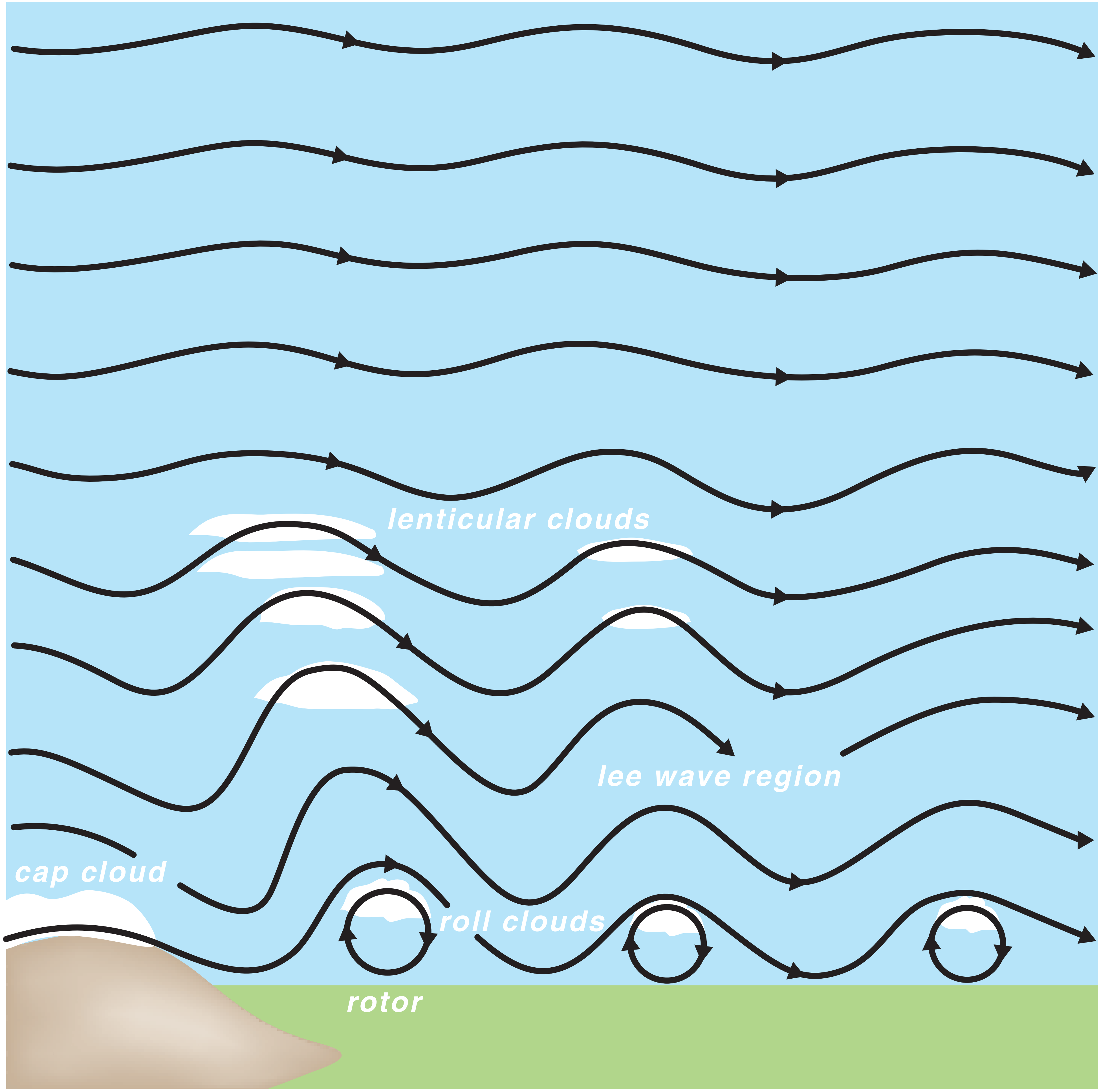
Mountain Waves and Downslope Windstorms


lenticular clouds
lee wave region
cap cloud
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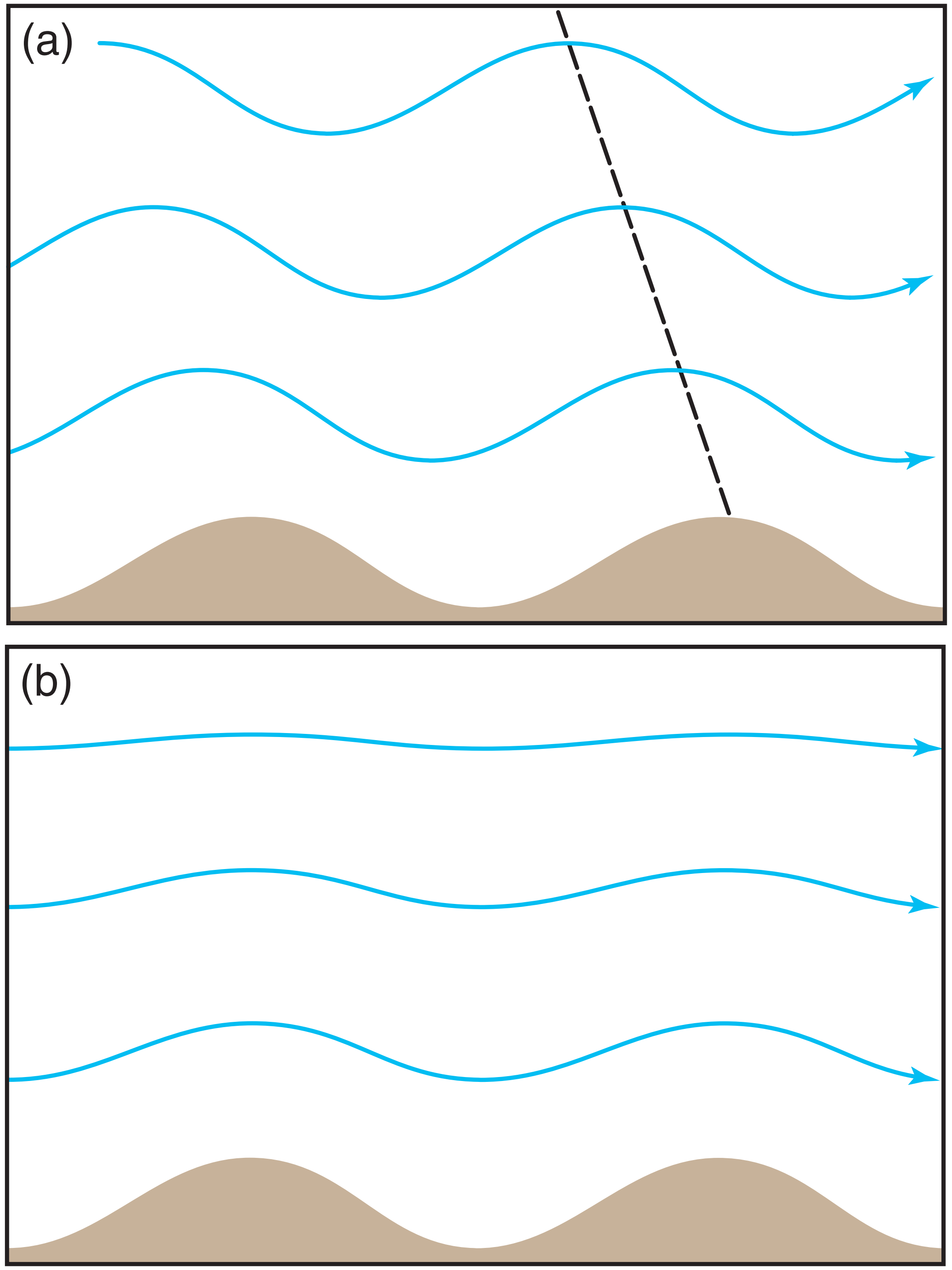
rotor



vertically propagating waves

evanescent waves

Figure 12.3 Streamlines in steady flow over an infinite series of sinusoidal ridges (a) for the case where $N^2 > u_0^2 k^2$ and (b) for the case where $N^2 < u_0^2 k^2$. The dashed line in (a) shows the phase of maximum upward displacement, which tilts westward with height. (Adapted from Durran [1990].)

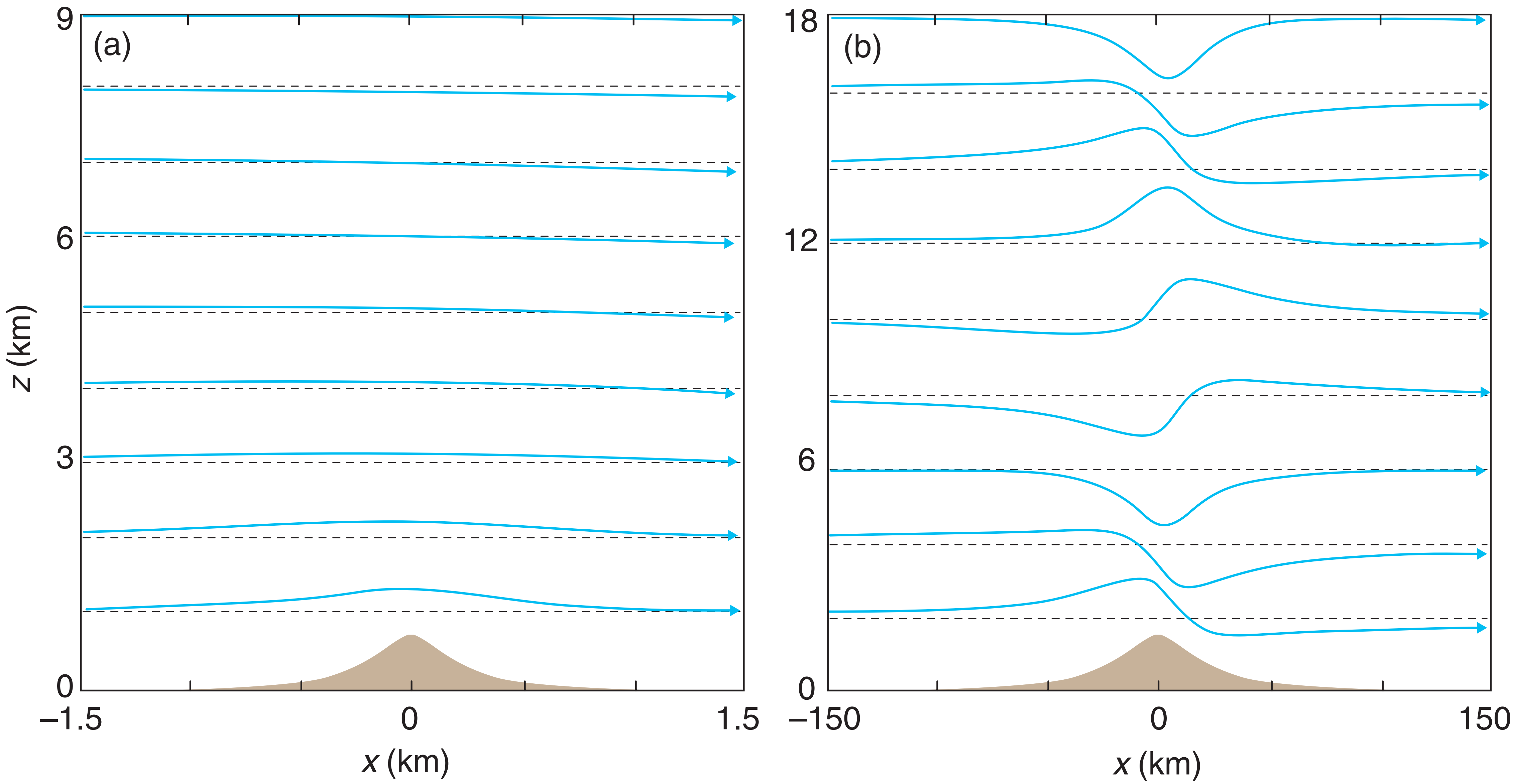


Figure 12.4 Streamlines in steady airflow over an isolated ridge when (a) $u_0 a^{-1} \gg N$ and (b) $u_0 a^{-1} \ll N$. (Adapted from Durran [1986a].)

Boundary Conditions

- *Surface:* Topography
- *Top:* Transport energy out of domain
- *Lateral:* Transport energy out of domain

Surface Boundary Conditions

- Rigid and free-slip
- Topography:
  - Terrain-following coordinate system
  - Immersed boundary method
  - Linearized: $w(x, 0) = v(x, 0) \dfrac{dz_s}{dx}$

Top Boundary Conditions

- The radiation boundary condition, which requires energy transport out of the domain, is approximated.
- This condition is essential for successful simulation of vertically propagating mountain waves.
- This b.c. is approximated by adding an absorbing layer to the top of the domain.
- Waves entering this layer from below have negligible amplitude when they reach the top of the domain.

Lateral Boundary Conditions

- The lateral b.c. are also designed to radiate energy out of the domain.
- The goal is to minimize spurious reflection of outward propagating waves at the lateral boundary.
- The phase speed c of a gravity wave impinging on the boundary is estimated.
- The horizontal velocity u is advected outwards at the boundary with speed $u + c$.

Lateral Boundary Conditions

- For other variables at the *outflow* boundary, centered differences are replace by upstream differences.
- At the inflow boundary, the horizontal gradients are set to zero.

Numerical Smoothing

- A small amount of numerical smoothing us applied to all fields except the Exner function to control growth of non-linear instability and remove short wavelength modes.

Testing the Model

- Linear hydrostatic waves in an isothermal atmosphere
- Mountain contour: $z_s(x) = \dfrac{ha^2}{x^2 + a^2}$
- *a* = 10 km, *h* = height of mountain
- Use linearized b.c. for *w(x,0)*.
- Analytic solution exists.

A Compressible Model for the Simulation of Moist Mountain Waves

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ABSTRACT

A two-dimensional, nonlinear, nonhydrostatic model is described which allows the calculation of moist airflow in mountainous terrain. The model is compressible, uses a terrain-following coordinate system, and employs lateral and upper boundary conditions which minimize wave reflections.

The model's accuracy and sensitivity are examined. These tests suggest that in numerical simulations of vertically propagating, highly nonlinear mountain waves, a wave absorbing layer does not accurately mimic the effects of wave breakdown and dissipation at high levels in the atmosphere. In order to obtain a correct simulation, the region in which the waves are physically absorbed must generally be included in the computational domain (a nonreflective upper boundary condition should be used as well).

The utility of the model is demonstrated in two examples (linear waves in a uniform atmosphere and the 11 January 1972 Boulder windstorm) which illustrate how the presence of moisture can influence propagating waves. In both cases, the addition of moisture to the upstream flow greatly reduces the wave response.

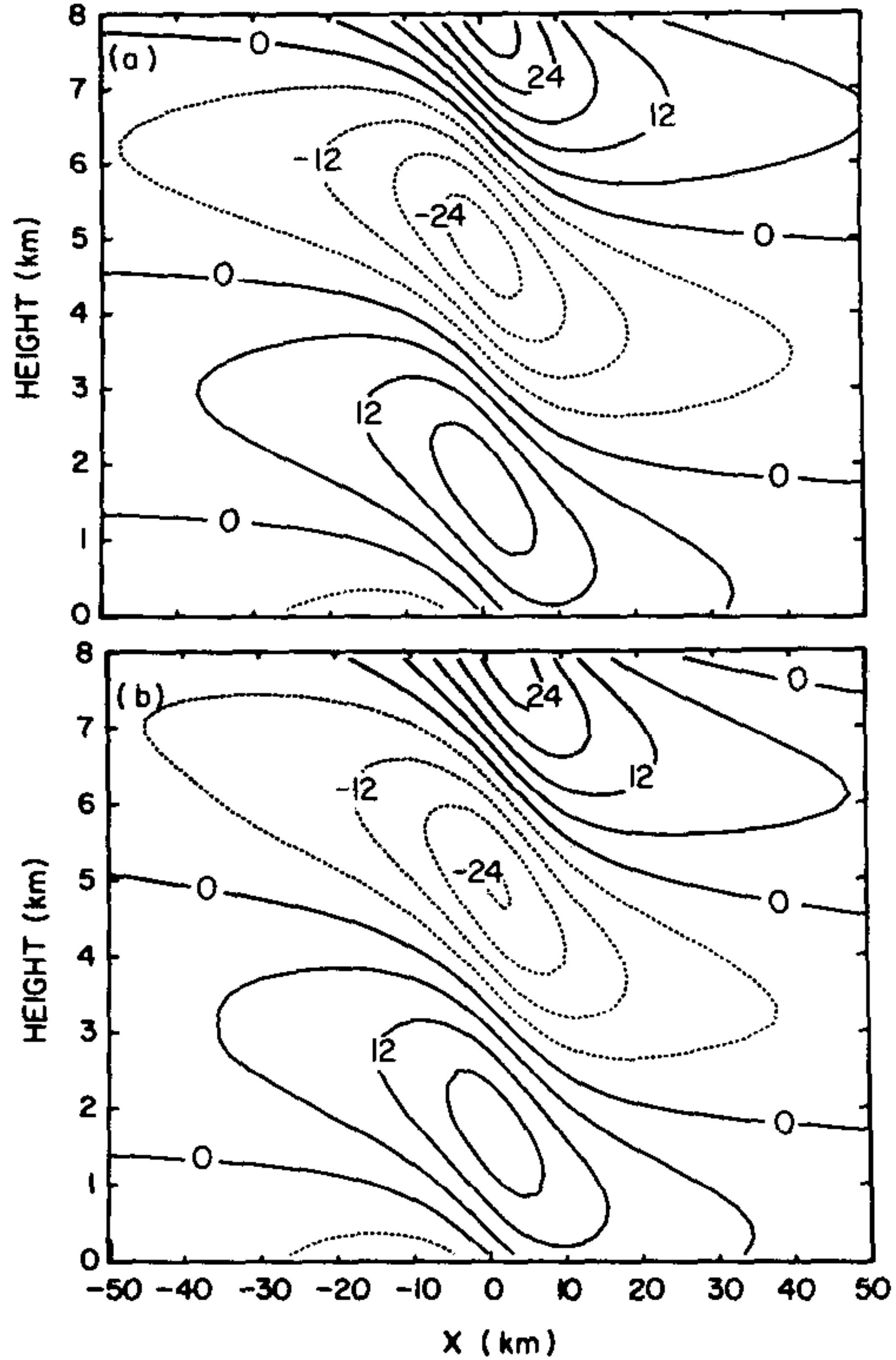

FIG. 1. (a) Steady state perturbation horizontal velocity (m s^{-1}) from the linear hydrostatic solution for a 1000 m high mountain. (b) Perturbation horizontal velocity (m s^{-1}) obtained by numerical simulation for a 1 m high mountain at $\bar{u}t/a = 60$; the perturbations have been amplified by 1000.

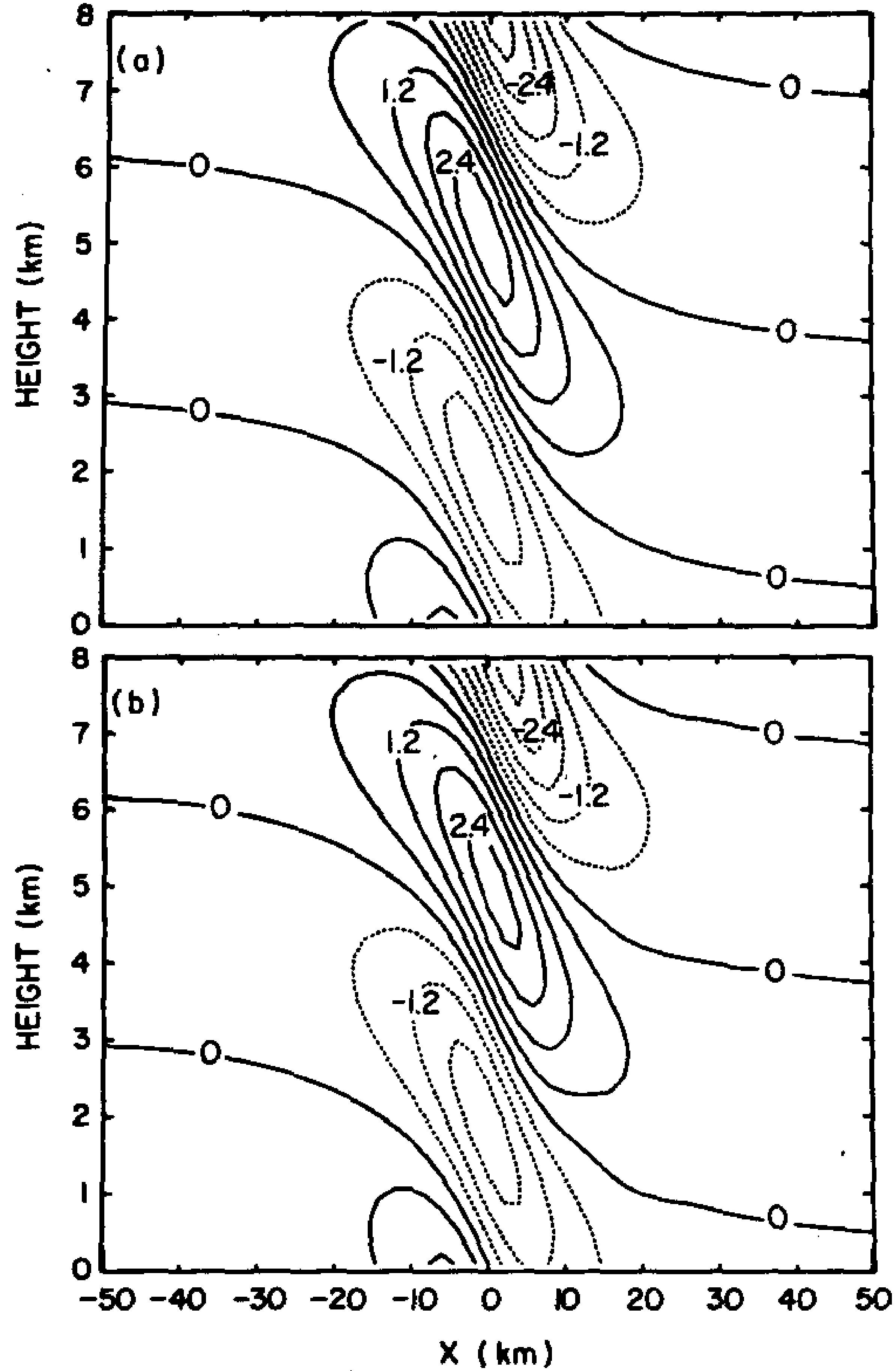

FIG. 2. As in Fig. 1, except that the fields plotted are vertical velocity (m s^{-1}).

CLOUD MODELING FINAL PROJECT REPORT
MOUNTAIN WAVE

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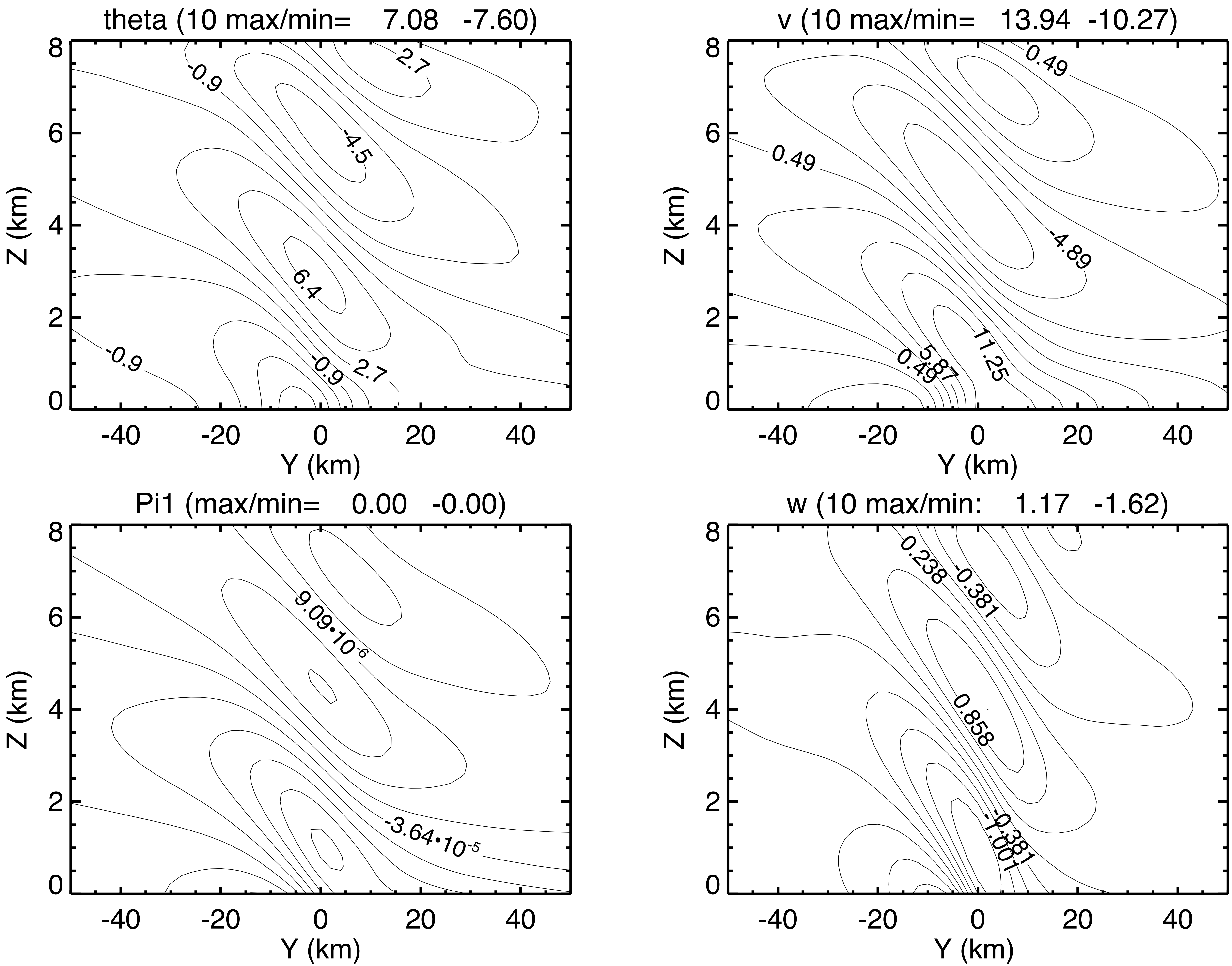
theta (10 max/min= 7.08 -7.60)
-0.9
2.7
-4.5
6.4
-0.9
2.7
-0.9
Z (km)
Y (km)
v (10 max/min= 13.94 -10.27)
0.49
0.49
-4.89
11.25
5.87
0.49
Z (km)
Y (km)
Pi1 (max/min= 0.00 -0.00)
9.09•10^-6
-3.64•10^-5
Z (km)
Y (km)
w (10 max/min: 1.17 -1.62)
0.238
-0.381
0.858
-0.381
-1.001
Z (km)
Y (km)

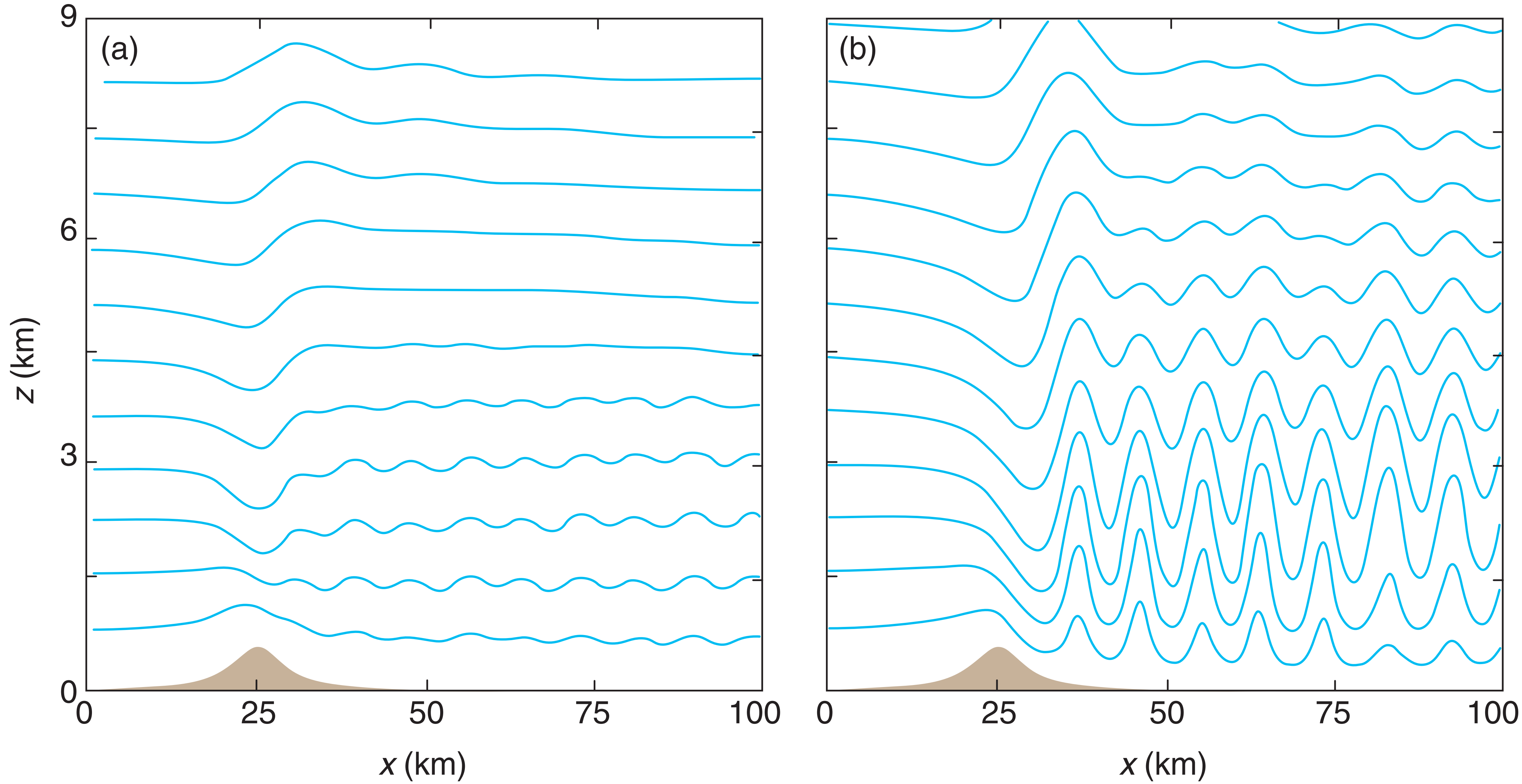

Figure 12.5 Streamlines in air flow over a mountain for (a) steady flow subject to the linear approximation and (b) the fully nonlinear and unsteady solution. (Adapted from Durran [2003a].)

Downslope Windstorms

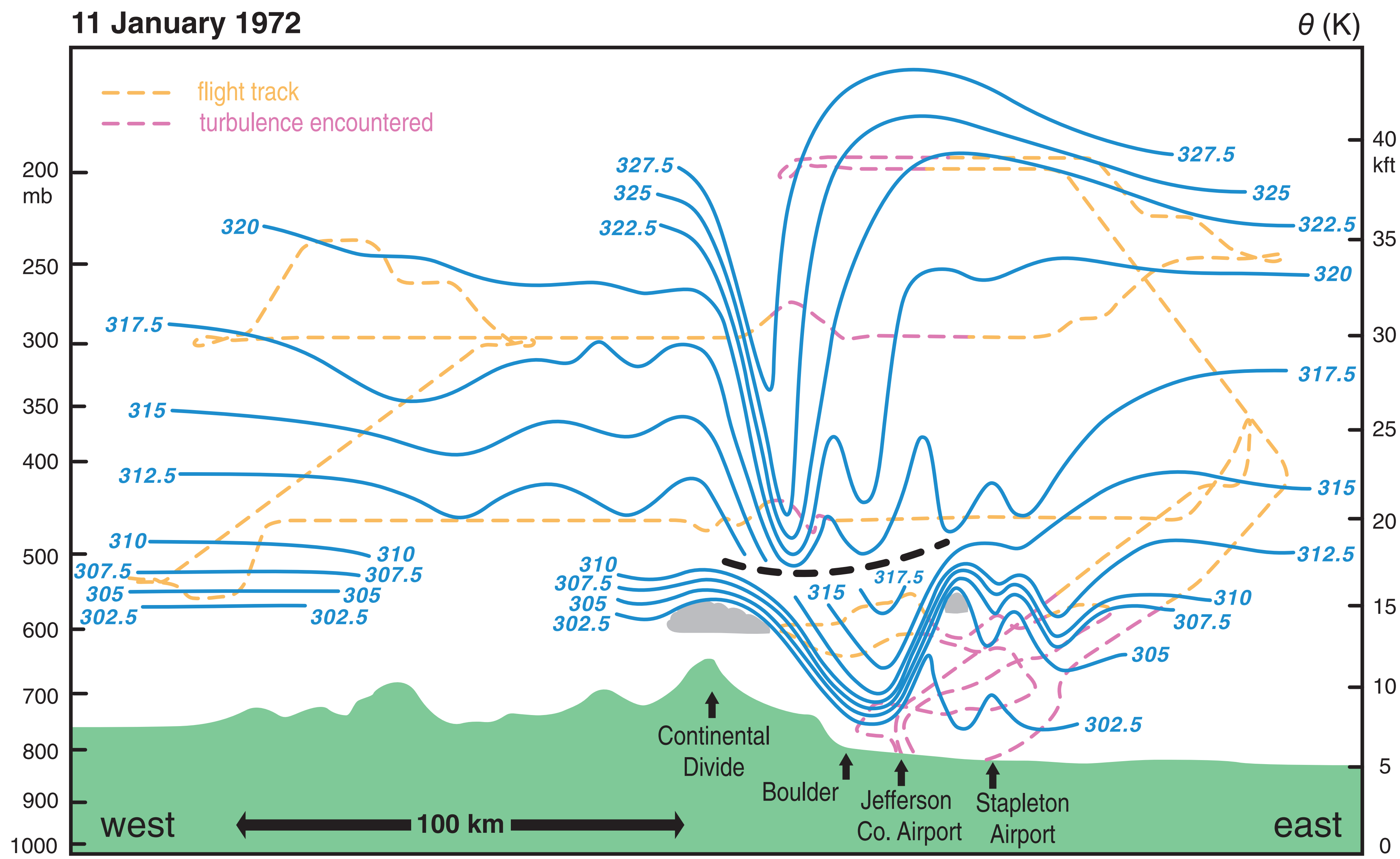

Figure 12.9 Analysis of potential temperatures (blue contours; K) from aircraft flight data (aircraft flight tracks are indicated with dashed lines) and rawinsondes on 11 January 1972 during a downslope windstorm near Boulder, CO. The heavy dashed line separates data taken by the Queen Air at lower levels before 2200 UTC from that taken by the Sabreliner aircraft in the middle and upper troposphere after 0000 GMT (12 January). The aircraft flight tracks were made along an approximate 130°–310° azimuth, but the distances shown are along the east–west projection of these tracks. (Adapted from Lilly [1978].)

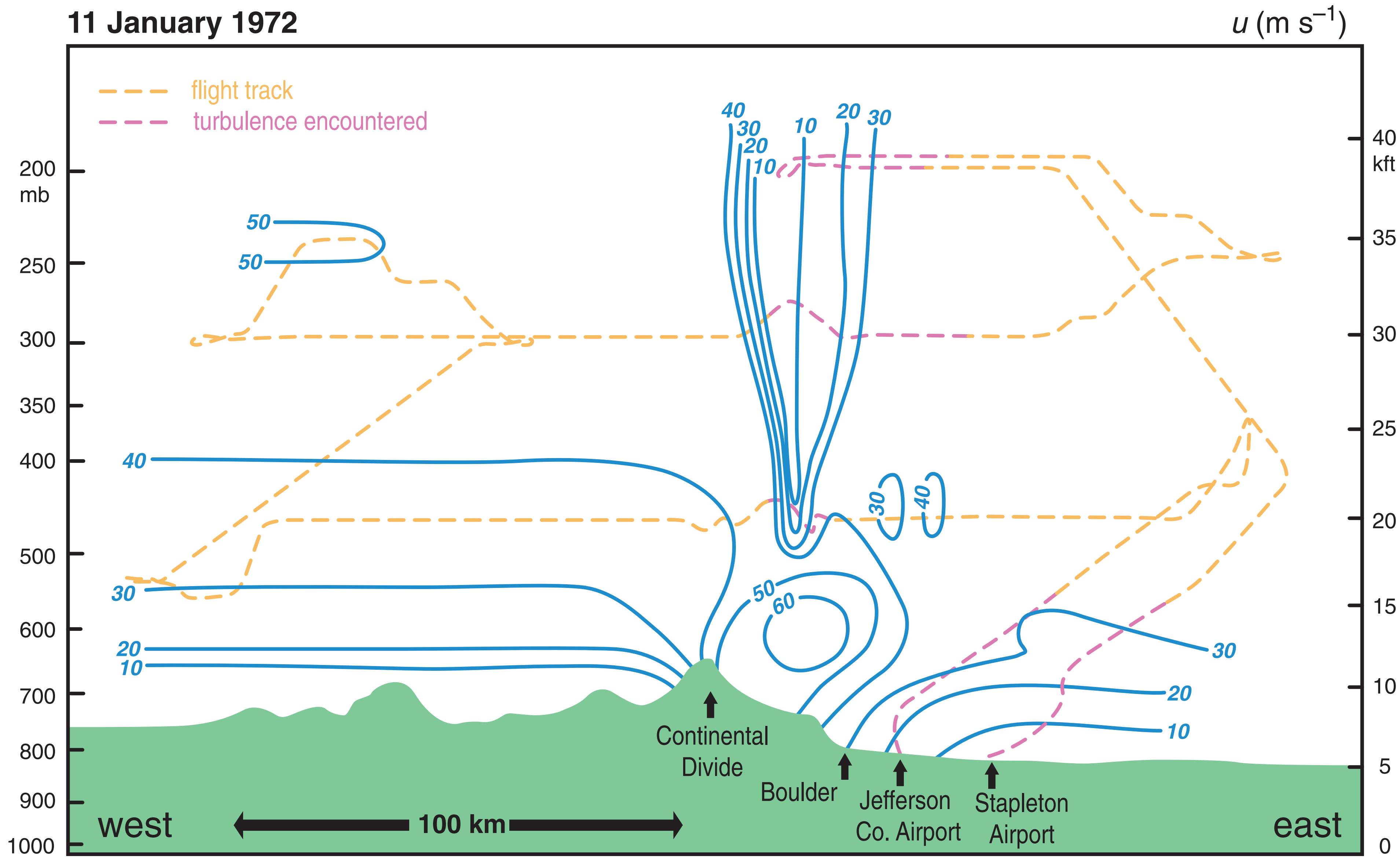

Figure 12.10 Analysis of the westerly wind component (blue contours; m s^{-1}) on 11 January 1972 during the downslope windstorm near Boulder, CO, shown in Figure 12.9. The analysis below 500 mb was partially obtained from vertical integration of the continuity equation, assuming two-dimensional steady-state flow. (Adapted from Klemp and Lilly [1975].)

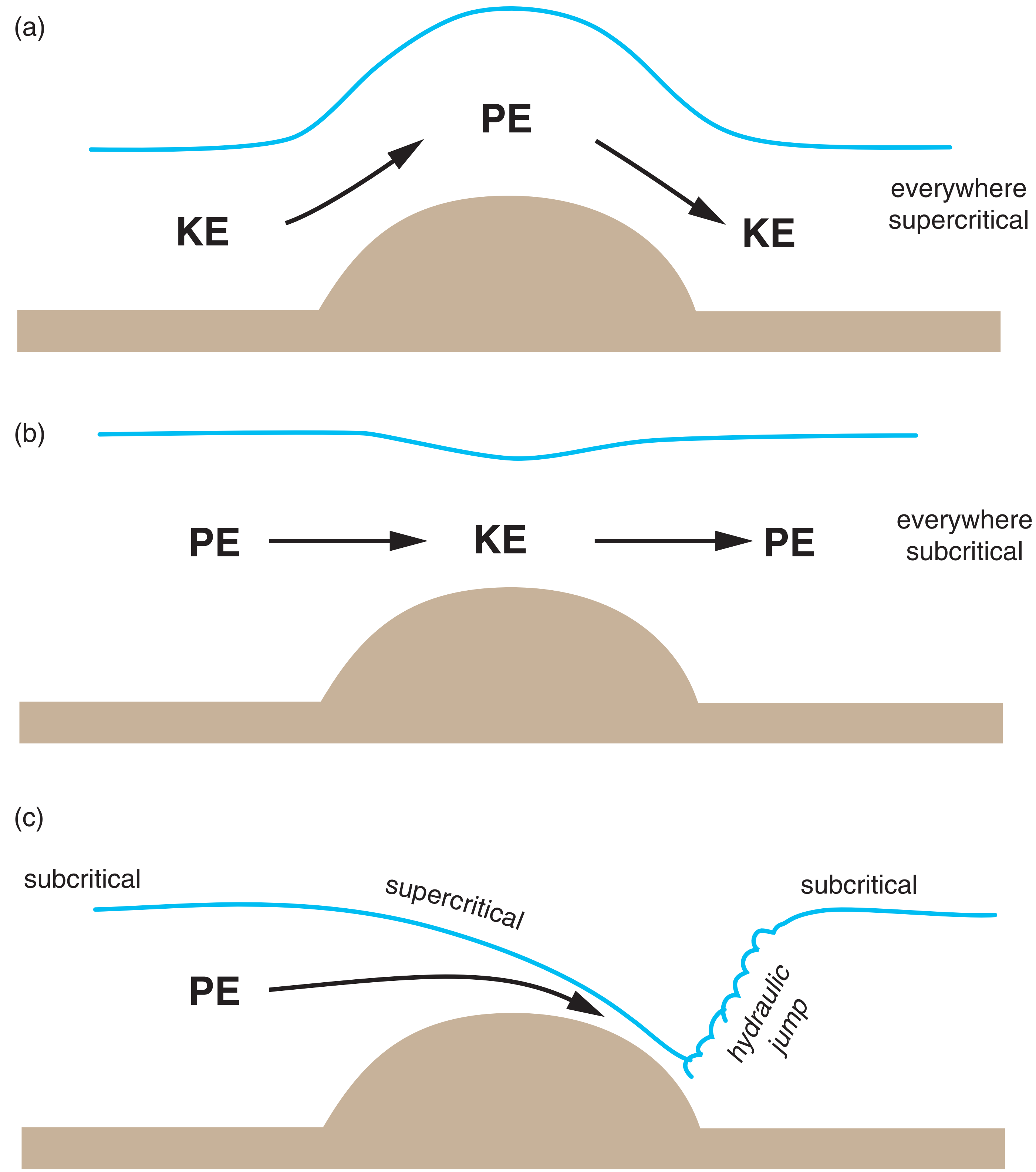

Figure 12.12 Flow over an obstacle for the simple case of a single layer of fluid having a free surface. (a) Supercritical flow ($Fr > 1$) everywhere. (b) Subcritical flow ($Fr < 1$) everywhere. (c) Supercritical flow on the lee slope with adjustment to subcritical flow at a hydraulic jump near the base of the obstacle. (From Durran [1990].)

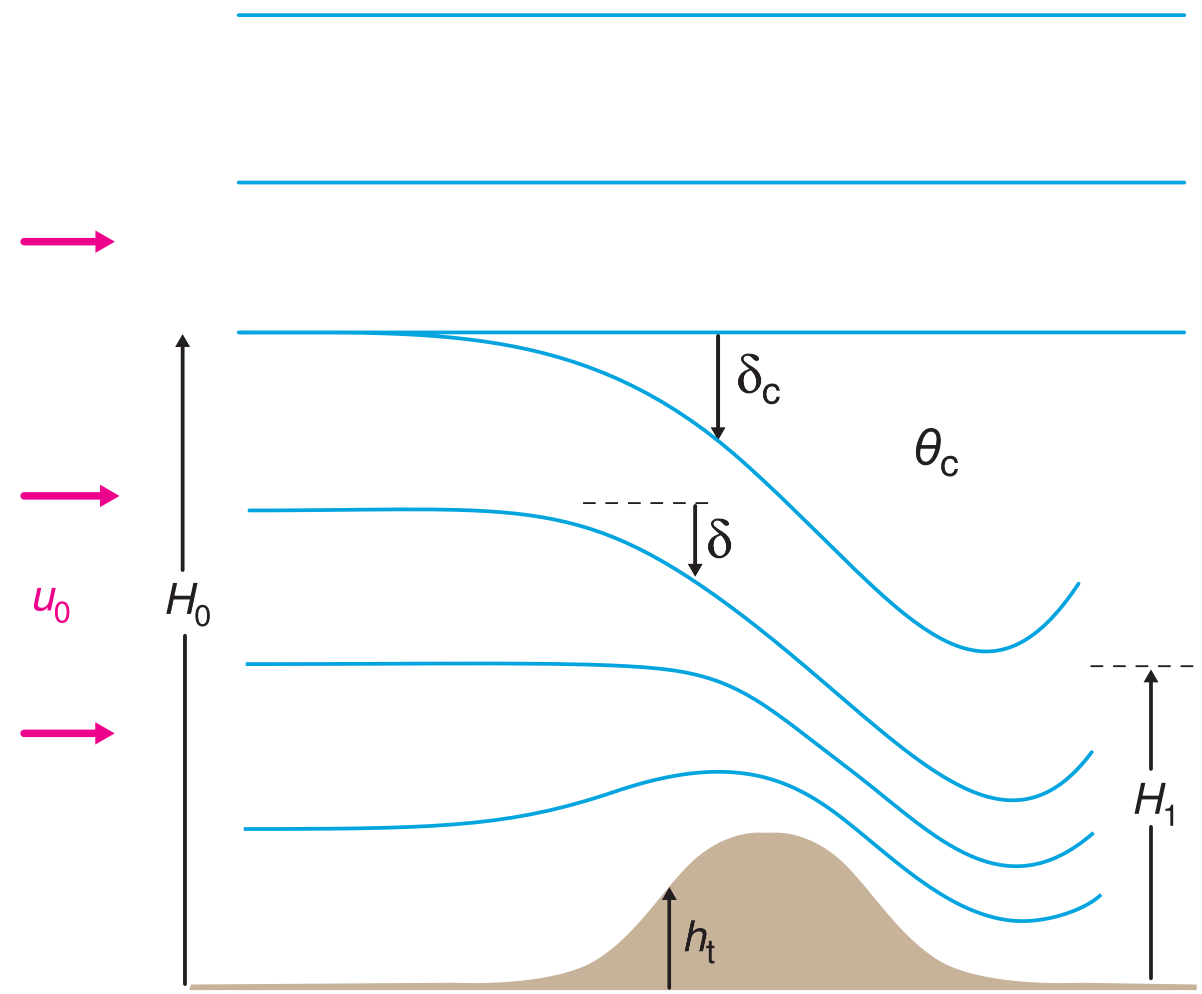

Figure 12.13 Schematic of the idealized high-wind-speed flow configuration, derived from aircraft observations and numerical simulations. A certain critical streamline divides and encompasses a region of uniform potential temperature. H_0 is the original height of the dividing streamline, θ_c is the potential temperature in the well-mixed region between the split streamlines, δ is the displacement of an arbitrary streamline, δ_c is the displacement of the dividing streamline, and H_1 is the nadir of the lower dividing streamline. (From Smith [1985].)

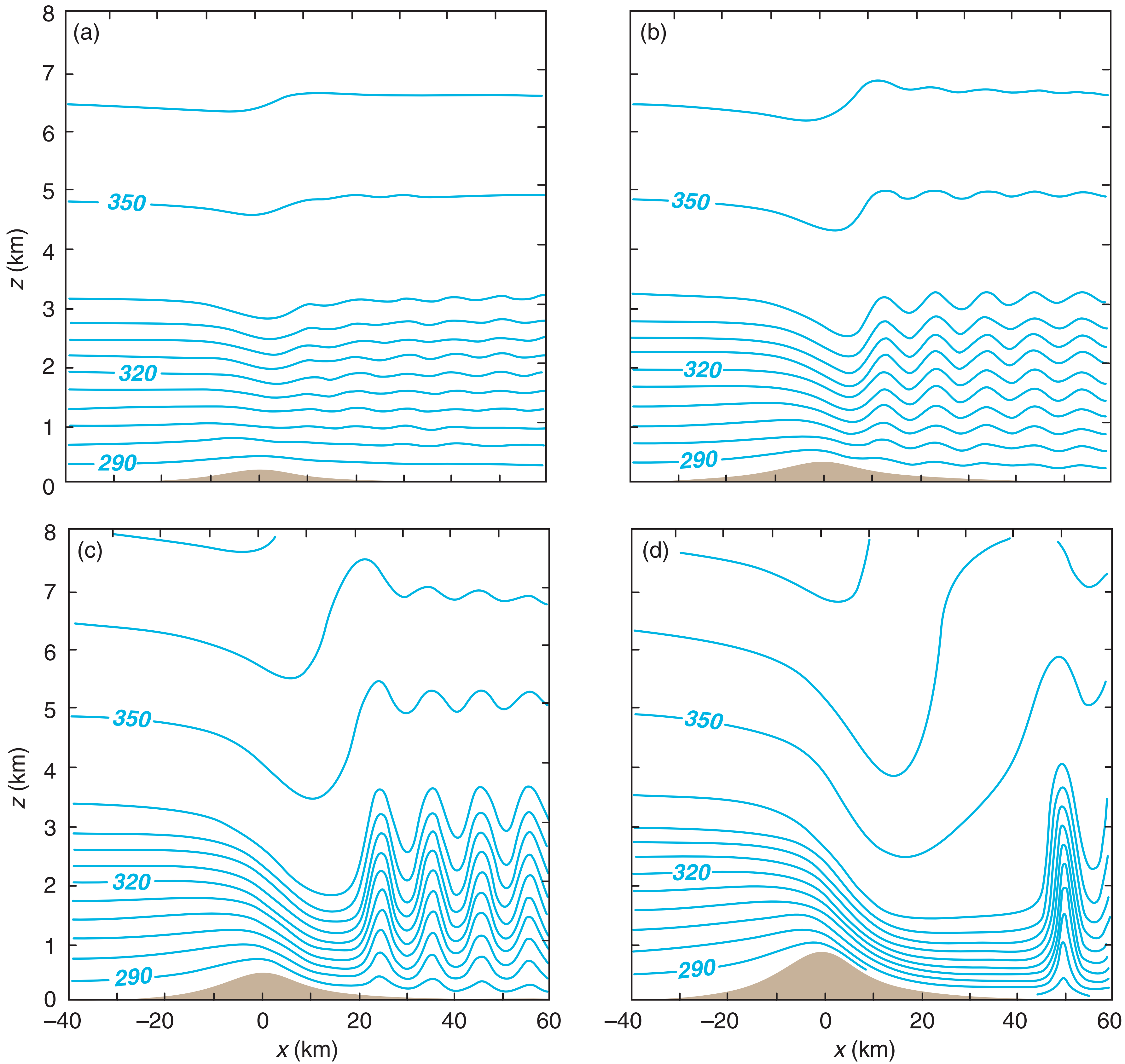

Figure 12.14 Isentropes for the airflow in a two-layer atmosphere when the interface is fixed at 3000 m, and the mountain height is (a) 200, (b) 300, (c) 500, and (d) 800 m. (From Durran [1986b].)

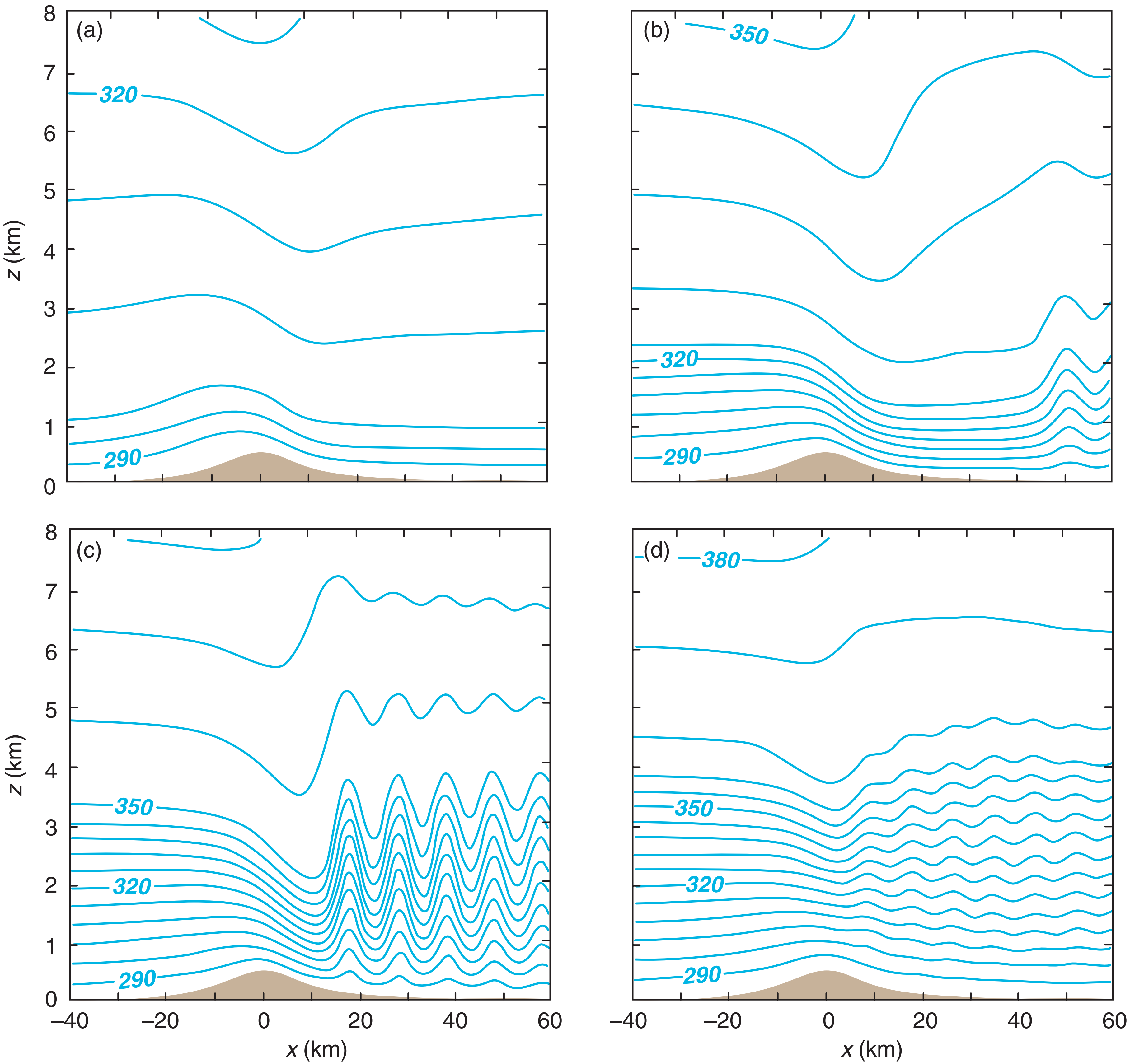

Figure 12.15 Isentropes for the airflow in a two-layer atmosphere when the mountain height is fixed at 500 m, and the interface is at (a) 1000 m, (b) 2500 m, (c) 3500 m, and (d) 4000 m. (From Durran [1986b].)

Putting all of this together, here are some of the conditions that forecasters look for when predicting downslope windstorms:

- an asymmetric mountain with a gentle windward slope and a steep lee slope
- strong cross-mountain geostrophic winds ($>15\,\mathrm{m\ s^{-1}}$) at and just above mountain-top level associated with surface high pressure upstream and surface low pressure downstream
- an angle between the cross-mountain flow and the ridge that is greater than $\sim 60^\circ$
- a stable layer near or just above the mountain top, and a layer of lesser stability above

- a level that exhibits a wind direction reversal or where the cross-barrier flow simply goes to zero (the mean state critical level); the existence of weak, vertical wind shear or reverse shear is more favorable than forward shear

- situations of cold advection and anticyclonic vorticity advection, which promote downward synoptic motion to generate and reinforce the vertical stability structure

- absence of a deep, cold, stable layer in the lee of mountains, which may keep the downslope flow from penetrating to the surface.