An Alternate Procedure for Analyzing Surface Geostrophic Winds and Pressure over Elevated Terrain

ROGER A. PIELKE AND JENNIFER M. CRAM

Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523

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ABSTRACT

A methodology to analyze a flat surface geostrophic wind and pressure is presented which eliminates the arbitrariness of the standard reduction of surface pressure to mean sea level. The procedure utilizes a surface geostrophic wind defined in terms of a terrain-following coordinate system to derive a flat ground surface pressure field which is consistent in concept (i.e., nondivergent except for the f variation with latitude) with the currently applied MSL analyses. With this approach, interpretation of synoptic weather patterns in areas of elevated complex terrain will be more accurate.

1. Introduction

Even though many surface observing stations are well above sea level, conventional synoptic weather map analyses reduce surface pressure to mean sea level (MSL), because the display of station pressure alone from sites of different elevations is of little use in identifying synoptic weather patterns. Such analyses are produced and used both operationally (such as by the National Weather Service) and in research (from model simulations and observational data).

Unfortunately, the reduction of pressure to sea level from higher elevations requires an arbitrary assumption of a hypothetical temperature lapse rate within the ground. This results, for example, in the characteristic strong MSL analyzed high pressure systems in the Great Basin of the western United States in the winter, when cold air is trapped within the basin. The National Weather Service (NWS) incorporates a *plateau correction* (Manual of Barometry, 1963) to stations above 305 m based on the stations' mean annual temperature. This correction improves the analyses but does not completely reduce the error. In this paper, a simple method is introduced that derives a flat ground surface pressure field which is consistent in concept (i.e., nondivergent except for the f variation with latitude) with the currently applied MSL analyses.

2. Methodology

Pielke (1984), Pielke and Martin (1981), Martin and Pielke (1983), and Pielke et al. (1985) discuss the use of a terrain-following coordinate system to solve the conservation equations of motion. The vertical coordinate of this system is defined as

$$\sigma = s\frac{z - z_G}{s - z_G}$$

where z_G is the terrain elevation, z is the height above the surface, and s is an arbitrary height in the atmosphere. Figure 1 is an example of a terrain-following coordinate system. As shown by Pielke (1984), the simplified momentum equation for σ-parallel (terrain-following) flow can be written as:

$$\begin{aligned}\frac{du}{dt} &= -\theta\left.\frac{\partial\pi}{\partial x}\right|_\sigma + g\frac{\sigma - s}{s}\frac{\partial z_G}{\partial x} + fv \\ \frac{dv}{dt} &= -\theta\left.\frac{\partial\pi}{\partial y}\right|_\sigma + g\frac{\sigma - s}{s}\frac{\partial z_G}{\partial y} - fu.\end{aligned} \quad (1)$$

The pressure gradient term in the conventional x-y-z coordinate system is now the sum of the π gradient along a σ surface and terrain-gradient terms. The variables u and v are the σ-parallel flow in the east–west (x) and north–south (y) directions, respectively, f is the Coriolis parameter, θ is potential temperature, $\pi = c_pT/\theta = c_p(p/p_0)^{R/c_p}$, and T is temperature. The scaled pressure π is directly proportional to pressure p. Neglecting acceleration,

$$\begin{aligned}0 &= -\theta\left.\frac{\partial\pi}{\partial x}\right|_\sigma + g\frac{\sigma - s}{s}\frac{\partial z_G}{\partial x} + fv \\ 0 &= -\theta\left.\frac{\partial\pi}{\partial y}\right|_\sigma + g\frac{\sigma - s}{s}\frac{\partial z_G}{\partial y} - fu\end{aligned}$$

which simply is the definition for the geostrophic wind (u_g, v_g) in the σ-coordinate system, i.e.,

$$\begin{aligned}v_g &= \frac{\theta}{f}\left.\frac{\partial\pi}{\partial x}\right|_\sigma - \frac{g}{f}\frac{\sigma - s}{s}\frac{\partial z_G}{\partial x} \\ u_g &= -\frac{\theta}{f}\left.\frac{\partial\pi}{\partial y}\right|_\sigma + \frac{g}{f}\frac{\sigma - s}{s}\frac{\partial z_G}{\partial y}.\end{aligned} \quad (2)$$

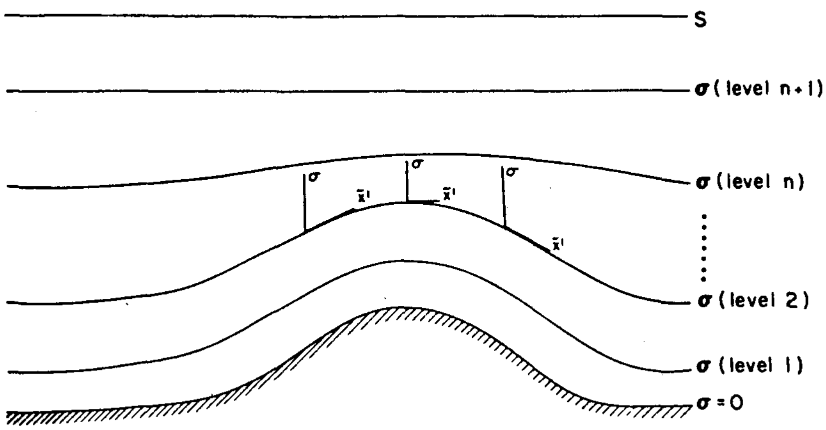

FIG. 1. A schematic of the terrain-following coordinate system, σ (from Pielke, 1984).

If there is no terrain slope, (2) reduces to the x-y-z representation of geostrophic wind:

$$v_g = \frac{\theta}{f}\frac{\partial \pi}{\partial x}$$

$$u_g = -\frac{\theta}{f}\frac{\partial \pi}{\partial y}.$$

At the surface, $z = z_G$ ($\sigma = 0$), so that (2) reduces to

$$v_g = \frac{\theta}{f}\frac{\partial \pi}{\partial x} + \frac{g}{f}\frac{\partial z_G}{\partial x} = \frac{\theta}{f}\frac{\partial \tilde{\pi}}{\partial x}$$

$$u_g = -\frac{\theta}{f}\frac{\partial \pi}{\partial y} - \frac{g}{f}\frac{\partial z_G}{\partial y} = \frac{-\theta}{f}\frac{\partial \tilde{\pi}}{\partial y}. \tag{3}$$

Equation (3) is an equation for the surface geostrophic wind, which can be used to obtain a corresponding horizontal pressure gradient over flat terrain ($\partial\tilde{\pi}/\partial x$, $\partial\tilde{\pi}/\partial y$) which defines the surface geostrophic wind components, u_g and v_g. The values of $\tilde{\pi}$ are obtained from the equation

$$\frac{\partial^2 \tilde{\pi}}{\partial x^2} + \frac{\partial^2 \tilde{\pi}}{\partial y^2} = \frac{\partial}{\partial x}\left(\frac{v_g f}{\theta}\right) - \frac{\partial}{\partial y}\left(\frac{u_g f}{\theta}\right) \tag{4}$$

where u_g and v_g are evaluated from (3). The wind components u_g and v_g are parallel to σ-surfaces (see Pielke et al., 1985), and therefore include a nonzero vertical component. The component of the σ-system pressure gradient which we want to display for analysis purposes, however, is the one on a flat surface. Since in a flat, mean sea level, z-system the geostrophic wind is nondivergent except for the effect of north–south f-variations, we differentiate v_g by $\partial/\partial x$ and u_g by $\partial/\partial y$ and subtract, yielding the elliptic equation for $\tilde{\pi}$.

Potential temperature, θ, values must be known and the horizontal boundary values of $\tilde{\pi}$ need to be specified in order to permit the solution of (4) to obtain $\tilde{\pi}$ (and thus, pressure) everywhere within the domain. For the purpose of this paper, the boundary values of $\tilde{\pi}$ were specified using the standard lapse rate reduction, and the interior values of $\tilde{\pi}$ were obtained using a relaxation procedure on (4). Surface values of θ were used for θ, although the procedure was found to be relatively insensitive to the θ-field. In general, the most consistent specification of the lateral boundary conditions needed in (4) would be from a domain in which the perimeter is at sea level.

An important aspect of this procedure is its simplicity. Relaxation methods are easy to program and already available in packages on many computer systems. A terrain-following coordinate system may seem confusing to those used to the more conventional x-y-z system, but is really only used in this procedure to derive an accurate surface geostrophic wind. The end result is that the pressure analysis derived from (4) is less arbitrary and thus more accurate than that obtained with a conventional reduction. A lapse-rate assumption or plateau correction is not needed for this method.

Sangster (1960) developed the idea that the streamline and potential fields of the surface geostrophic winds can provide a better intuitive estimate of the MSL pressure gradients than reduced pressure. The pressure analysis in our paper is derived from the flat surface (or nondivergent) component of the terrain-following surface geostrophic winds. This analysis is less arbitrary than the conventional reduced MSL pressure analyses and more easily and directly interpreted by the forecaster than Sangster's derived fields. In the next section, our introduced and the conventional methods will be contrasted for both a winter and summer case.

3. Results

Figure 2 illustrates the smoothed topography of the western United States and northern Mexico. The USAF 30-minute average elevation data were splined to a 1° latitude by 1° longitude grid (40 × 30 grid points, from 25° to 49°N and 130° to 91°W) and then operated on with five passes of a two-dimensional, 5-point smoother. The data for the two cases discussed in this

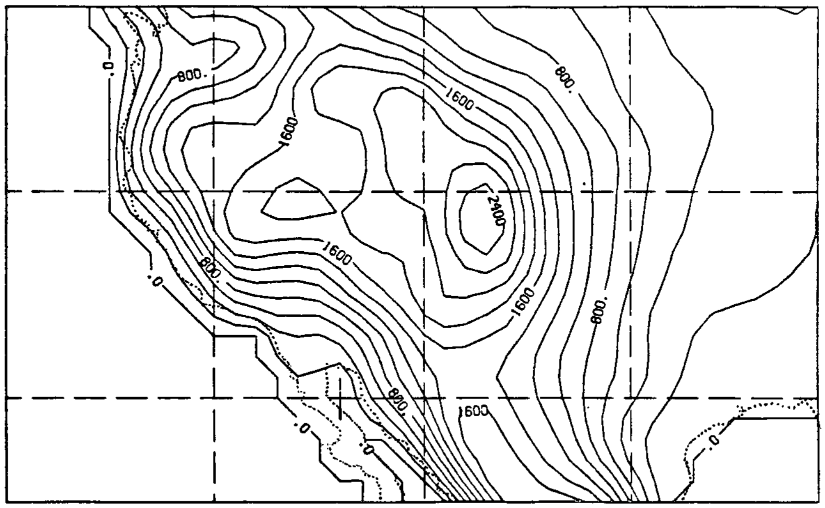

FIG. 2. Surface elevation (m).

section were obtained from the NMC (National Meteorological Center) 2.5° global analyses of heights and temperatures on the standard pressure surfaces. These were splined horizontally and interpolated vertically to the 40 × 30 grid and surface elevations.

The conventional MSL reduced pressure analyses were calculated by using the assumption of a standard lapse rate of temperature $\partial T/\partial Z = -6.5 \times 10^{-3}$ K m^{-1} below the ground surface. The plateau correction procedure should improve the analysis of mean sea level pressure; however, an assumption of temperature lapse rate below the terrain height is still required. To illustrate our proposed procedure, we retained the standard large assumption for simplicity. These analyses are compared to those obtained using the methodology described in section 2 of this paper. The boundary conditions for that solution are obtained by using the conventional pressure reduction.

The conventionally reduced mean sea level pressure analysis for 1200 UTC 5 February 1980 is shown in Fig. 3. The geostrophic wind vectors and wind magnitude computed from this analysis, i.e.,

$$u_{g_s} = -\frac{\theta}{f}\frac{\partial \pi}{\partial y}; \quad v_{g_s} = \frac{\theta}{f}\frac{\partial \pi}{\partial x}$$

are given as Figs. 4 and 5. A large pressure gradient and corresponding large geostrophic wind speeds are evident along the base of the high pressure ridge. In contrast, using (3) along with the terrain gradients from

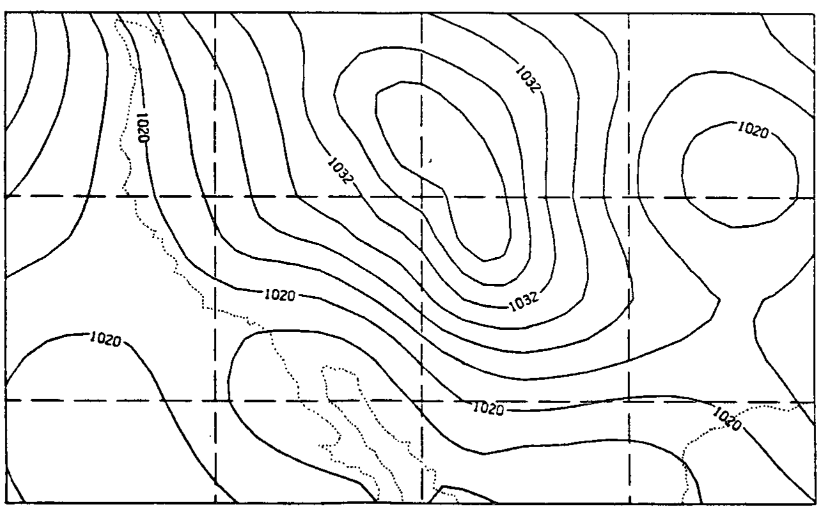

FIG. 3. MSL pressure (mb), p_{MSL}, obtained by using a standard lapse rate reduction for 5 February 1980.

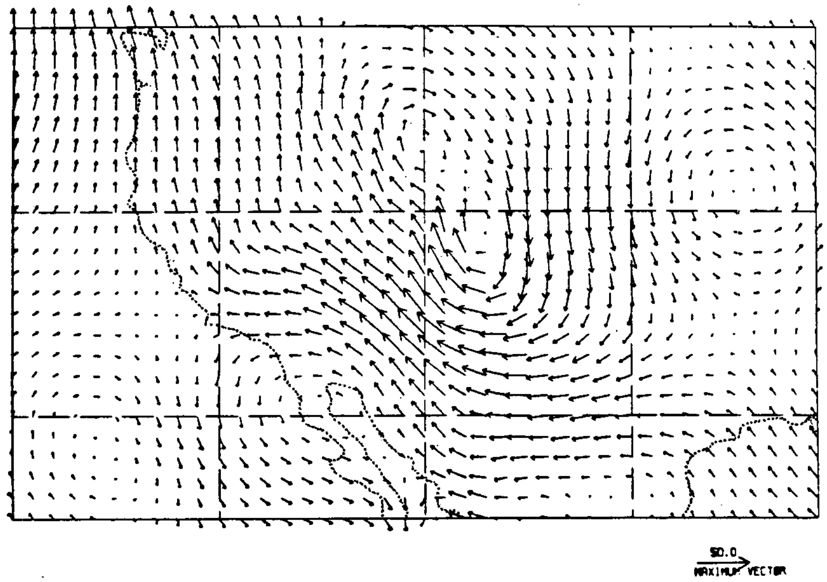

FIG. 4. Geostrophic wind vectors for 5 February 1980 from p_{MSL} in Fig. 3.

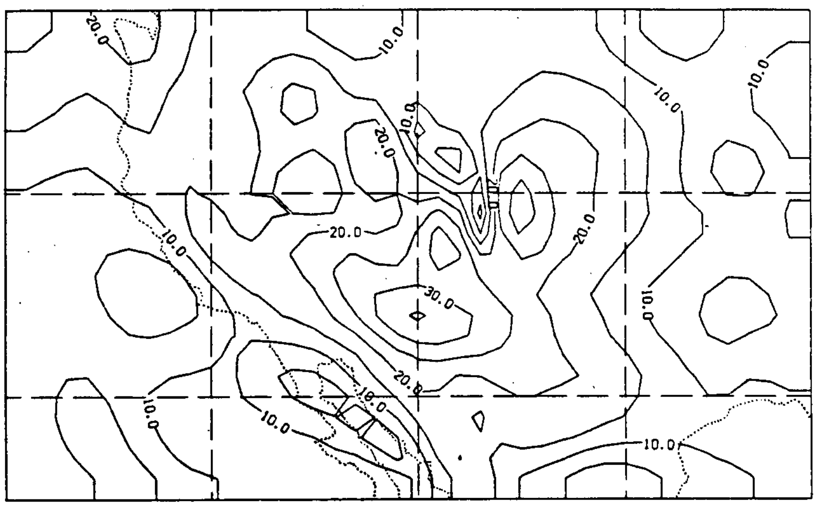

FIG. 5. Geostrophic wind magnitudes (m s^{-1}) for 5 February 1980 from p_{MSL} in Fig. 3.

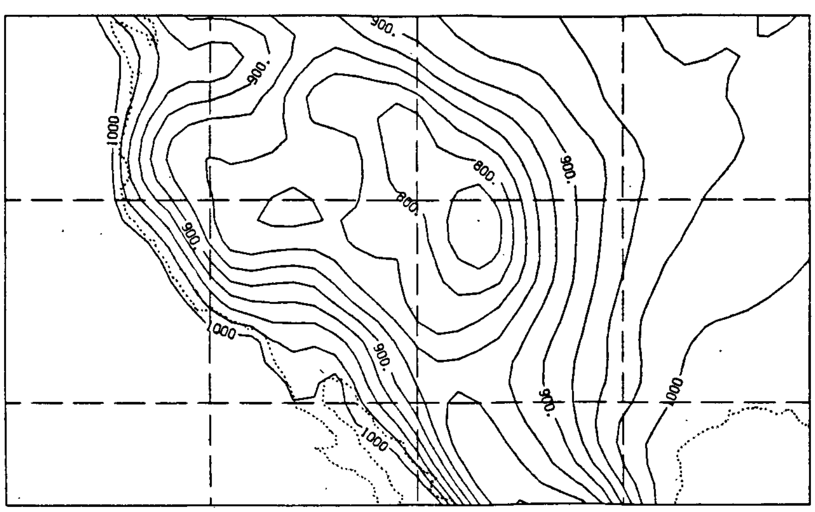

FIG. 6. Surface pressure (mb) for 5 February 1980.

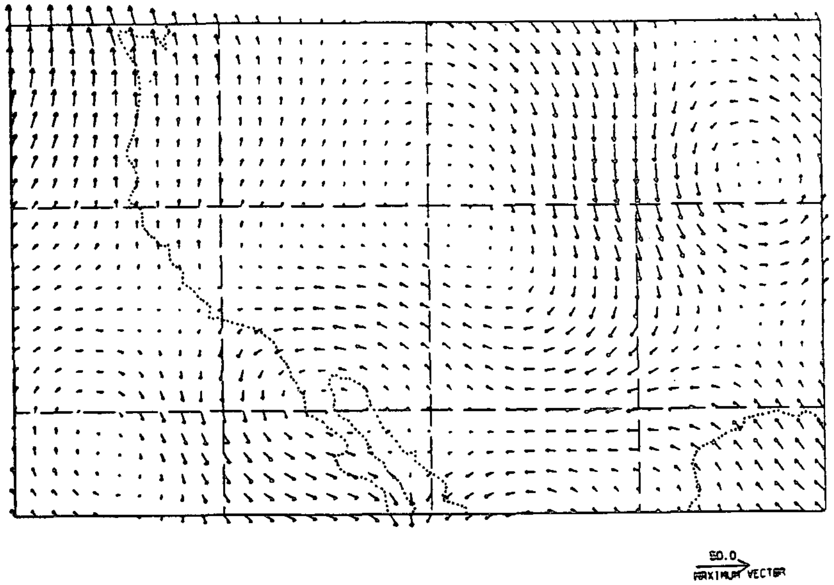

FIG. 7. Geostrophic wind vectors for 5 February 1980 calculated using (3).

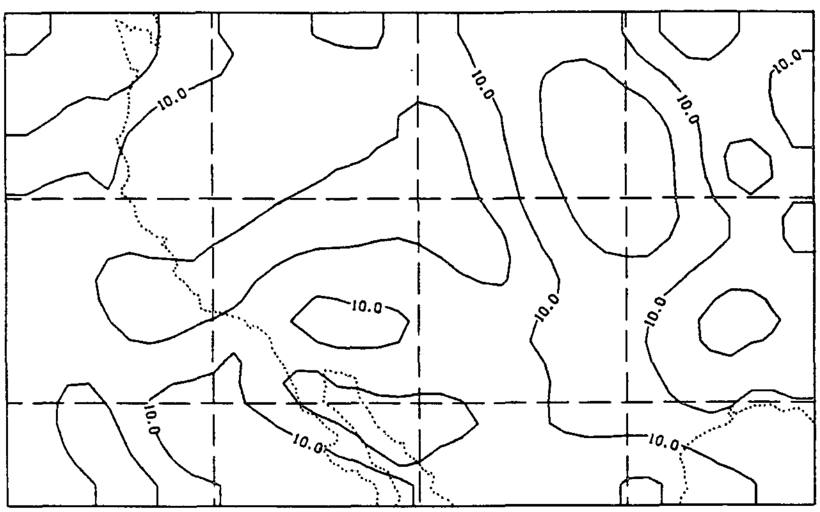

FIG. 8. Geostrophic wind magnitudes (m s^{-1}) for 5 February 1980 calculated using (3).

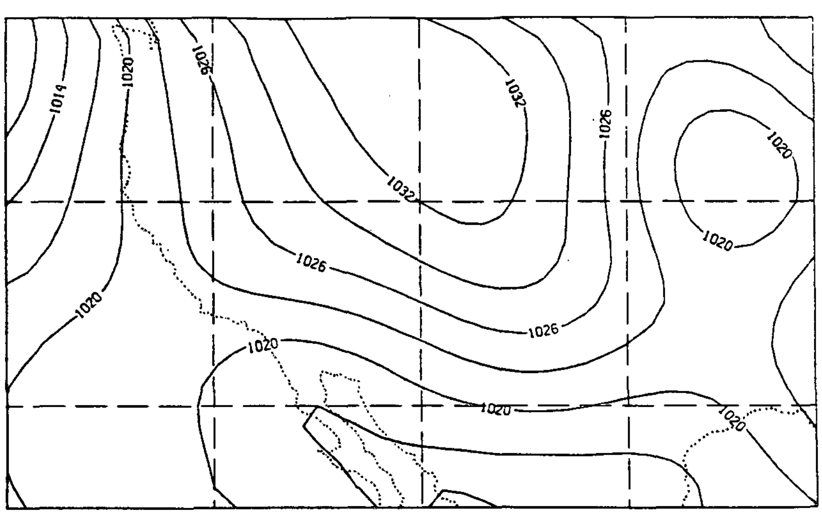

FIG. 9. Geostrophic pressure analysis obtained from (4) for 5 February 1980.

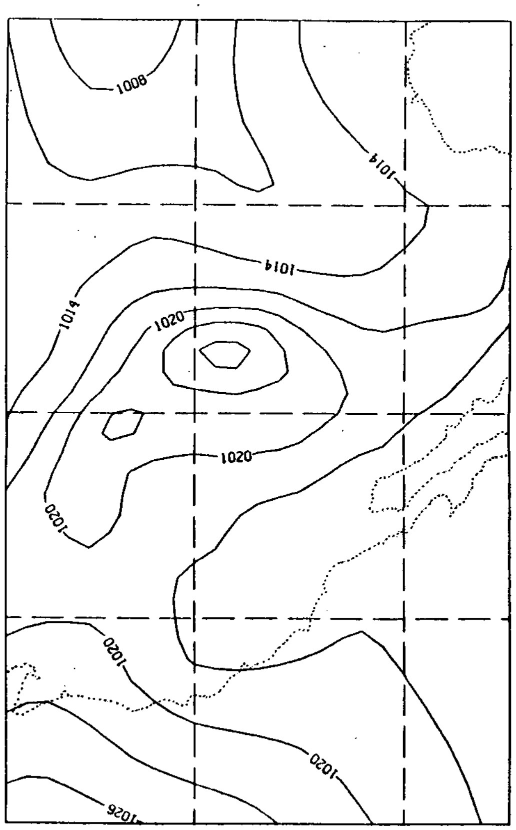

FIG. 10. MSL pressure (mb), p_{MSL}, obtained by using a standard lapse rate reduction for 20 July 1981.

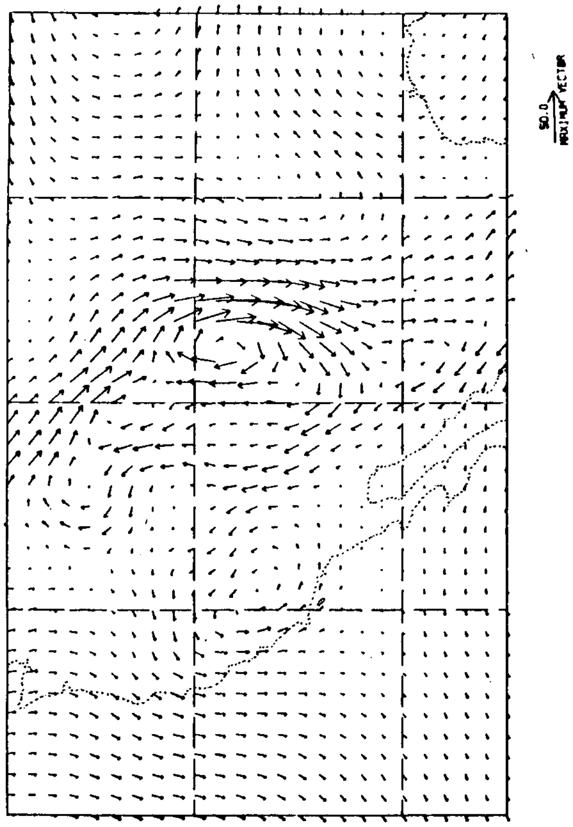

FIG. 11. Geostrophic wind vectors for 20 July 1980 from p_{MSL} in Fig. 10.

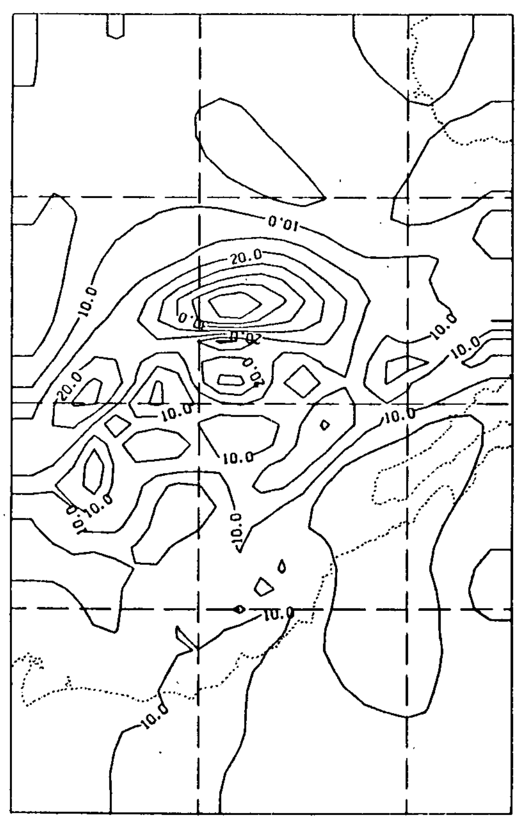

FIG. 12. Geostrophic wind magnitudes (m s^{-1}) for 20 July 1981 from p_{MSL} in Fig. 10.

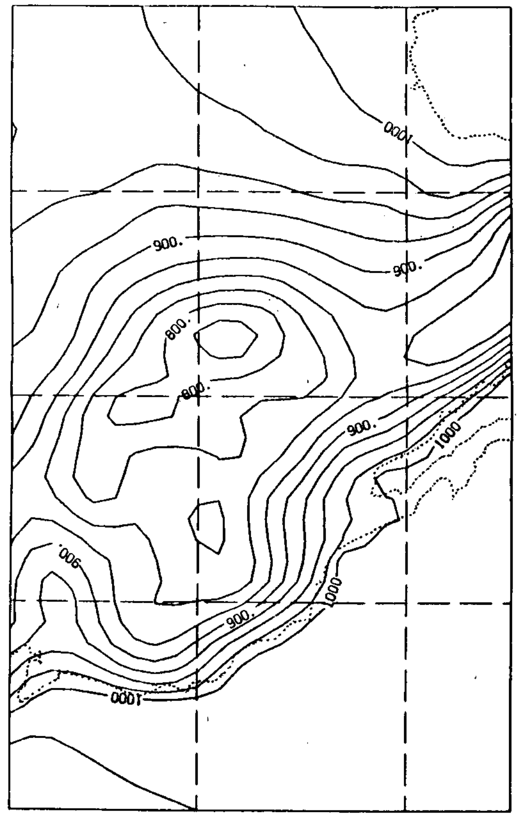

FIG. 13. Surface pressure (mb) for 20 July 1981.

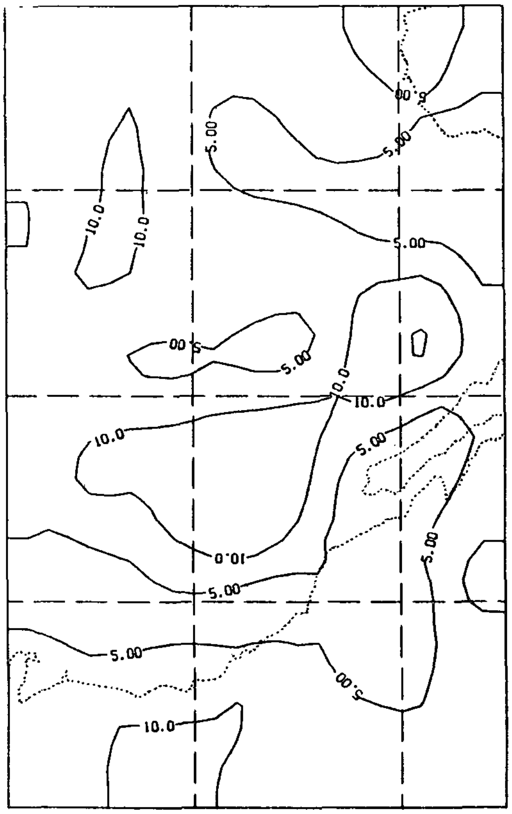

FIG. 15. Geostrophic wind magnitudes (m s^{-1}) for 20 July 1981 calculated using (3).

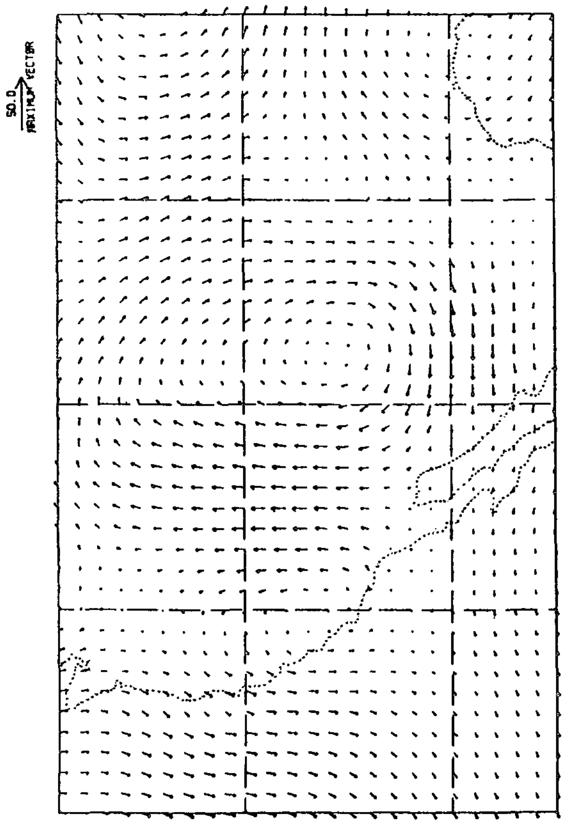

FIG. 14. Geostrophic wind vectors for 20 July 1981 calculated using (3).

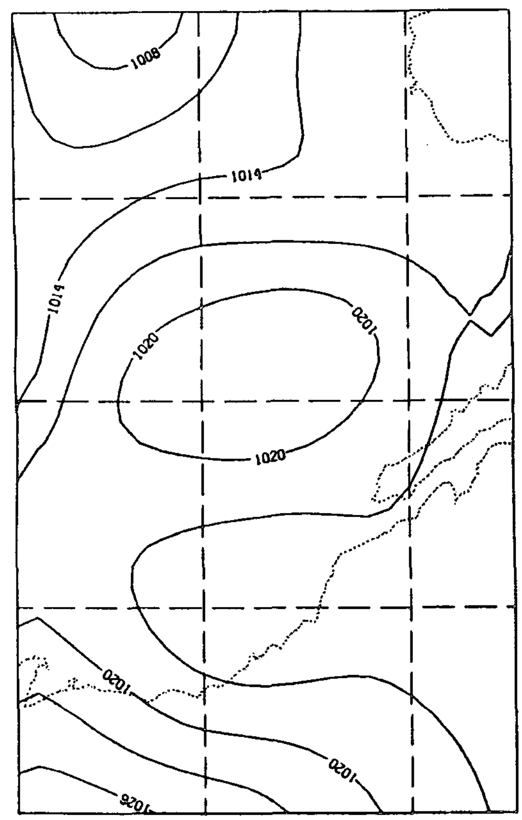

FIG. 16. Geostrophic pressure analysis obtained from (4) for 20 July 1981.

Fig. 2 and the surface pressure distribution in Fig. 6, the much smoother and somewhat reduced geostrophic wind speed pattern illustrated in Figs. 7 and 8 results. The much more chaotic distribution of wind speeds in Fig. 5 as contrasted with that in Fig. 8 is a result of the arbitrary reduction of pressure to sea level used to obtain Fig. 5. The corresponding pressure analysis derived using (4) is shown in Fig. 9. The conventional MSL reduction analysis has a much stronger high pressure area (stronger by as much as 6 mb) over the Great Basin, and associated stronger horizontal pressure gradients. The conventionally reduced pressure analysis results in overly strong pressure gradients and thus overly strong surface geostrophic winds.

A summertime situation (1200 UTC 20 July 1981) is presented in Figs. 10 through 16. As with the 5 February 1980 example, a comparison between Fig. 12 (geostrophic wind evaluated from reduced MSL pressure) and Fig. 15 (geostrophic wind evaluated at the ground surface) shows that the large geostrophic wind speed and somewhat chaotic pattern is eliminated when the ad hoc, arbitrary reduction of pressure to sea level is not performed. Figure 16 is the derived pressure analysis [from (4)] for the summer case. The strength of the analyzed high pressure area over the western United States is again reduced by approximately 6 mb and the surrounding pressure gradients are correspondingly decreased. The surface pressure analysis in Fig. 16 is less misleading than that in Fig. 10.

4. Conclusion

A simple methodology to analyze surface geostrophic wind and pressure is presented which eliminates the arbitrariness of reducing pressure to mean sea level in areas of elevated terrain. The method reduces the apparently excessive pressure gradients that result from conventional MSL pressure reduction analyses. The procedure utilizes a geostrophic wind defined in terms of a terrain-following coordinate system to derive a flat ground surface pressure field which is consistent in concept (i.e., nondivergent except for the f variation with latitude) with the currently applied MSL analyses. This approach is easy to implement and should be useful to both operational meteorologists in interpreting real-time synoptic data and researchers in their analysis of model output and observational data.

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