC MODE

The elimination of thermal forcing from a prognostic model can provide a non-prognostic model for resolving dynamical mesoscale influences. The advantage of such a mode is the capability to investigate the impact of forcings such as that due to strong airflow over topographical barriers without considering diurnal thermal effects. Since a steady-state solution will often result, computer resources required are generally reduced. This is most beneficial when the dynamical effect on the flow is the most significant mesoscale forcing. Mahrer and Segal (1984) used this option while simulating the southeastern coastal region of the Mediterranean sea for situations with strong synoptic flow. Figure 4, adopted from that study, illustrates the dynamical effect due to the topography on cases involved with northwesterly (Figure 4a) and southwesterly (Figure 4b) synoptic flow which are frequent in the winter season in that region. The patterns illustrate locations of maximum intensification of the flow, as well as providing an evaluation as to the effect of a change of synoptic wind direction on the forced mesoscale airflow.

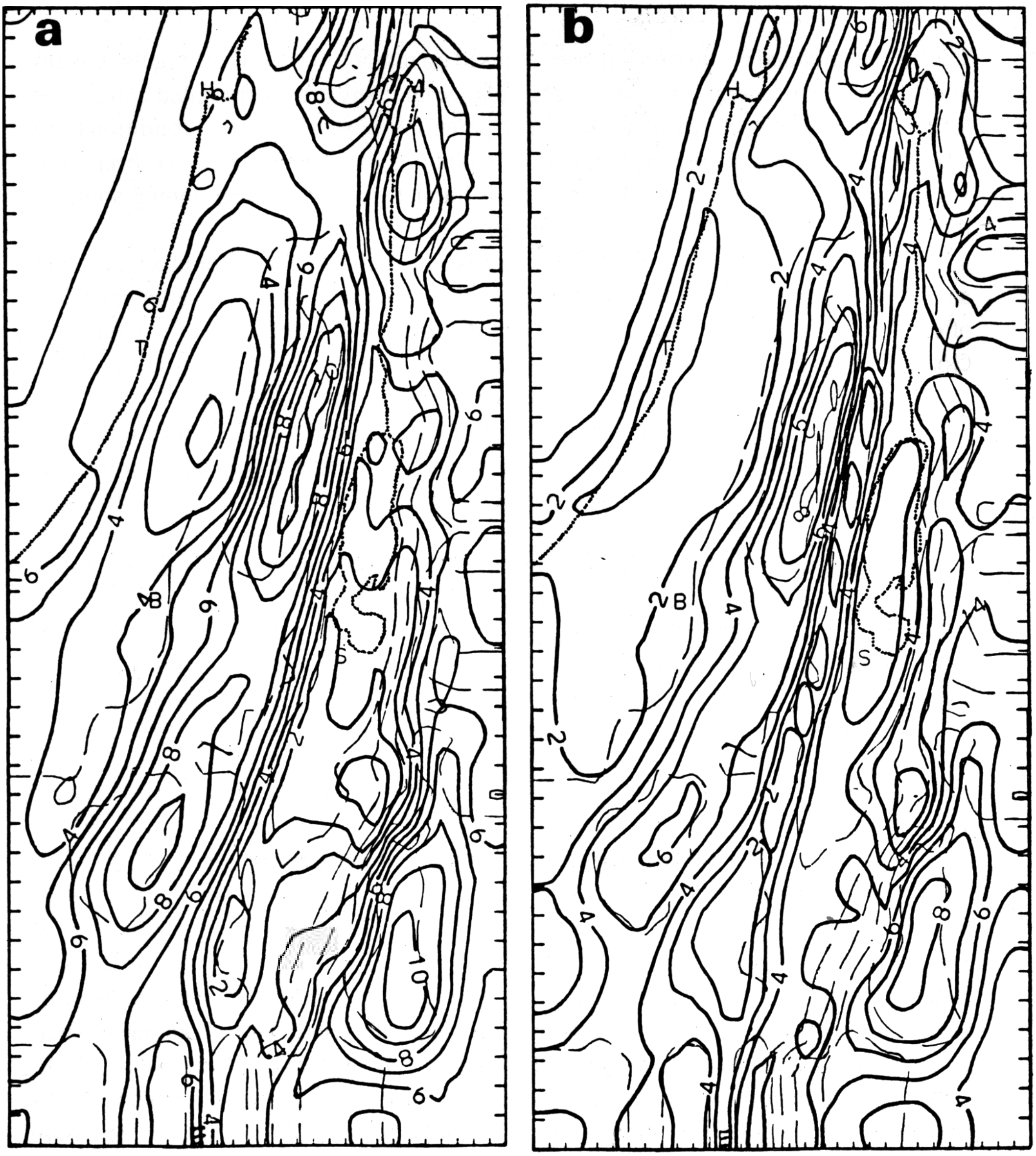

Fig. 4. Model evaluation of the flow at 50 m height in the southeastern Mediterranean for typical winter synoptic flows (a) northwesterly synoptic flow of 15 m s^{-1}; (b) southwesterly synoptic flow of 15 m s^{-1}. (From Mahrer and Segal, 1984.)

3.2. Quasi-predictive mode

Assimilation of available data during the simulation process may improve the overall accuracy of the model prediction. Since in wind energy evaluations the 'prediction' is done after the fact using archived data, this option is available. Such a procedure for using prognostic mesoscale models has been rarely discussed in the literature. Hoke and Anthes (1976) proposed this type of procedure for model initialization purposes. The focus of this type of method is that measurements at synoptic observation times (as well as asynchronous observations) would be fed into the prognostic model solution at the times to which they apply. The solutions at all times would be nudged toward these measurements using a weighting factor which is inversely proportional to distance from an observing site and to time from the measurement. This approach is somewhat distinct from the traditional diagnostic models in that a more complete set of the equations of motion is used to integrate forward-in-time. The diagnostic constraint of this mode is the availability of observations at selected times which are used to 'guide' the solutions. In the absence of observations (except at the initial time), the model reverts to a predictive model. This approach can be used for both thermally-forced and dynamically-forced mesoscale flows.

4. Discussion

In the present paper the utilization of numerical models for wind energy has been overviewed. The application of such models for regional evaluations is expected to provide information about subregions with a relatively high wind energy potential, rather than indicating specific sites with these characteristics. An alternate situation exists when observed data are considered for regional wind energy assessments since measurement data are only representative of the site around the wind observing system. Physical models may in fact have to be used to assess localized regions of maximum wind energy. The mesoscale model, however, may be able to provide the lateral and top boundary conditions for use by wind tunnel or fluid tank models. Even with respect to predicting general regions of higher wind energy, however, numerical models cannot, with generally available existing computer resources, provide day-by-day properties relating to the wind energy characteristics. Rather, their applications should be adopted for simulation of representative situations in order to obtain estimates of the climatologically more common situations (e.g., see Pielke, 1982). If we consider, for example, the 3-D simulations described in Mahrer and Segal (1984) in which the CRAY1 computer at NCAR was used, 80 min of computer time was needed for 24 hr of simulation. If we consider a 365 day simulation which is necessary to produce a year of day-by-day calculations, the needed computer resources is about 487 hr which is unrealistic from an economical point of view. Hence, the application of models for regional wind energy assessments can be oriented in two directions: (i) research and (ii) refined resolution of wind energy in situations of high significance for applied purposes. In the second class we refer mainly to synoptic situations of high seasonal persistence, that are likely to have a high wind energy potential. These could be evaluated using a climatological classification scheme such as discussed in Lindsey (1981), Snow (1981), and Pielke (1982). Alternatively it may include synoptic situations which are of relatively low frequency, but which are associated with a relatively high potential of wind energy that may be of value to exploit.

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