Use of Mass Conservation and Critical Dividing Streamline Concepts for Efficient Objective Analysis of Winds in Complex Terrain

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(Manuscript received 9 October 1990, in final form 3 March 1991)

ABSTRACT

Observed winds and temperature profiles can be used to generate three-dimensional, mass-conserving wind fields that reflect topographical influences. The concept of critical dividing streamlines is used to define quasi-horizontal, flow-confining two-dimensional surfaces. Adjustment toward two-dimensional nondivergence on those surfaces forces flow around obstacles under stable conditions when some flow surfaces intersect higher terrain features. Unlike most mass-conserving wind models, the approach described here includes objective evaluation of the effects of atmospheric stability. Efficiency is achieved by casting the three-dimensional problem as several two-dimensional problems and by using an iterative scheme to adjust toward nondivergence. A $20 \times 20 \times 5$ gridpoint analysis requires approximately 2 min on an IBM-AT personal computer.

1. Introduction

The objective analysis methodology described here was developed to provide fast, objective wind analyses in complex terrain by incorporating important physical constraints. The term *objective analysis* is used because the term *model* (whether prognostic or diagnostic) has come to imply the solution of a set of differential equations. What is described solves some differential equations, but primarily it invokes important physical principles in the adjustment of interpolated values. The methodology is still evolving, but it has already proven quite practical in a variety of applications. It can easily be changed in the future when airflow in complex terrain is better understood. The approach can also be extended to meet different needs. Some recognized shortcomings remain, which are described later, along with possible corrective measures. Some major extensions of the concepts used are also discussed.

This winds on critical streamline surfaces (WOCSS) approach incorporates mass conservation and critical dividing streamline concepts as constraints on the analysis. Simple interpolation techniques do well if the atmosphere is well mixed and the terrain is flat, but methods based on sound physical principles are needed to generate wind fields in areas above complex terrain when the atmosphere is stably stratified. The WOCSS methodology evolved from the wind-energy planning model of Bhumralkar et al. (1980) that used a variational calculus numerical scheme similar to Sherman's (1978), but applied it in sigma coordinates, rather than in Cartesian coordinates.

Endlich (1984) replaced the variational calculus numerical scheme for achieving nondivergence with a more general iterative technique that he had developed earlier (Endlich 1967). He also allowed the coordinate surfaces to intersect the terrain, because it had proven difficult to simulate the effects of the terrain on the flow using sigma surfaces that never intersect, even in a stably stratified atmosphere. In sigma coordinates, the methods for adjustment to nondivergence always leave a component along the direction passing over the obstacle, so they fail to reproduce the diffluence of the flow around the obstacle that has been found in field and laboratory experiments (Lavery et al. 1982; Hunt and Snyder 1980). Endlich (1984) set the winds to zero at "subterranean" points, so that the nondivergence constraint would force the flow around the intersected obstacles. This approach requires subjective definition of the coordinate surface shapes. Field studies (see, for example, Lavery et al. 1982) that defined the conditions when flow passes over an obstacle (as opposed to around it) provide a basis for replacing the subjective approach with an objective definition of flow surface shapes.

2. Using the critical dividing streamline concept to define flow surfaces

The concept of critical dividing streamlines applies when potential temperature increases with height (i.e., $d\theta/dz > 0$) and atmospheric processes are approximately adiabatic. The principle underlying the critical dividing streamline concept (Sheppard 1956; Hunt and Snyder 1980; McNider et al. 1984) is that there is some

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height where the work, done against the buoyant restoring force (as the air is displaced from its equilibrium position), equals the original kinetic energy of the wind. The above authors derive the algebraic relationships among wind speed, vertical temperature gradient, and the height of an obstacle that can be surmounted by the flow. It is sufficient, for our purposes, to show the results of the equivalence of the potential and kinetic energies in terms of $Z_{\max}$, the greatest height to which the air at height z can be lifted against the local potential temperature gradient, $d\theta/dz$, given the wind speed V_0 at the lowest altitudes on the flow surface:

$$Z_{\max} - z_0 = V_0\left(\frac{d\theta}{dz}\frac{g}{\bar{T}}\right)^{-1/2}, \qquad (1)$$

where $\bar{T}$ is the average temperature in the layer between z and $Z_{\max}$.

Equation (1) provides the basis of an objective method for defining coordinate surfaces like Endlich's (1984) subjectively defined flow surfaces. These coordinate surfaces will approximate the shape of the flow and will intersect the terrain in areas where the flow cannot pass over it. As mentioned earlier, winds are set to zero for points that are below the local terrain height so that adjustments toward nondivergence cause the flow to pass around the obstacle. Figure 1 is a flow chart that shows the steps required to define these flow-following surfaces objectively.

3. Achieving nondivergent flow on coordinate surfaces

Mass-conserving wind interpolation schemes begin with an "initial guess" and adjust it to remove the divergence. The adjustments can use either rectangular coordinates (e.g., Sherman 1978) or a curvilinear coordinate system. The WOCSS code uses curvilinear coordinates and assumes that there is no flow through those surfaces. These "flow" surfaces are determined from the critical dividing streamline concept as described in the preceding section. They differ from the sigma surfaces used by others (e.g., Bhumralkar et al. 1980; Ross et al. 1988) because they are objectively defined, can intersect the underlying terrain, and are presumed to conform to the shape of the flow. Wherever they intersect the terrain, the wind will be zero so that mass conservation adjustments will force the flow around the intercepted obstacle. The use of these surfaces not only incorporates the critical dividing streamline effects into the analysis, but also reduces the three-dimensional problem to several, more easily solved two-dimensional problems. Ross et al. (1988) introduce the critical streamline effects by making the weighting of vertical adjustments relative to horizontal adjustments a function of the "hill Froude number." This still leaves a three-dimensional problem. Furthermore, the unambiguous definition of the hill Froude number is difficult in complex terrain with many features of differing height.

The separation of the flow surfaces varies from place to place, therefore, mass fluxes (not the horizontal wind components, u and v) must be adjusted toward nondivergence. Endlich et al. (1982) replace the wind component variables with flux-related variables, u' and v', where

$$u' = u\Delta z,$$
$$v' = v\Delta z, \qquad (2)$$

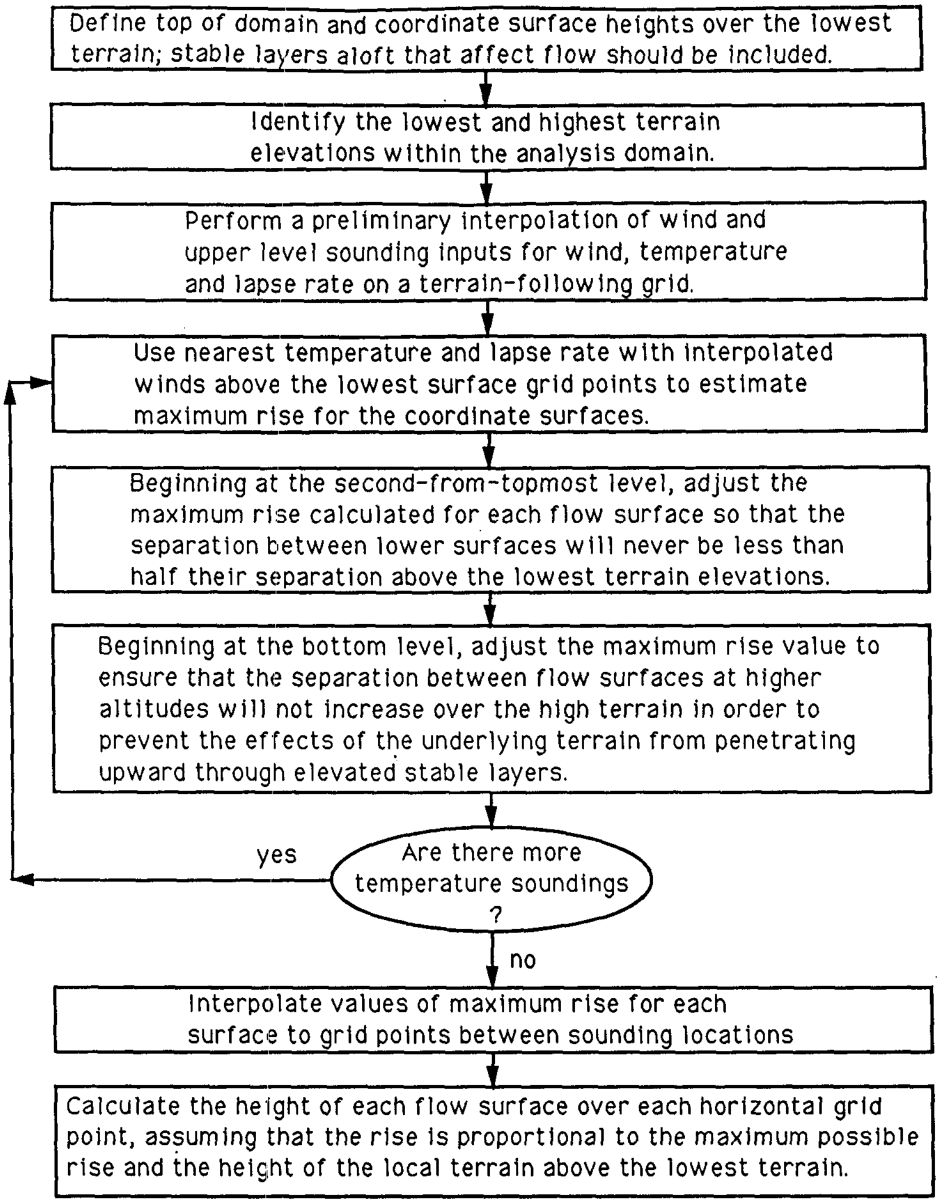
and Δz is the average separation between the surface and the two adjacent flow surfaces. At the bottom and top of the domain, Δz is half the distance to the one adjacent flow surface. If the slopes of the flow surfaces are not overly large, the continuity equation is approximated by

$$\frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} = 0. \qquad (3)$$

The iterative scheme described by Endlich (1967) is used to adjust the wind estimate to satisfy (3). Although Endlich's original scheme provided for vorticity constraints, none was imposed in this application. The iterative scheme is generally faster than the variational calculus methods used elsewhere (e.g., Sherman 1978; Ross et al. 1988). However, there will be situations where some divergence will remain after the flow has been adjusted because the approach forces the flow to take place within the defined surfaces. Sea-breeze circulations, some slope flows, and convective conditions with cell sizes resolved by the calculation grid are examples of situations where some remaining divergence is apt to exist. Corrections for these effects have not been attempted in the currently available version. This shortcoming is discussed in greater detail in section 6.

4. Other considerations

The objective analysis scheme described above deals with positive (stable) vertical potential temperature gradients. Otherwise, the flow is taken to be terrain-following; that is, $(Z_{\max} - z_0)$ is the same as the elevation difference between the highest and the lowest terrain. Recently published comparisons of observed tracer behavior in complex terrain with trajectories calculated from winds obtained by the objective methodology just described (Thykier-Nielsen et al. 1990) indicate that the terrain-following approach is inferior to Troen and deBass's (1986: as cited by Thykier-Nielsen et al. 1990) modification of Jackson and Hunt's (1975) analytical theory for the perturbation of neutral flow by small hills. Not surprisingly, Thykier-Nielsen et al. report that the WOCSS methodology performed



Define top of domain and coordinate surface heights over the lowest terrain; stable layers aloft that affect flow should be included.

Identify the lowest and highest terrain elevations within the analysis domain.

Perform a preliminary interpolation of wind and upper level sounding inputs for wind, temperature and lapse rate on a terrain-following grid.

Use nearest temperature and lapse rate with interpolated winds above the lowest surface grid points to estimate maximum rise for the coordinate surfaces.

Beginning at the second-from-topmost level, adjust the maximum rise calculated for each flow surface so that the separation between lower surfaces will never be less than half their separation above the lowest terrain elevations.

Beginning at the bottom level, adjust the maximum rise value to ensure that the separation between flow surfaces at higher altitudes will not increase over the high terrain in order to prevent the effects of the underlying terrain from penetrating upward through elevated stable layers.

Are there more temperature soundings ?

Interpolate values of maximum rise for each surface to grid points between sounding locations

Calculate the height of each flow surface over each horizontal grid point, assuming that the rise is proportional to the maximum possible rise and the height of the local terrain above the lowest terrain.

FIG. 1. Flow diagram of the procedure for defining flow-surface shapes.

better for stable conditions. This problem is discussed further in section 6.

Unlike many air-quality models that use the base of an elevated inversion as their upper boundary, this model's domain must include elevated stable layers that may influence the flow. Otherwise, the flow surfaces will not respond to the damping effects of the elevated stable layer, and the resulting winds will be more terrain-following than is realistic.

There are provisions for holding the near-surface wind constant at grid points near observations to ensure consistency between the observations and the analysis after mass balancing. This feature need not be invoked when there is a question about the representativeness of the observations, and the adjusted winds might be more representative of the flow on scales comparable to the grid size.

5. Application to the Los Angeles basin

A consortium of public and private organizations conducted the Southern California Air Quality Study (SCAQS) during the summer and fall of 1987. The Southern California Edison Company sponsored a complementary study that included objective analysis of meteorological data collected during the SCAQS.

These data, provided on magnetic tape by the California Air Resources Board, include frequent observations (typically, six times per day during intensive periods) of temperature, pressure, and wind aloft and include hourly surface measurements of the same variables at the other sites shown in Fig. 2. This comprehensive dataset and the complex terrain indicated by the contours in Fig. 2 are ideally suited for application of the WOCSS analysis technique. Six separate hours have been analyzed for each day. They correspond to times with the most upper-air soundings taken within approximately 1 h. Data were not available from every site for every hour analyzed, but upper winds were typically available from seven or more sites.

A 20 × 36 grid of 5-km squares covers the area (100 km south–north × 180 km west–east) shown in Fig. 2, with wind calculations made at the 21 × 37 array of grid points marking the corners of the grid squares. Seven flow surfaces were used at heights of 20, 50, 100, 250, 500, 750, and 1000 m above the lowest (sea level) grid points. Winds at 10 m above ground level were obtained by interpolation. Each objective analysis required a few seconds CPU time on a VAX 8800. Similar runs for a smaller grid (21 × 21 × 5) require approximately 10 s, 1 min, and 2 min, respectively, on a Silicon Graphics Personal Iris workstation, a Macintosh II, and an IBM-AT personal computer.

Figures 3–6 show results from the SCAQS applications. Figure 3 shows two 1100 PST wind fields for 10 December 1987. Figure 3a shows the 10-m winds that have been log-linearly interpolated between the surface roughness height (z_0 = 10 cm) and the lowest flow surface (or between the lowest two flow surfaces when the lowest is below 10 m). The higher-altitude areas without winds lie above the top of the analysis domain. Figure 3b shows flow on a surface that is 500 m above the ocean. Contours of the height of the flow surface above the underlying terrain are also drawn. The apparent slight variability in height over the ocean is an artifact of the contouring package's attempts to contour a flat surface. Both examples show that the objective analysis reproduces some of the topographic channeling effects that are known to occur when a stable layer aloft prevents flow over the higher obstacles and forces it through the lower passes and valleys. However, the winds are quite light, so the effects are not very pronounced.

Figure 4 shows flow-surface heights in four vertical planes from west to east at 20, 40, 60, and 80 km north of the origin. Their heights increase as the underlying terrain rises, but inversion layers aloft prevent them from rising as steeply as the underlying terrain so that they intersect it, or there is a reduction in the separation between surfaces. Intersection with the terrain and compression of the flow surfaces causes increased wind speeds and deflection of the flow around higher topography.

Figures 5a and 5b show wind analyses for 3 h later when the sea breeze is well established with pronounced westerly winds of approximately 3 or 4 m s^{-1} near the surface in the western parts of the domain. Inland, the winds are appreciably stronger than at the earlier hour.

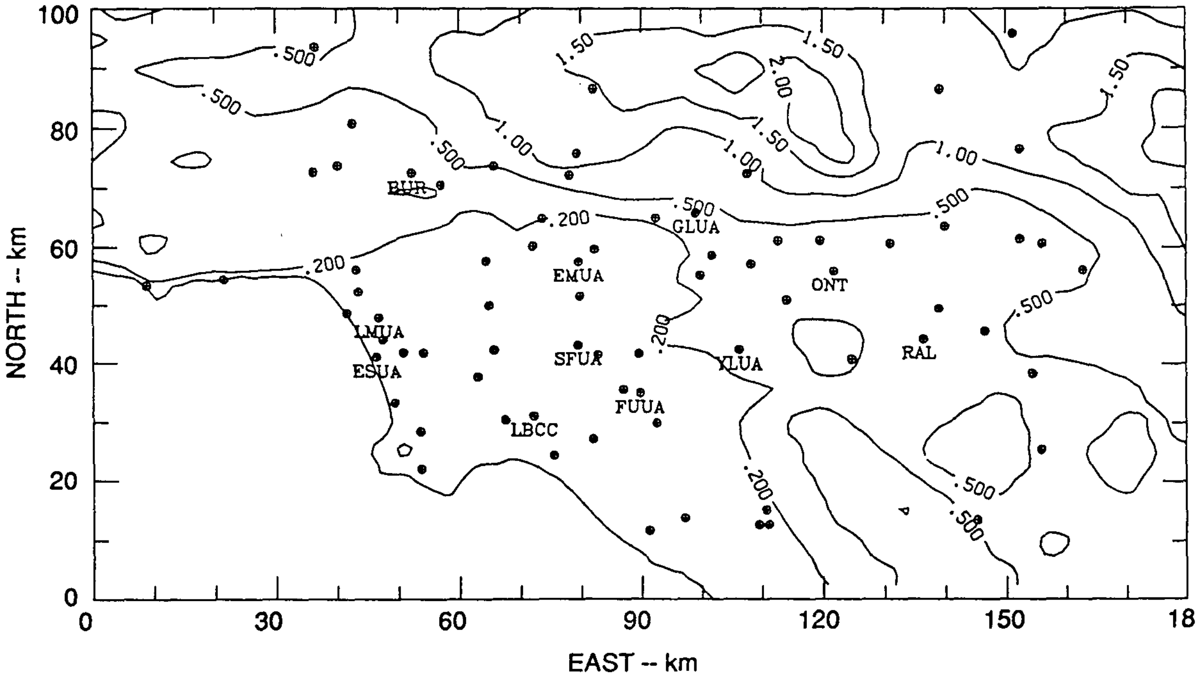


FIG. 2. Locations of SCAQS observation sites and terrain contours (km). (Named sites include observations aloft.)

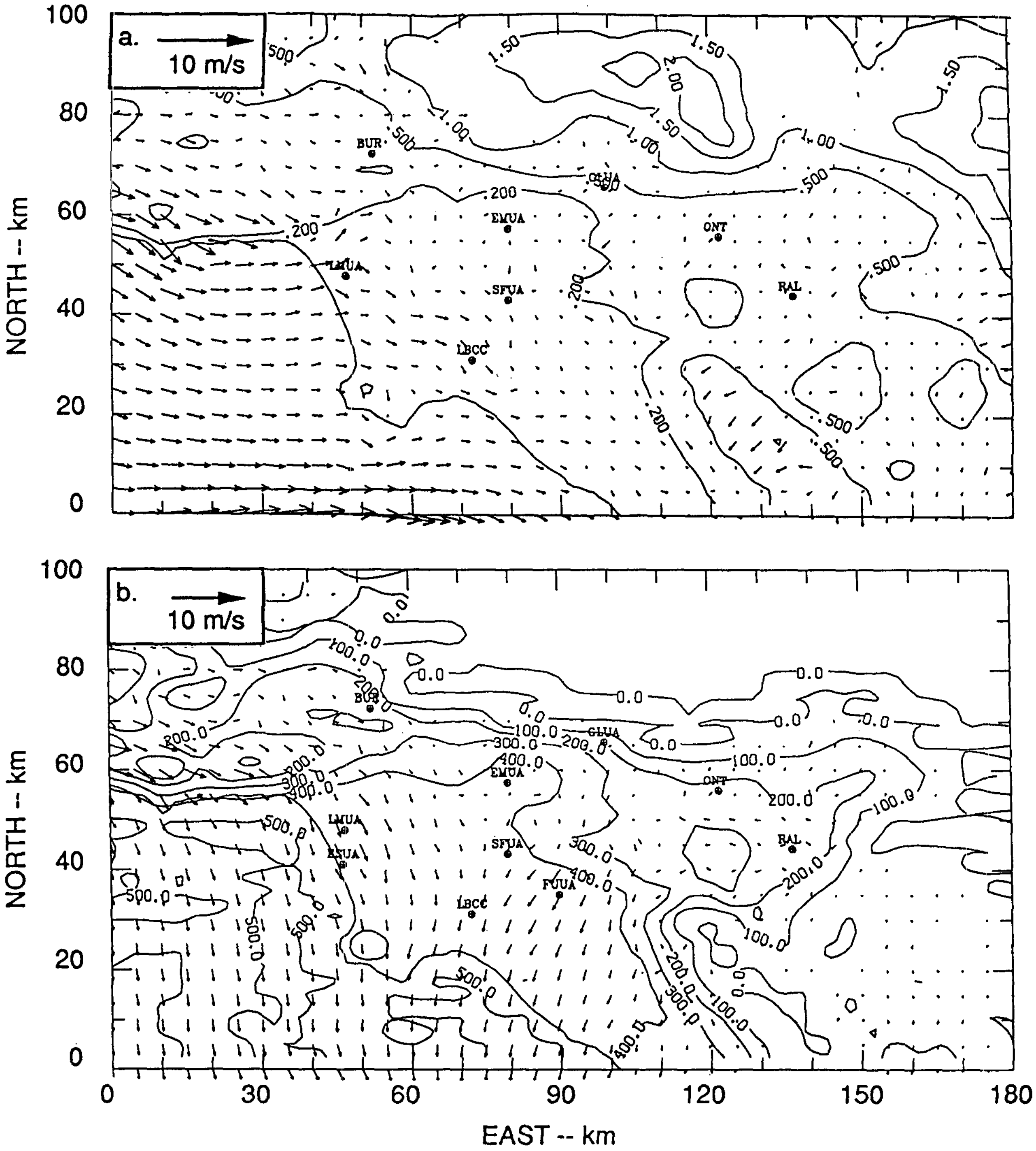


FIG. 3. WOCSS wind analyses of SCAQS data for 1100 PST 10 December 1987 at 10 m above the local terrain (a) and on the flow surface that was 500 m above the ocean surface (b).

The terrain effects are also more evident. Flow-surface cross sections for this case (Fig. 6) reflect reduced stability at the lower altitudes and higher wind speeds; accordingly, flow surfaces rise higher when they approach terrain obstacles, diminishing the tendency for deflection of the flow.

6. Performance and potential improvements

The objective analysis approach described above is efficient and has been found to be computationally stable, but applications to the SCAQS data and Thykier-Nielsen et al. (1990) have revealed some weaknesses.

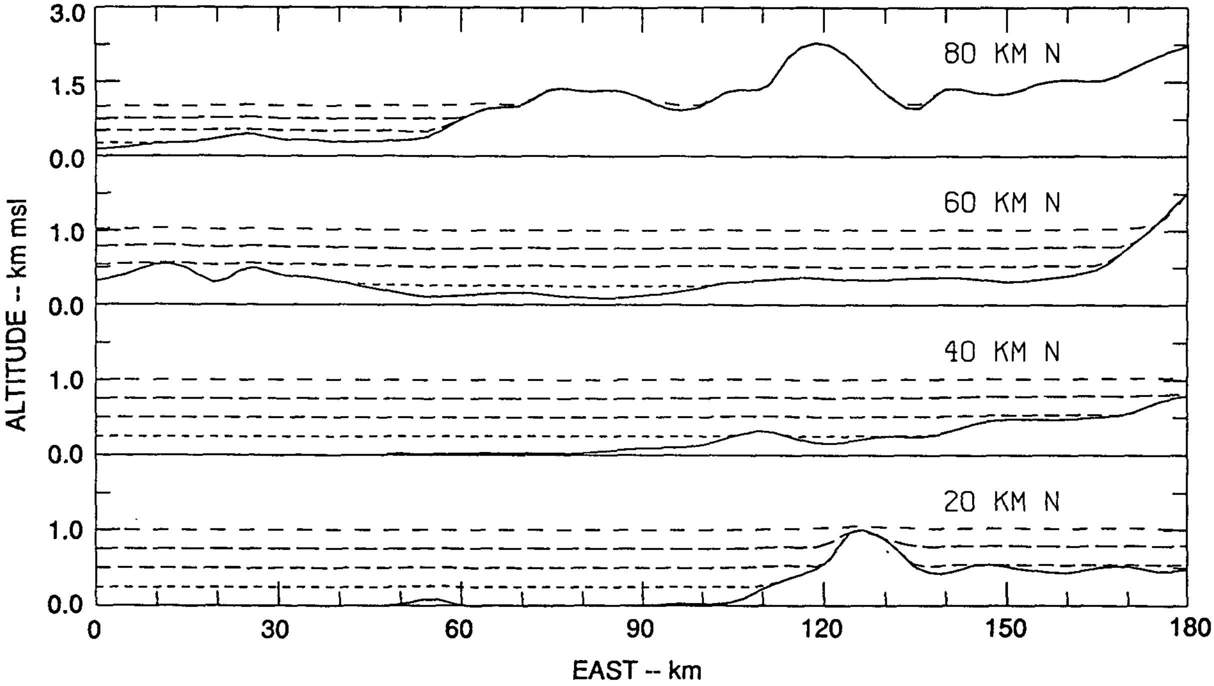


FIG. 4. East–west profiles of flow-surface heights for various ordinate values for 1100 PST 10 December 1987.

Foremost of these is the terrain-following treatment of flow during neutral and unstable conditions. Another shortcoming is the divergence (convergence) that remains in the analyses, especially for some important kinds of atmospheric circulations such as sea-breeze fronts. Wind fields with residual convergence or divergence are not suitable for transport and diffusion modeling applications that are often based on a presumption of mass-conserving flow. The remainder of this section discusses these problems in greater detail.

As noted before, Thykier-Nielsen et al. (1990) found that the WOCSS approach to objective wind analysis did not perform as well for neutral and unstable lapse rates as for stable conditions. Their evaluation was based on comparisons between measured and calculated location and extent of an inert tracer gas plume in the complex terrain around Vandenberg Air Force Base on the southern California coast. The two measures that they used were dose isopleth correlation area (DICA) and dose isopleth area (DIA). The DICA is the ratio of the area of overlap of modeled and measured isopleths (weighted for the isopleth value) to the correspondingly weighted union of these areas. Thus, values of DICA range from zero for no overlap to one for perfect agreement. The DIA compares the observed and modeled areas without regard to their location; therefore, it is not very effective as a measure of wind-field characterization. For the eight cases that they studied, the WOCSS analysis produced an average DICA of 0.33 versus 0.32 for the Troen and de Baas (1986) model, which used spectral solution of linearized equations of motion. The objective analysis method described here outperformed the other model in half the cases. Values of DICA ranged from 0.027 (for a case involving transition from evening northerly flow to nocturnal stagnation) to 0.56 (for a winter, northwesterly sea breeze).

The most important changes that could be made to the WOCSS code in order to improve its performance during less than stable conditions would be to change the way in which flow-surface shapes are defined during those conditions. In essence, the spacing of the flow surfaces needs to be consistent with observed wind profiles in rough terrain. For neutral and slightly unstable conditions, where there are minimal effects from elevated stable layers, the work of Jackson and Hunt (1975), Hunt and Snyder (1980), Ross et al. (1988), and others can serve as a guide. They have shown that there should be an increase in speed over an isolated hill. The increase is greatest when the flow is normal to the long axis of the hill. It should be possible to treat these effects by introducing a corresponding compression of the flow-surface spacing in order to increase flow speeds over high terrain. For isolated, reasonably regular hills or ridges this would be fairly easy to do. As an example, Ross et al. (1988) introduce differences in the vertical and horizontal weights used to achieve nondivergence by variational calculus methods in their sigma-surface model. In a general sense, this is analogous to a change in the relative slopes of the coordinate surfaces in the WOCSS approach. However, it is not clear how this approach can be extended to arbitrarily

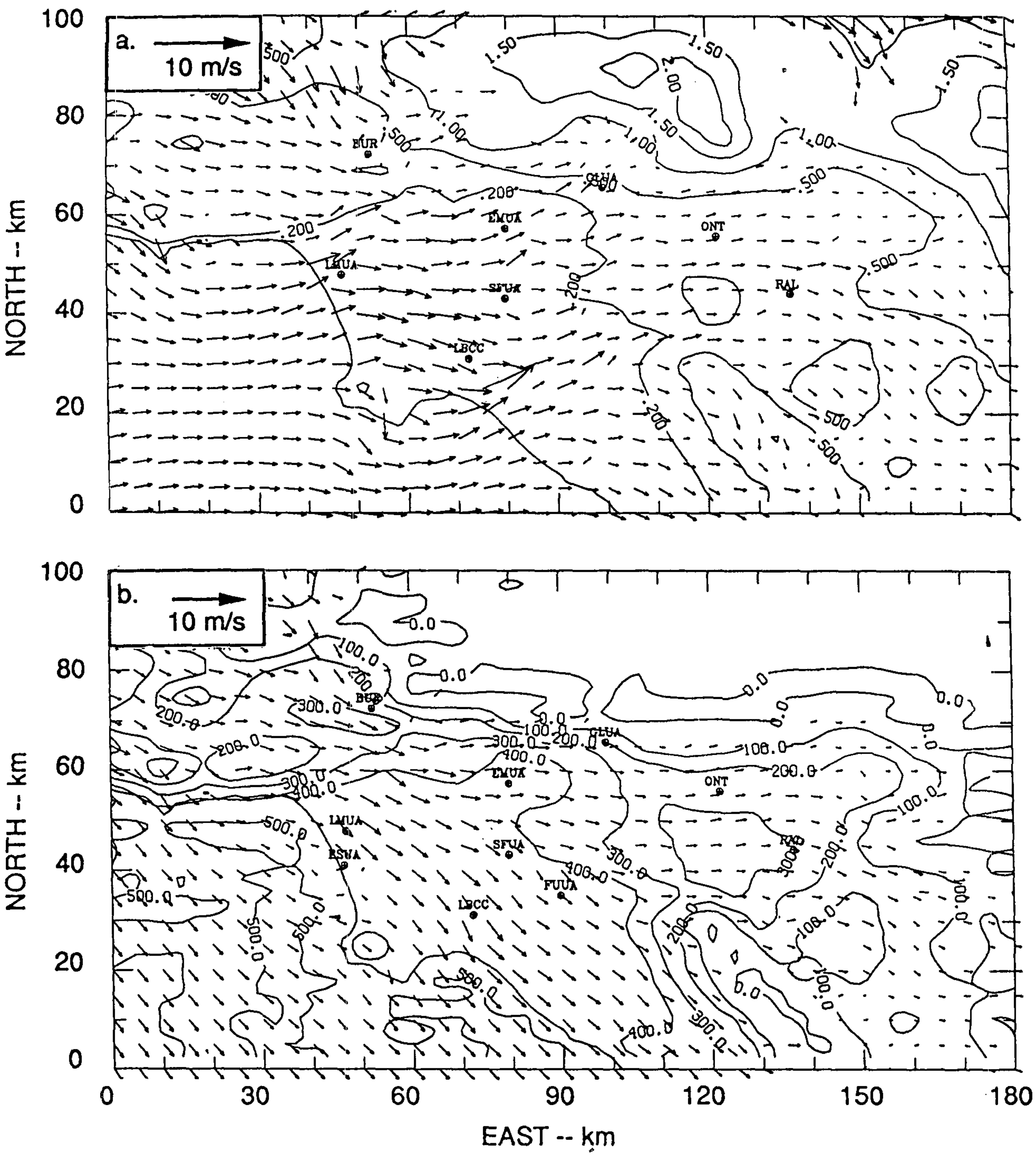


FIG. 5. WOCSS wind analyses of SCAQS data for 1400 PST 10 December 1987 at 10 m above the local terrain (a) and on the flow surface that was 500 m above the ocean surface (b).

shaped terrain or to situations where a neutral or unstable layer lies below a stable layer. In both cases, it is virtually impossible to define an unambiguous Froude number.

We have adopted Endlich's (1967) iterative scheme for removing divergence because of its speed and numerical stability. Numerical stability is essential for general application because it is quite possible for the input observations to define strongly converging (or diverging) flows, or for the flow surfaces to intersect the terrain in geometric configurations of above- and below-ground points for which it is impossible to re-

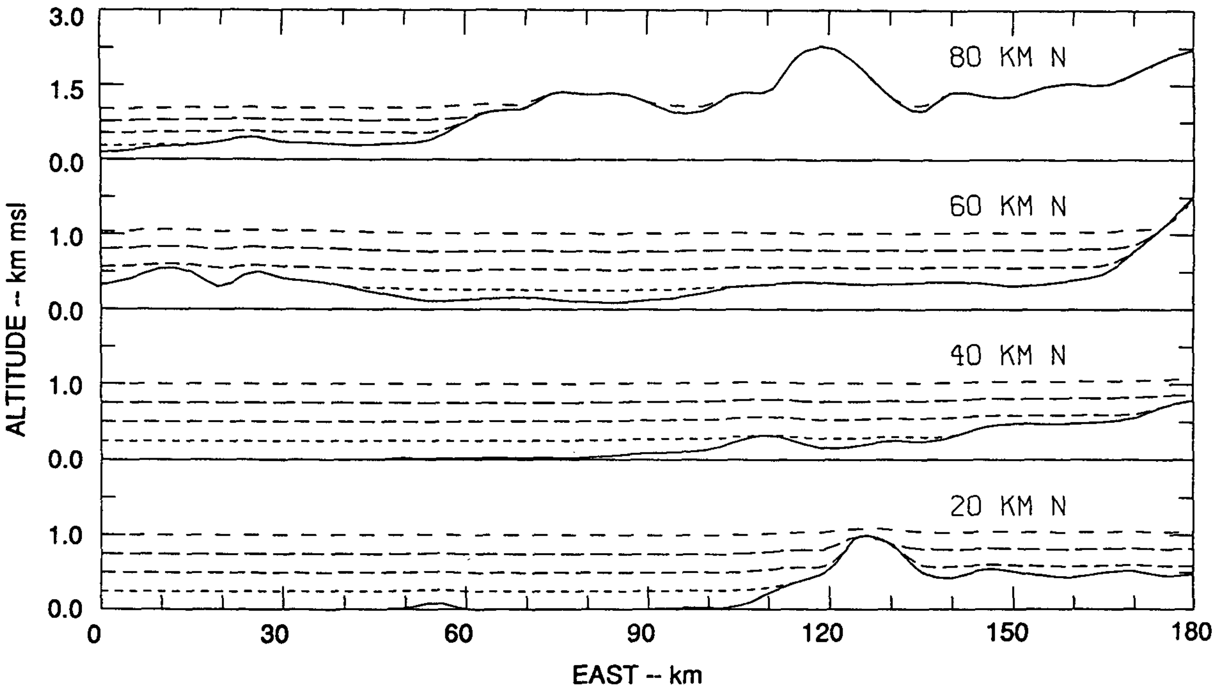


FIG. 6. East–west profiles of flow-surface heights for various ordinate values for 1400 PST 10 December 1987.

move the divergence. A simple example of the latter is the case where a point with a finite wind is surrounded by three or four underground, zero-wind points. The algorithm iterates until the divergence is removed or until a specified number of iterations has been performed. A maximum of 20 iterations have been used for most of our applications. As a result, there will be instances with residual divergence in complex terrain or with strongly convergent input flows. In the applications to the Los Angeles basin discussed above, the residual divergence in the sea-breeze convergence zone after 20 iterations was typically on the order of 10^{-4} s^{-1}. Divergence remains because the flow-surface concept is not appropriate for simulating flows that involve recirculation and strong vertical motions.

The residual divergence could lead to spurious dispersion effects in some air-quality modeling applications. All that is required to obtain fully mass-conserving flow is the addition of vertical wind components obtained from the vertical integration (upward from the surface) of whatever divergence remains after a specified number of iterations. This would be added to the vertical component w, which is derived from the horizontal velocity and the slope of the flow surfaces,

$$w = \mathbf{v} \cdot \nabla z_{\mathrm{sfc}}, \tag{4}$$

where $\mathbf{v}$ is the horizontal velocity and ∇z_{sfc} is the slope of the flow surface. If the slope is not too great, then the velocity in the flow surface can be used for $\mathbf{v}$. The resulting cross-surface flow would, to some extent, account for dynamic effects and recirculation. It is hoped that such a modification can be incorporated in future versions of the scheme.

There are other, less critical areas where improvements could be made in the WOCSS objective analysis approach, such as improving the iterative mass-balancing scheme in the vicinity of obstacles and improving the initial interpolation methods. The iterative divergence-removing algorithm makes adjustments only at grid points contiguous to the area where the divergence is being reduced, so the effects of terrain or convergence zones are spread gradually during subsequent iterations. In most applications, there are "underground" grid points (with zero winds) located adjacent to points with appreciable velocities. The effects of obstacles can be enhanced by adding logic that requires the winds adjacent to points of terrain intersection to be more nearly parallel to the local terrain contours. Such logic has been introduced in one version of the methodology, and initial testing indicates that the results are more realistic.

The quality of the initial interpolation is important because the final result tends to look much like the first guess, although this is less true of WOCCS analyses than it is for models using sigma-surface methods. Stability effects can be incorporated into the initial interpolation by introducing a maximum rate of conversion of kinetic energy to potential energy that is a function of atmospheric stability. The interpolated wind direction would then be changed to ensure that the upslope component meets the constraint. It may well be that the changes in the iterative adjustment procedure described in the preceding paragraph will accomplish much the same result.

7. Major extensions of the WOCSS concept

Knowledge of the turbulent state of the atmosphere can be used in many practical applications. Typically, the estimation of turbulence requires some or all of the following information:

- wind profiles
- temperature profiles
- surface heating
- surface characteristics such as roughness, albedo, and evaporative characteristics.

The objective analyses provide the necessary winds. A potential temperature field can easily be derived from the same temperature information used to define the flow surfaces. Many parameterizations of heat flux and other turbulence-related measures (e.g., Holtslag and van Ulden 1983; Sorbjan 1986; Stull 1988; Sutherland et al. 1986; van Ulden and Holtslag 1985) can provide estimates of surface heating (or cooling) from insolation, cloud cover, and surface characteristics. Finally, land-use categories provide estimates of the necessary surface properties. The WOCCS objective analysis scheme has been modified to provide turbulence estimates that pilots of low-flying aircraft can use to avoid hazardous regions (Ludwig and Lester 1991). Although the feasibility of incorporating turbulence estimates has been demonstrated, the estimates have yet to be quantitatively compared with measured turbulence.

Recently, Lewellan (1990) suggested that an objective wind and turbulence analysis methodology could be combined with a two-dimensional prognostic model to provide a very efficient three-dimensional boundary-layer model that could incorporate observational data much more easily than existing boundary-layer models can. Two-dimensional prognostic modeling would be done in vertical planes that are located and oriented so that the results would reproduce the important dynamic effects. These planes would be in dynamically active regions, such as normal to coast lines or heated slopes. The two-dimensional prognostic models would provide dynamically driven wind components and temperature profiles to be combined with observations as input for a WOCSS objective analysis. The resulting analysis would be a physically consistent, three-dimensional interpolation that combined prognostically modeled and observed conditions. It would correct the failure of the WOCSS approach by itself to address the important diabatic effects of differential heating that produce many important atmospheric circulations such as drainage winds, anabatic flows, and land and sea breezes.

8. Conclusions

A computerized objective analysis methodology has been developed to provide fast, objective wind analyses, incorporating two important physical constraints, mass conservation and the limitations of atmospheric stability on vertical displacement. It has proven to be practical and easy to apply. The applications have also revealed some weaknesses that should be addressed in the future. The comparisons presented by Thykier-Nielsen et al. (1990) show the analyses based on the WOCSS approach to be at least as good for use in plume modeling as the outputs of a linearized spectral model, but they also found that improvements are needed in the analyses during neutral and unstable conditions. Their results, based on comparisons of the location and extent of modeled and observed plumes, may also have shown the effects of the residual divergence that has been found in the WOCSS analyses. Section 6 discussed the manner in which both the problems that have been identified could be corrected. It is clear that the corrections are feasible, though difficult.

We feel that it is fair to conclude that some of the major extensions of the concepts that are presented here have great practical potential. Ludwig and Lester (1991) have demonstrated the feasibility of extending the objective analysis techniques to provide low-level turbulence estimates under dry convective conditions. If their approach (which requires only 1 or 2 min of computation on a personal computer) can provide reliable turbulence information, it will have many practical applications for both aviation and air pollution. Combining a two-dimensional boundary-layer model with the WOCSS objective analysis methodology would not present insurmountable problems, and the resultant model would meet an important need in the field of air pollution modeling. It would alleviate the heavy costs and computational requirements of the full-scale planetary boundary layer models that are frequently used to provide inputs for air-quality simulations. These computational requirements are so prohibitive that the air pollution models can rarely be applied for the broad variety of meteorological conditions that is required in the development of sound control strategies.

Versions of the computer code for the WOCSS objective analysis are in the public domain, although the sponsors of its development have placed some restrictions on distribution. The authors will be pleased to answer any questions regarding availability.

Acknowledgments. We are grateful for the U.S. Army's support under Contract DAAL03-86-D0001. Ms. Sue Hansen, Mr. Frank Hansen, and Dr. Walter Bach of the U.S. Army were helpful throughout the development of the most recent versions of the code. The SCAQS application was supported by Southern California Edison. As noted earlier, the work described here has grown from the work of many others whose contributions we gratefully acknowledge, especially those of Drs. C. Bhumralkar and M. Estoque.

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