Western Region Technical Attachment
No. 90-31
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DOWNSLOPE WINDSTORMS AND MOUNTAIN WAVES

Many windstorms in the lee of mountain ranges occur when very strong gradients aloft produce strong winds at the surface through the downward transfer of momentum (Bower, 1985). Over the years, forecasters have been quite successful in predicting this type of event based on upstream observations, and more recently, from numerical weather prediction guidance. Sundowner windstorms which occasionally occur in the lee of the Santa Ynez Mountains near Santa Barbara, California (Western Region Technical Attachment 90-30) are an example of another class of windstorms which develop in the absence of strong winds aloft. Since the operational observational network is too sparse, both spatially and temporally, to conduct rigorous diagnostic studies of this class of windstorm, it is not surprising that controversy over the physical causes has arisen. These events are frequently accompanied by strong sea-level pressure gradients, and forecasters have found that pressure gradient rules have some forecast skill. However, recent numerical and observational studies strongly suggest that this class of windstorm is due to "amplified mountain waves." The strong sea-level pressure gradient patterns are incidental to the synoptic upper air patterns which generate vertical stability and wind shear patterns necessary for wave amplification.

Durran (1990) provides an excellent discussion of mountain-wave amplification and downslope winds by comparing three theoretical models. The first model argues that the development of strong downslope winds is analogous to a hydraulic jump. However, the atmosphere is not bounded by a free surface, which in the hydraulic model prevents energy transport through the upper boundary of the hydraulic layer. Thus, the simple hydraulic model is likely not proper for application to the atmosphere.

The second model discussed by Durran is the "reflected wave" theory. Eliassen and Palm (1960) showed that when an upward propagating gravity wave encounters a region in which the shear and stability change rapidly, part of the wave's energy can be reflected back into a downward propagating wave. Klemp and Lilly (1975) extended this reflected wave theory to a multilayer atmosphere. Their model suggests that downslope windstorms occur when the atmosphere is **tuned** so that partial reflections at each interface produce an optimal superposition of upward and downward propagating waves. Durran (1986) introduced a slightly more complex model which consisted of two-layers, with the potential temperature varying in each layer. Figure 1 illustrates some of the solutions from this two-layer model when the depth of the lower, more stable layer, is allowed to increase from 1000 meters in Fig. 1a to 4000 m in Fig. 1d in flow over a 500 m high mountain.

The third conceptual model was proposed by Clark and Peltier (1977, 1984). Using a comprehensive numerical model, they found significant increases in lee-slope surface winds occurred after vertically propagating gravity waves became unstable and **broke**, i.e., the isentropes overturned and a resonant cavity formed. In this "breaking wave" theory, Clark and Peltier proposed that the wave induced **critical layer** acts as a boundary, reflecting upward propagating waves back toward the mountain. They defined a critical layer as a region where the phase speed of the wave is equal to the mean flow velocity. Thus, for the case of stationary mountain waves, a critical level occurs where the mean flow is zero (or more precisely, where the cross-barrier flow is zero). They also suggested that if the depth of the "cavity" between the self-induced critical layer and the mountain is suitably tuned, the reflections should produce a resonant wave which amplifies with time and ultimately produces very strong surface winds.

Thus a model which generates reflected waves through stability considerations and a model which uses a critical layer to generate reflected waves both produce strong downslope wind solutions without the overly restrictive requirements of the hydraulic model. It should be noted that a breaking wave, which requires strong cross-barrier flow through a significant depth of the atmosphere, is not the only means of producing a critical layer. An evolving synoptic-scale pattern can also produce a mean state critical layer.

A recent, excellent operationally oriented study of Taku wind events in southeast Alaska by Colman and Dierking (1990) further supports the findings from numerical simulations. For 19 events studied, Colman and Dierking found that the occurrence of a Taku is very sensitive to the vertical structure of stability and wind. Three necessary conditions are (i) an inversion extending above ridgetop, (ii) moderate to strong cross-barrier flow near ridgetop, and (iii) cross-barrier flow decreasing in height to a critical level. The importance of an upstream stable layer in some amplified wind events is further illustrated in Fig. 2 from Durran's (1986) simulation of the 11 January 1972 Boulder, Colorado windstorm. In Fig. 2a, the actual sounding data from Grand Junction was used as initial conditions. In Fig. 2b, the Grand Junction inversion was removed. Note, also, the similarities between Fig. 1 and Fig. 2. Colman and Dierking found that Taku winds generally occur at night. Observations from other areas, including the Sundowner, suggest a tendency for many downslope windstorms to occur at night. This diurnal signal is likely due to a diurnal modulation of boundary layer friction, e.g., the boundary layer decouples from the flow aloft and, thus, friction is reduced after sunset.

The Sundowner events in the Santa Barbara area of southern California appear to be triggered by the same three criteria as the Taku winds. In Western Region Technical Attachment (WRTA) 90-30, Fig. 3, the Vandenberg AFB sounding for 1200 UTC 26 June 1990, indicated an inversion extending to 1500 meters above sea level, well above the 1000 m height of the Santa Ynez Mountains. A moderate cross-barrier component of the wind also extends to above ridgetop level, and then decreases to near zero around 3000 m. The Vandenberg sounding for 1200 UTC 27 June 1990 presented here in Fig. 3 also shows these characteristics. Note that this is a case where the critical layer was **not** produced by a breaking wave, but rather by an evolving synoptic pattern where the Eastern Pacific High, first at sea-level, then at 850 mb pushed inland from the west, just north of the Santa Ynez Mountains, while above about 850 mb, the winds began to back over the area in response to a deepening trough in the Gulf of Alaska.

As noted in WRTA 90-30, forecasters have long noted that Sundowners occur when sea-level high pressure noses into central California from the west, with cooler marine air moving into Santa Maria. As a result, the thermal trough is depressed southward. Pressure gradient rules have been found to have some success in forecasting Sundowners. Thus, it has been suggested that the winds are driven by the pressure gradient, with air flowing through the Santa Maria and Santa Ynez Valleys, over the mountains, and down to Santa Barbara. There may, in fact, be cases where winds flow through San Marcos Pass and other gaps in the Santa Ynez Mountains. However, the June 25-28, 1990 Sundowner was much more likely due to amplified mountain waves. Not only did the atmospheric structure fit the criteria for a reflected wave, but note that on 25 June, the maximum temperature at Santa Maria was 71 degrees F and Santa Barbara recorded a high of 84 degrees prior to the onset of the Sundowner winds. On 26 June, Santa Maria reached 76 degrees and Santa Barbara 103. On 27 June, Santa Maria had a high of 72 degrees, while Santa Barbara noted 109. Thus, even in a best-case scenario where the air ascended the windward side of the Santa Ynez Mountains from the Santa Maria Valley entirely at the moist adiabatic rate, and descended the south slopes entirely dry adiabatically, it would not reach Santa Barbara at much more than 90 degrees F. Referring again to Fig. 3 from WRTA 90-30, the Vandenberg AFB 1200 UTC sounding for 26 June 1990, the air reaching Santa Barbara at 103 degrees appears to have descended from about 1500 m above sea level. On 27 June (Fig. 3 here), it appears the air had to descend from near 2500 meters to produce a maximum temperature of 109 at Santa Barbara. It is interesting to note that prior to Death Valley recording 134 degrees, Santa Barbara held the record for the highest U.S. temperature. On 17 June 1859, during a Sundowner, a U.S. Geodetic Survey ship, anchored in Santa Barbara Harbor, recorded an air temperature of 133 degrees!

Sea-level pressure gradient rules may enjoy some success as a forecast tool for Sundowners because the sea-level pattern is associated with the synoptic pattern which can lead to the production of amplified mountain waves. At this point, further study is required to determine the necessary upstream stability and critical level criteria for the atmosphere over the Santa Ynez to become "tuned".

References

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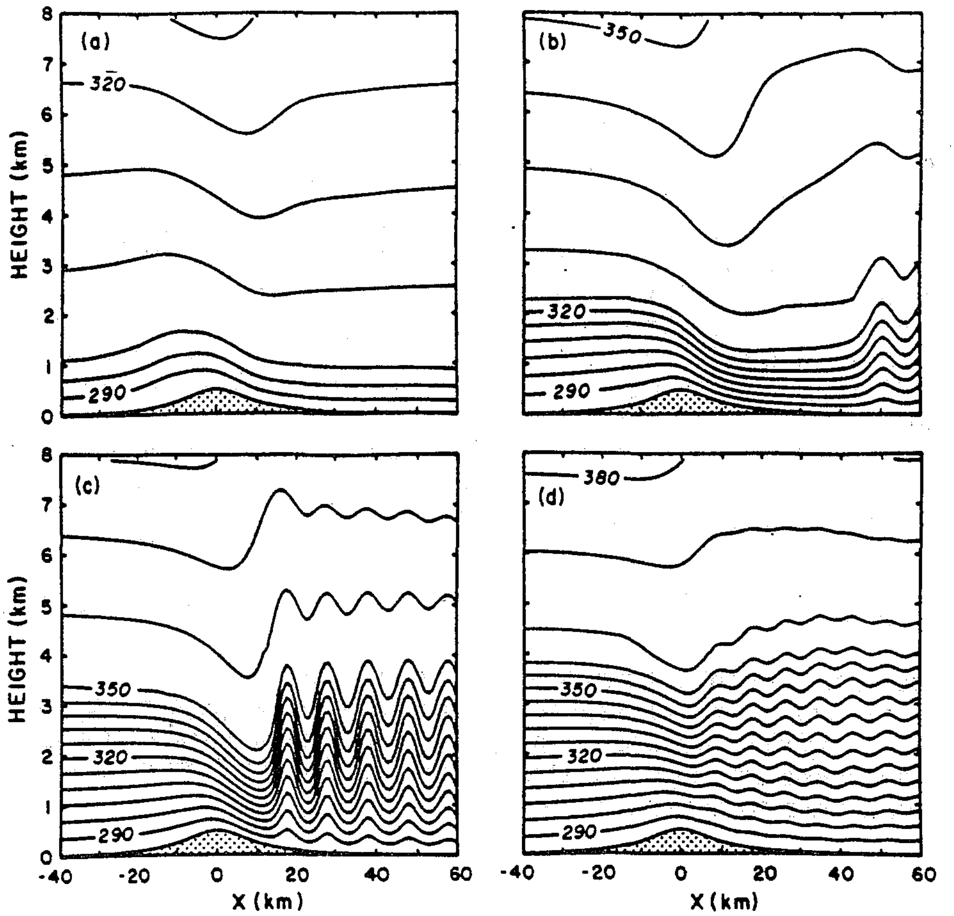

Fig. 1. Isentropes for airflow in a two-layer model atmosphere. (from Durran 1986).

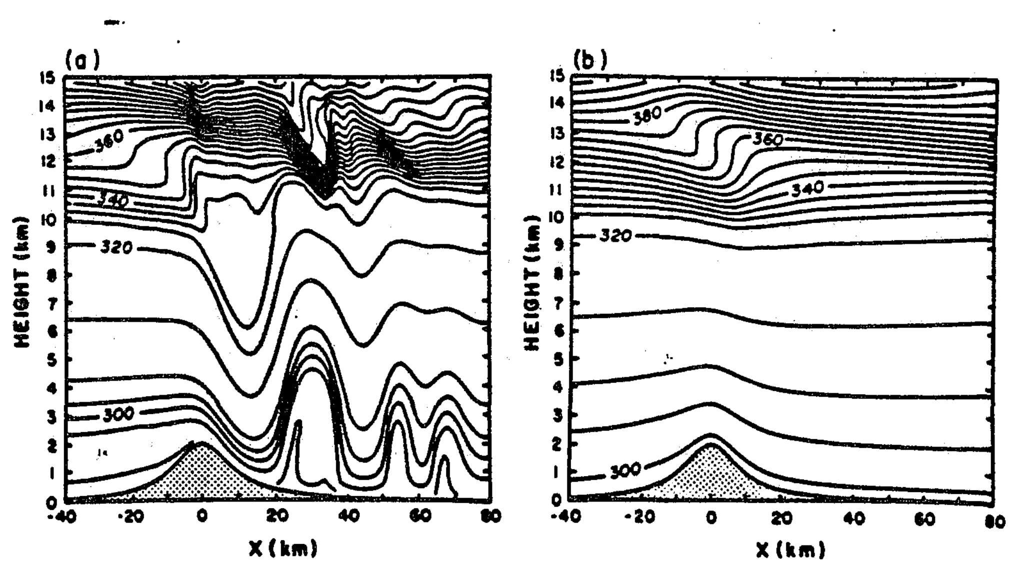

Fig. 2. (a) Isentropes from a simulation of the 11 January 1972 Boulder windstorm. (b) same as in (a) except upstream sounding has been modified to remove the elevated inversion. (From Durran 1986).

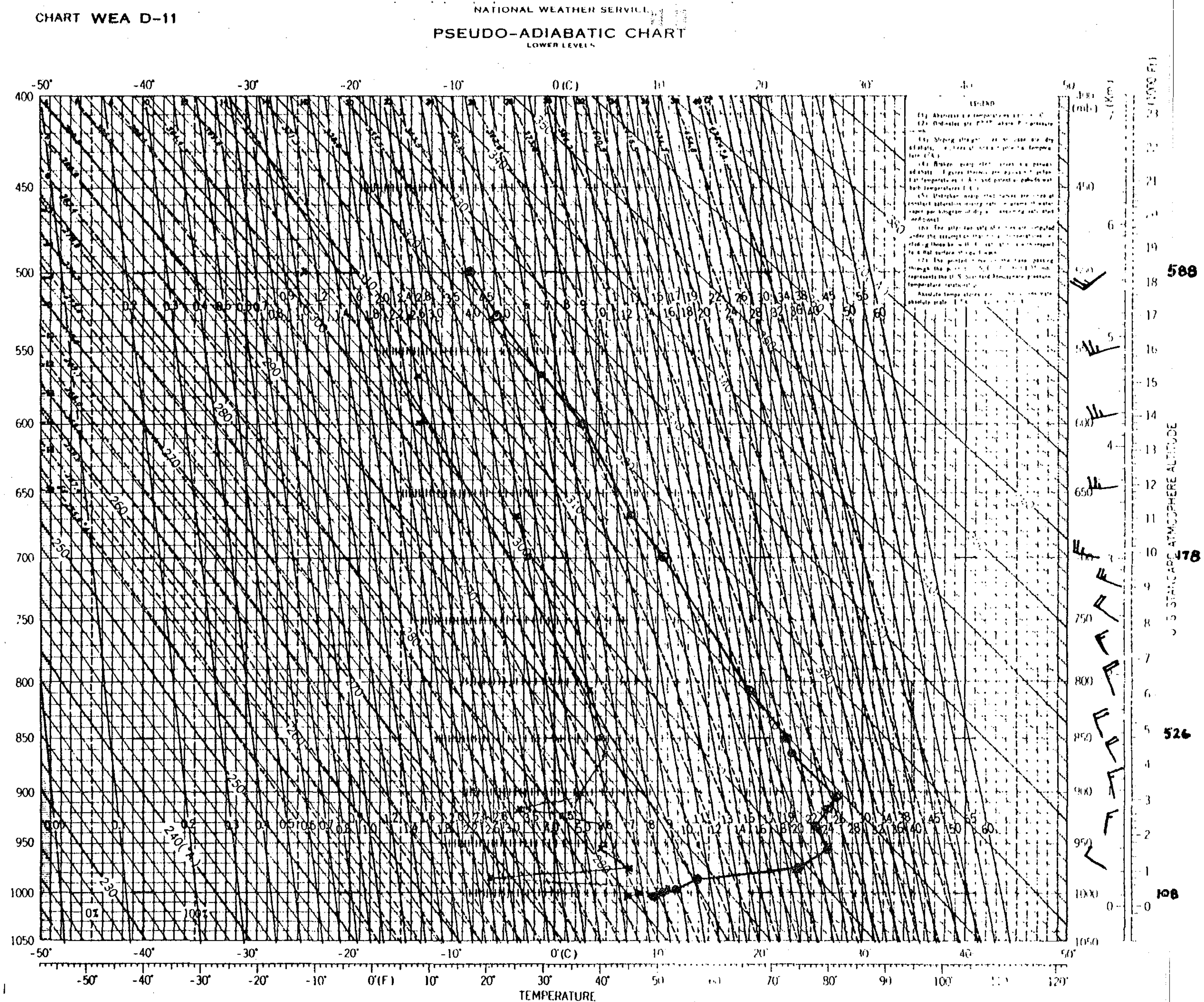

Fig. 3. Vandenberg AFB sounding for 1200 UTC 27 June 1990.