Western Region Technical Attachment
No. 94-11
March 22, 1994

A SOUTHERN CALIFORNIA WIND EVENT: AN ALTERNATIVE EXPLANATION

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Introduction

For a variety of different reasons, terrain-induced wind events occur in many different locations around the world, many of which occur within the Western Region. Chinook winds in Montana, canyon winds in Utah, gap (or down gradient) winds in the Puget Sound, and Santa Ana winds in southern California are regional examples of terrain induced wind events. Other examples are downslope windstorms in the Front Range of Colorado and Taku winds in southeastern Alaska, both of which have been known to produce winds exceeding 100 knots.

Many of these wind events are forced primarily by the overlying synoptic pressure gradient and wind field, and are consequently well forecast using typical upper-air and surface observations and model forecasts (e.g. gap, Chinook, and Santa Ana winds). In contrast, Taku winds, downslope windstorms, and canyon wind events are typically over forecast using only upper-air and surface charts within the current understanding of these phenomena. In many cases, the tendency to over forecast these types of wind events is related to the complexity of the problem and the factors responsible for their formation.

Recently, a moderate wind event occurred in southern California that was unexplained using typical forecast rules for wind events in this area. Wind gusts from 30 to 50 knots, with some isolated reports from 60-80 knots, were reported in some of the mountainous areas east-northeast of Los Angeles, beginning during the night of 31 January through the evening of 2 February 1994. Many of the wind events in southern California are typically thought of as being primarily forced by the strength of the sea-level pressure gradient. An alternative explanation for this recent case, which considers the dynamics associated with downslope wind storms and mountain wave activity, is offered below. It is believed that this particular event may have been a result of the same type of mechanisms found in association with the Taku winds of southeast Alaska, downslope windstorms in the Front Range of Colorado, and canyon wind events west of the Wasatch Range in Utah.

This Technical Attachment will analyze the particular case in southern California. Background information on the mechanisms involved with this type of wind event will be discussed as well. In addition, some ideas for determining situations favored for these types of events will be discussed.

Case Specifics

On the evening of 1 February 1994, moderate (10-30 knots) north to northeasterly winds were developing over the western Great Basin and the southeastern California deserts, as illustrated (Fig. 1) by the 0000 UTC and 1200 UTC 1 February 1994 upper-air soundings at Desert Rock, Nevada (DRA). Weak offshore sea-level pressure gradients were also present across southern California, but were less than those typically associated with wind events in this area (Maggie Gross, WSO Riverside, personal communication). At the same time, a moderate inversion (10-15 °C km^{-1}) existed over southern California (Fig. 2) with inversion height from 6,000 to 8,000 feet above mean sea level (MSL). It is postulated that the combination of the moderate north to northeasterly winds, west-east to northwest-southeast terrain orientation, the stable layer between 6,000 and 8,000 feet MSL, and a critical level (to be discussed below) near 8,000 feet MSL contributed to the development of this wind event, similar to mechanisms associated with Taku and canyon winds, and downslope windstorms. Some peak winds recorded during this event include: Santa Rosa Island-44 knots, Bell Canyon-44 knots, Potrero-40 knots, Acton-43 knots, and Fremont Canyon-85 knots.

Possible Mechanism--Description

Wind flow over and around topography has received a large amount of attention from the research community, particularly mesoscale modelers. An increased understanding on the role of topography in blocking or diverting the wind flow has resulted from this research. Many mechanisms have been proposed for downslope windstorms, a few of which are addressed in this Technical Attachment.

Shallow water equations have been used to study the influence of barriers on fluid flow. In extending shallow water theory to air flow in the atmosphere, wind flowing perpendicular to a terrain ridge may flow over the terrain ridge in two manners: 1) supercritical and 2) subcritical flow. Supercritical flow, simply stated, means that the vertical depth of the wind flow is maintained as it flows over the terrain barrier (Fig. 3a) and converts kinetic energy to potential energy (at ridgetop), and back to kinetic energy in the lee. Subcritical flow means the vertical depth of the wind flow actually decreases as it moves over the top of the terrain ridge (Fig. 3b), which converts potential energy to kinetic energy (at ridgetop) as the vertical depth is decreased, and back to potential energy.

Subcritical flow may be thought of as a constricting of the flow within the vertical, between the terrain ridgetop and the statically stable layer. Similar to water flowing through a constricting pipe, the flow speed is increased at ridgetop level. In some cases, once the wind flow has traversed the ridgetop in subcritical flow, the flow in the lee of the ridge becomes supercritical, with a continuation of energy transfer from potential energy to kinetic energy in the lee. When this occurs, very strong winds can be experienced in the immediate lee of the ridge tops as this flow is said to "break," or undergo a hydraulic jump (Fig. 3c).

Western Region Technical Attachment 90-31 summarizes the various theories surrounding downslope windstorm formation. One such theory (Durran 1986) postulates that when a topographically-forced, upward propagating gravity wave encounters a region of rapidly changing stability and shear (commonly referred to as a critical level), part of the energy of the gravity wave can be reflected downward towards the surface. These critical levels are often associated with wind profiles showing cross-barrier flow reversal. An example of cross-barrier flow reversal is low-level easterlies underlying mid- to upper-level westerlies, which impinge on a north-south barrier. The theory continues to suggest that if the atmosphere is "tuned" such that optimal superposition of upward and downward propagating waves occurs, downslope windstorms may result. Similarly, Clark and Peltier (1977, 1984) considered upward propagating gravity waves, which they postulated became unstable and broke, forming a wave-induced critical level. This wave-induced critical level is thought to act as a boundary that reflects upward propagating waves down toward the mountain. For stationary mountain waves, the critical level occurs where the cross-barrier flow is zero. Clark and Peltier (1977, 1984) have also postulated that if the depth between the wave-induced critical level and the mountain is properly "tuned," strong surface winds may result from an amplifying resonant wave.

Features that have been identified as being favorable for mountain wave formation and amplification are: 1) cross-barrier flow; 2) a stable layer near or just above ridgetop level; and 3) the existence of a critical level or a stable layer. In this particular case, both were present. One parameter typically used by researchers to determine the flow characteristics of cross-barrier flow is the Froude number (Fr). The Froude number is defined as follows:

$$Fr = \frac{U}{N\,h_m}$$

where, U = mean upstream wind speed below inversion height
h_m = relative terrain height (vertical rise from region upstream of barrier to ridgetop level

$$N = \sqrt{\frac{g}{\theta}\frac{\partial\theta}{\partial z}}$$

Thus, the Froude number considers the strength of the cross-barrier flow, the relative height of the barrier, and the static stability as expressed in the Brunt-Vaisala frequency (N). Research has shown that supercritical flow can generally be expected when Fr > 1, while Fr < 1 suggests subcritical flow. Thus, when:

$$\frac{U}{N\,h_m} \leq 1$$

or,

$$U \leq N\,h_m$$

subcritical flow may be expected.

For this particular case in southern California, the inversion strength of 5-10 °C km^{-1} [4°C $(500\ m)^{-1}$] yields $N \approx 1.5\text{-}2.0 \times 10^{-2}\ s^{-1}$ and the relative height of the barriers was in the range of

500 to 750 m. Multiplying N and h_m suggest wind speeds below 10 to 15 m s^{-1} are capable of being subjected to subcritical flow. Durran (1986) and Smith (1987) have suggested that the relative depth between the stable layer or critical level and the ridgetop level can determine if downslope windstorms occur and influence the magnitude of such events.

Although this Technical Attachment is not intended to answer all the questions related to this particular case or the theory of cross-barrier flow, it is offered to provoke thought and interest in these terrain-induced wind events, particularly related to subcritical flow situations. A very good overview of the theoretical ideas related to these types of wind events is contained in section 2 of Colman and Dierking (1992). A complete theoretical approach to the mechanisms of wind events may be found in chapter 4 (by Dale Durran) of Atmospheric Processes Over Complex Terrain (Blumen, 1990).

Acknowledgements

Special appreciation is extended to Maggie Gross, Fire Weather Forecaster at WSO Riverside, for providing much of the data used in analyzing this event. If she had not questioned the author for reasons for this event, the unique nature of this event may have went undocumented. Also, appreciation is extended to Brad Colman, SOO at WSFO Seattle, for providing comments on this Technical Attachment.

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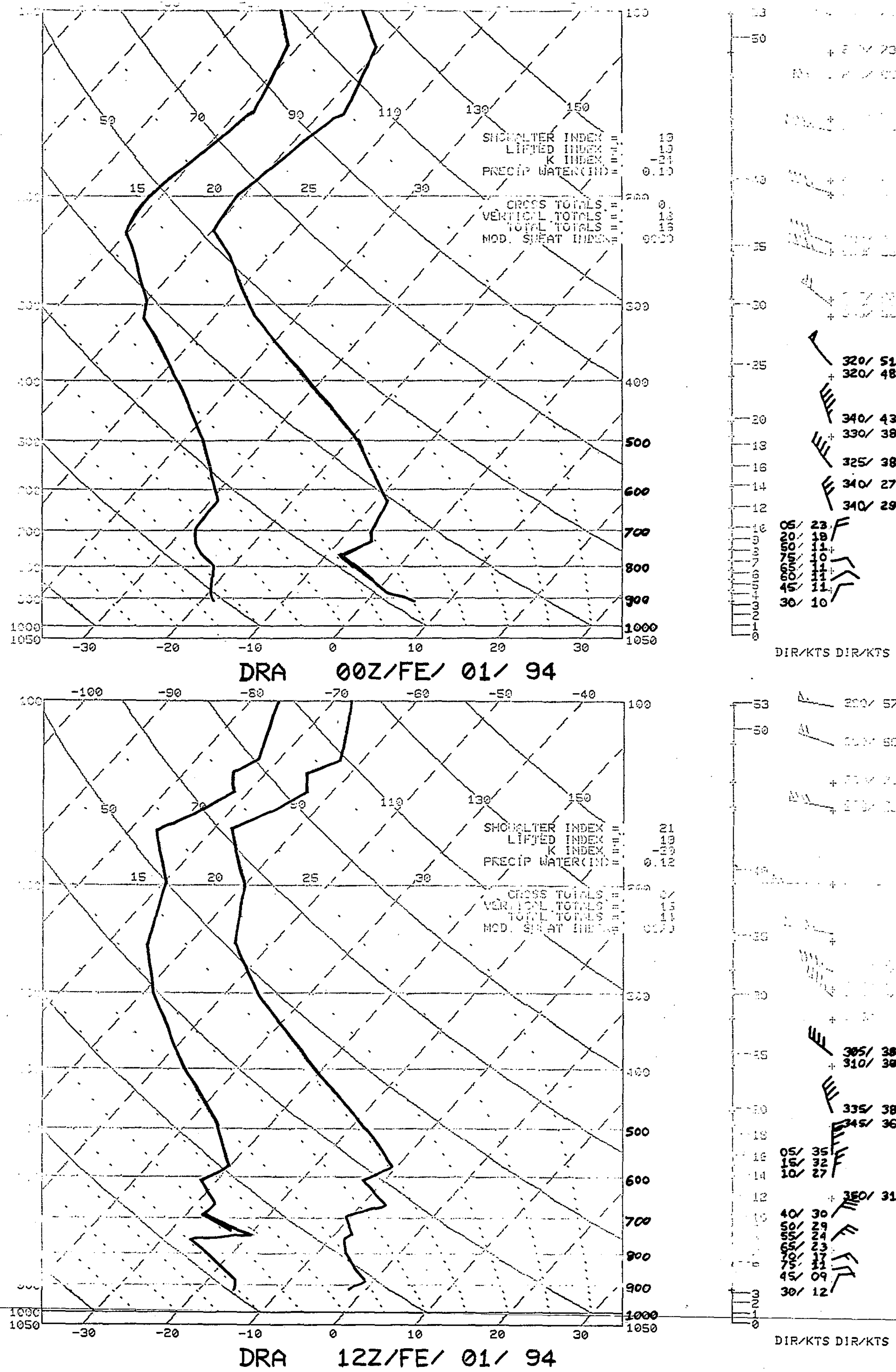

Fig. 1 Desert Rock, Nevada (DRA) sounding at a) 0000 UTC and b) 1200 UTC 1 February 1994.

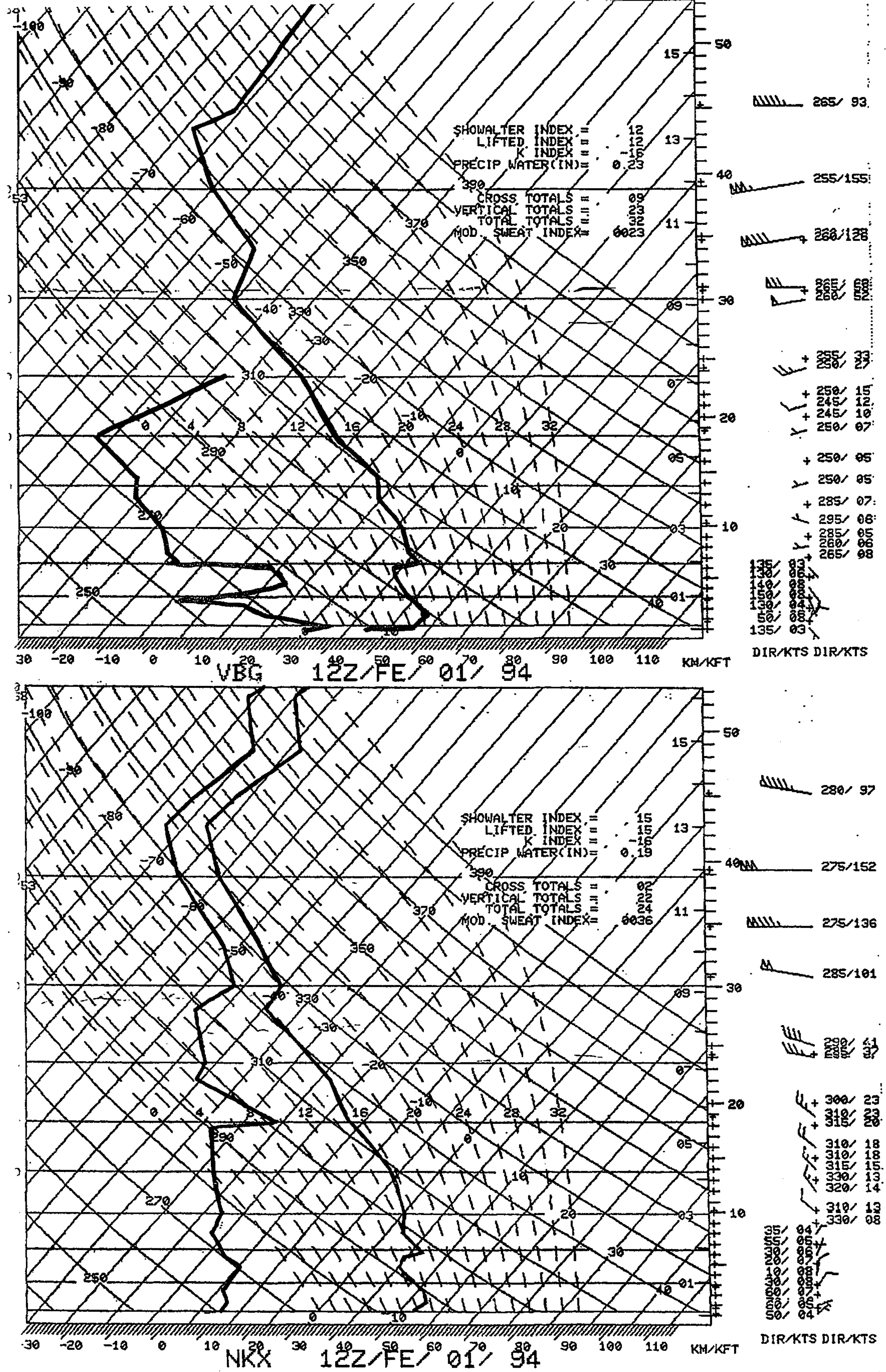

Fig. 2 1200 UTC 1 February sounding at a) Miramar Naval Air Station (NKX), and b) Vandenberg Air Force Base (VBG) California.

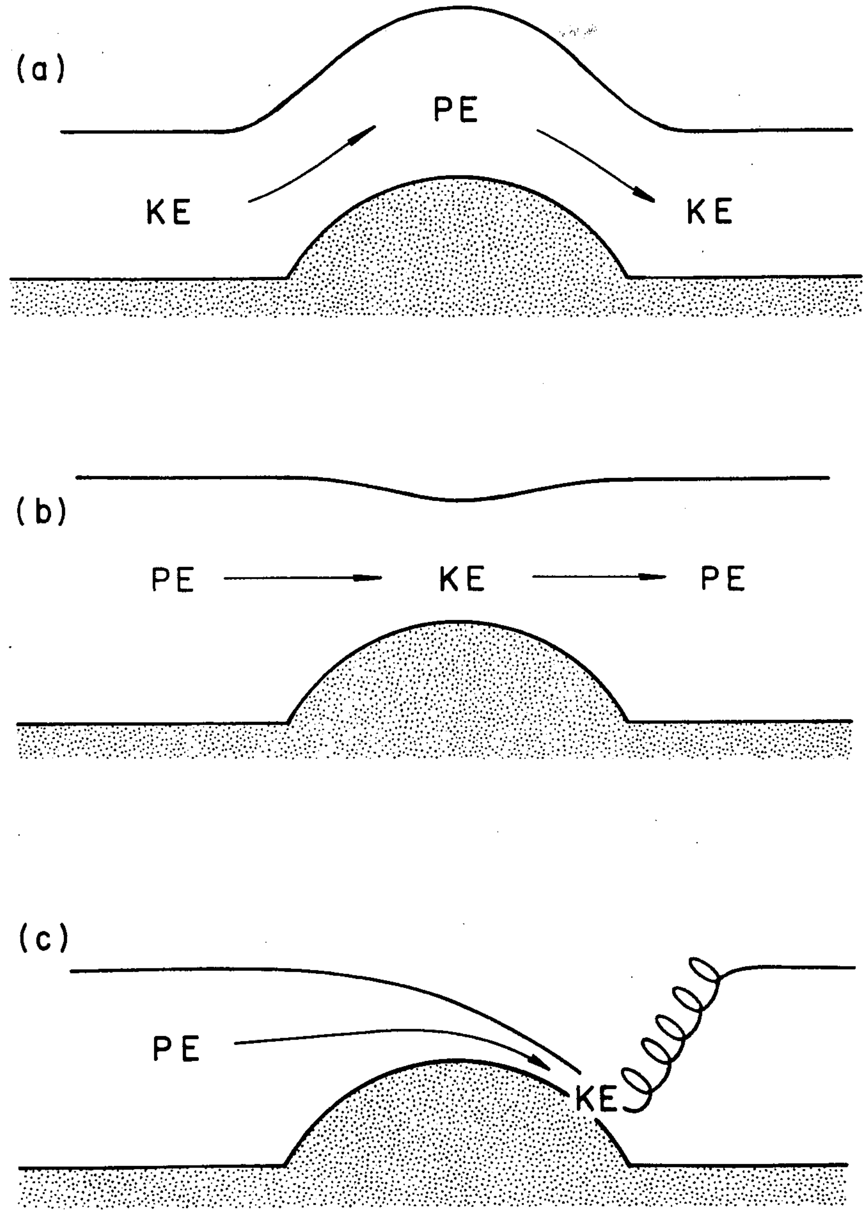

Fig. 3 Behavior of shallow water flowing over an obstacle: a) everywhere supercritical flow, b) everywhere subcritical flow, and c) hydraulic jump. (from Durran 1990)