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Forecasting Hydrologically Critical Storms in Northern and Central California

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ABSTRACT

Heavy rain and flooding are of major concern to forecasters, hydrologists, emergency personnel, and the public in northern and central California. The floods of January and March 1995, in which the damage to property and agriculture reached the hundreds of millions of dollars but loss of life was very small, demonstrate the importance of advance warning. Quantitative Precipitation Forecasts estimates tend to understate the heaviest precipitation while often overestimating precipitation in the weakening (dissipating) stage of the event.

A hydrologically critical storm is defined as an anomalous storm with heavy rain that has the potential for widespread flooding. The typical synoptic pattern of hydrologically critical storms in northern and central California is represented by strong undercutting of a high latitude blocking ridge over Alaska or western Canada. The physical processes that cause the excessive precipitation rates are an active warm rain process, large amounts of precipitable water, strong orographic lift, and an active seeder-feeder mechanism. The antecedent soil moisture and river basin conditions needed for a hydrologically critical storm include saturated soil conditions, river and creek basins overgrown with trees and other vegetation, and the varied topography of northern and central California which can augment heavy rain events and storm runoff.

Forecasters must be aware of the various antecedent, synoptic and mesoscale conditions necessary that cause hydrologically critical storms. The authors have developed an empirical checklist that will assist forecasters in the prediction of a hydrologically critical storm.

I. Introduction

What is a hydrologically critical storm? In the context of this paper, a hydrologically critical storm is one with heavy rain that has the potential for widespread flooding. Of vital importance in defining hydrologically critical storms, is not so much the total amount of rain, but the intensity of rain and the antecedent conditions.

Floods are the number one weather-related killer in the United States. The National Weather Service, Office of Meteorology, Warning and Forecast Branch has estimated that on average, 140 people die each year, and 300,000 persons are forced from their homes. Property damage averaged $3 billion per year in the early and middle 1980s (LaPenta et al., 1995a). In order to minimize losses, the Quantitative Precipitation Forecasts (QPF) need to be as accurate as possible. Knowledge of past significant flooding events, recognition of the meteorological patterns that led to these events, careful analysis of current observations including satellite and radar data, atmospheric soundings, and analysis of gridded model output are important factors in the QPF process.

This paper was developed to assist forecasters, hydrologists and staff in the northern and central California WFO's to become familiar with the meteorology associated with hydrological critical storms in their respective areas of coverage. It will help forecasters prepare emergency personnel and the public in advance of the threat of heavy rain. The California floods of January and March 1995 demonstrate the importance of advance warning.

II. Typical Synoptic Pattern of Hydrologically Critical Storms in Northern and Central California

Historically, most of the storms that have produced the greatest amount of rain in northern and central California are low latitude type storms that have a strong infusion of tropical/subtropical air. Some of these storms are occluded by the time they reach California with diffuse frontal systems (Monteverdi, 1976). These systems produce heavy rain primarily due to orographic enhancement, which occurs with low-level flow oriented perpendicular to the mountain ranges. An example of this type of system is the storm of February 11 through 20, 1986 in which extensive flooding occurred in the Napa and Russian Rivers and the American River in the Sacramento Valley (Goodridge, 1992). In addition, some heavy precipitation producing storms exhibit a tremendous amount of baroclinicity with major frontal bands, such as the January and March 1995 storms.

During the beginning of the rainy season, these heavy rain events are not typically hydrologically critical storms, unless they have excessive rain rates (> 1"/hr). As the antecedent conditions change during the course of the rainy season, it is more likely that these heavy rain events will become hydrologically critical storms.

Figure 1 shows one of the synoptic patterns of heavy rain events that can become hydrologically critical storms. This pattern is represented by a high latitude blocking ridge that is located over either Alaska or western Canada. Strong undercutting of the ridge occurs, forming a long southwesterly fetch into California from the Hawaiian Islands or even further south and west into the InterTropical Convergence Zone (ITCZ). In this scenario, the polar jet forms along 35°N, and could be quite strong with winds in excess of 75 ms^{-1}. Northern and central California are often located in the left front exit region of this jet which greatly enhances the large-scale vertical motion field. There is also a very strong 700 mb flow from the south and southwest, advecting very warm moist air into northern and central California. Condensate supply rates are maximized by a saturated lower troposphere having temperatures above 0°C to the 700 mb level and wind speeds greater than 25 ms^{-1}. An example of a sounding from Oakland, CA during the March 1995 storm indicated precipitable water of more than 200% of the March normal. This was almost entirely due to the very warm, moist lowest 3000 meters of atmosphere (Fig. 2).

III. Antecedent Conditions

The antecedent conditions must be considered in determining flood potential and the need for appropriate watches or warnings. These conditions include the following: 1) the antecedent soil moisture content and degree of foliation; 2) the river channel's current base flow; and 3) the basin's topography.

In northern and central California, almost all major flood-producing storms have closely followed previous heavy and/or prolonged rainfall creating saturated soil moisture conditions. Any subsequent rain will then quickly run off, adding to already swollen streams and rivers. Excessive precipitation rates are more important than rainfall totals. Flash floods are possible if precipitation rates exceed 1-3"/hr no matter how dry the soil conditions. In November 1994, San Francisco received more than 6" of rain during a 24 hour period, yet there was very little flooding reported. Soil conditions were dry from the long summer season, and more importantly, precipitation rates were not excessive. During the January and March 1995 storms, the soil was saturated from previous rain. Given the high rain rates produced by these two storms, there was a tremendous amount of run-off into creeks and rivers. In addition, these waterways were overgrown with trees and other vegetation which encouraged the flooding.

River flooding from a prolonged heavy rain event can last several days after the rain has stopped due to the run-off from higher elevations. The varied topography of northern and central California can augment heavy rain events from orographic lift which will be described further in section IV. A flood's severity can be greatly intensified by dam and levee failures as was the case in the town of Pajaro, California (near Monterey) during the March 1995 storm.

IV. Physical Processes

Understanding and identifying the physical processes leading to heavy rain are important in determining hydrologically critical storms. These processes include: 1) large-scale vertical motion; 2) orographic lift or shadowing; 3) precipitation mechanisms including the warm rain process; and 4) an active seeder-feeder mechanism.

The large-scale vertical motion field can be enhanced by direct and indirect circulations associated with ageostrophic flow around upper-level jet streaks. At times, two jet streaks can interact to produce significant vertical motions. In addition, enhanced localized regions of vertical motion can be established by what is called convective symmetric instability or CSI. Under strong vertical wind shear, near neutral stability, and a relatively moist airmass, narrow bands of enhanced precipitation can develop that may double precipitation rates over areas away from the bands.

Orographic lift can substantially enhance vertical motion. When the westerlies establish themselves over California, the low-level wind speeds can approach 25 ms^{-1} from the south and southwest. Given the orientation of the Sierra Nevada and coastal ranges, the component of the wind orothogonal to the mountain can approach 15 to 20 ms^{-1} and thus induce vertical motions of 0.3 to 0.4 ms^{-1} over the windward side of the Sierra Nevada and coastal mountains.

In addition to upward motions, the mechanism for precipitation formation is important in determining how the condensate produced by vertical motions will be converted to precipitation. Precipitation can be classified in two main categories; the Bergeron process which includes ice particles and the warm rain process which exclusively deals with liquid droplets (Reynolds, 1995). The heaviest precipitation will occur when both processes are active.

In complex terrain like California, an important precipitation process is the seeder-feeder mechanism (Fig. 3). This occurs when mid- to high-level clouds form precipitating ice or rain which falls through low-level liquid water produced either by large-scale lift or topographic lift. This low-level water is scavenged by the falling particles (Houze and Hobbs, 1982). It is estimated that the seeder cloud produces about 20-35 percent of the total mass of precipitation while the feeder cloud adds the additional 65-80 percent of the mass. In the coastal mountains of California, the feeder cloud can produce substantial amounts of precipitation if the cloud base temperature is warmer than +10°C and there is a sufficient depth of cloud to allow time for coalescence growth to take place. This would be an exclusive warm rain process. A substantial portion of the precipitation occurring during November 6-7, 1994, when San Francisco set their all-time 24 hour precipitation record of over 6", was produced from the warm rain process.

V. Future Precipitation Forecasting Applications

A checklist of important meteorological features to look for in forecasting hydrologically critical storms is shown in Table 1. As the list implies, many of these features are keyed to identifying aspects of the warm rain process or to enhanced vertical motions. Empirical precipitation rates could be associated with each of the predictors in Table 1 based on extensive analysis of precipitation events. Based on an expected duration of each event and which of these processes are active at any given time, a total rain rate could be developed. This checklist follows a similar methodology developed in 1980 at WSFO Pittsburgh and is currently used at WSFO Philadelphia (LaPenta et al., 1995b).

VI. Conclusion

Many factors must be considered in forecasting hydrologically critical storms. Northern and central California must be in an area of large-scale vertical motion, with strong 700 mb flow from the south and southwest advecting warm, moist air into northern and central California, with a large depth of cloud warmer than 0°C. The long fetch to the subtropics allows the front to align itself with the upper flow, either stalling the front or moving it very slowly, extending the duration of the event. An understanding of the antecedent soil and river conditions are of vital importance as is the role of topography in augmenting heavy rain events. Knowledge of the various physical processes that are involved is also important.

Utilizing all of this information, a hypothetical checklist was developed (see Table 1). The more criteria in this list that are met, the higher the probability that a significant precipitation event will occur. Other factors such as the antecedent conditions in the capture basin and the duration of the precipitation event then need to be investigated to determine if this is indeed a hydrologically critical storm.

References

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Table 1. WSFO SAN FRANCISCO HYDROLOGICALLY CRITICAL STORM FORECAST CRITERIA CHECKLIST FOR NORTHERN AND CENTRAL CALIFORNIA

1) Is airmass saturated between +10°C and 0°C?

2) Do the 700 mb winds equal or exceed 50 knots from a direction perpendicular to well defined topographic features?

3) Is the 700 mb temperature within 2°C of 0°C?

4) Is the cloud base temperature > 15°C?

5) Is convection present in bands? Can these be classified into cold or warm frontal bands?

6) Does QG Omega support strong upward vertical motion over the area? Can a cross-section be constructed that would show the interaction of jet streaks over the forecast area?

7) Is CSI present or expected?

8) Are cloud tops colder than -40°C?

9) Does satellite imagery show a long continuous cloud band extending from California to subtropical latitudes?

* The more criteria in this list that are met, the higher the probability that a significant precipitation event is likely to occur. Other factors such as the antecedent conditions in the capture basin and the duration of the precipitation event must be investigated before forecasting a hydrologically critical storm.

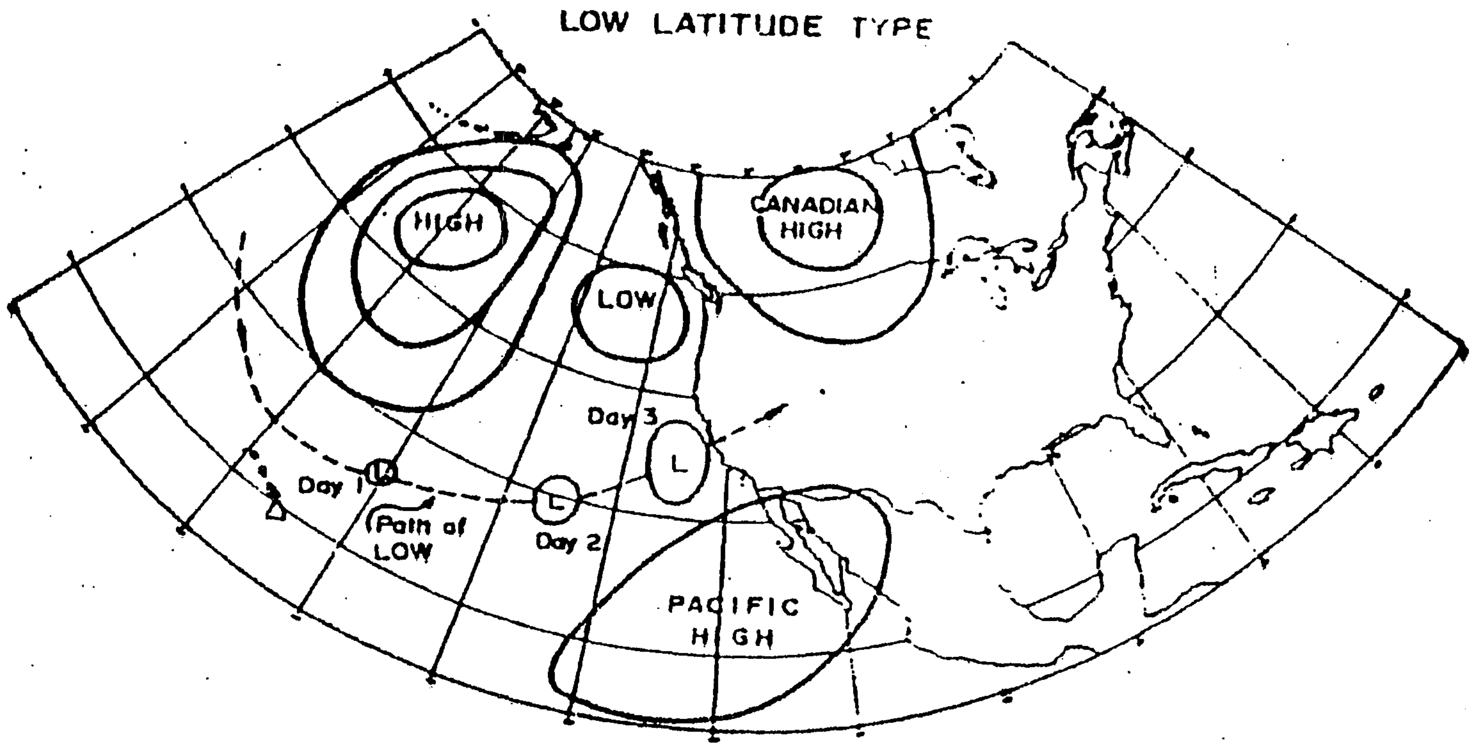

Figure 1. Schematic diagram showing Low Latitude type storm. Blocking in the Gulf of Alaska is an integral feature of this synoptic type. Disturbances pass north and south of the blocking anticyclone with southern breakthrough occurring near Hawaii. A quasi-stationary front with waves at various stages of development extends from the latitude of Hawaii northeastward into California (Monteverdi, 1976).

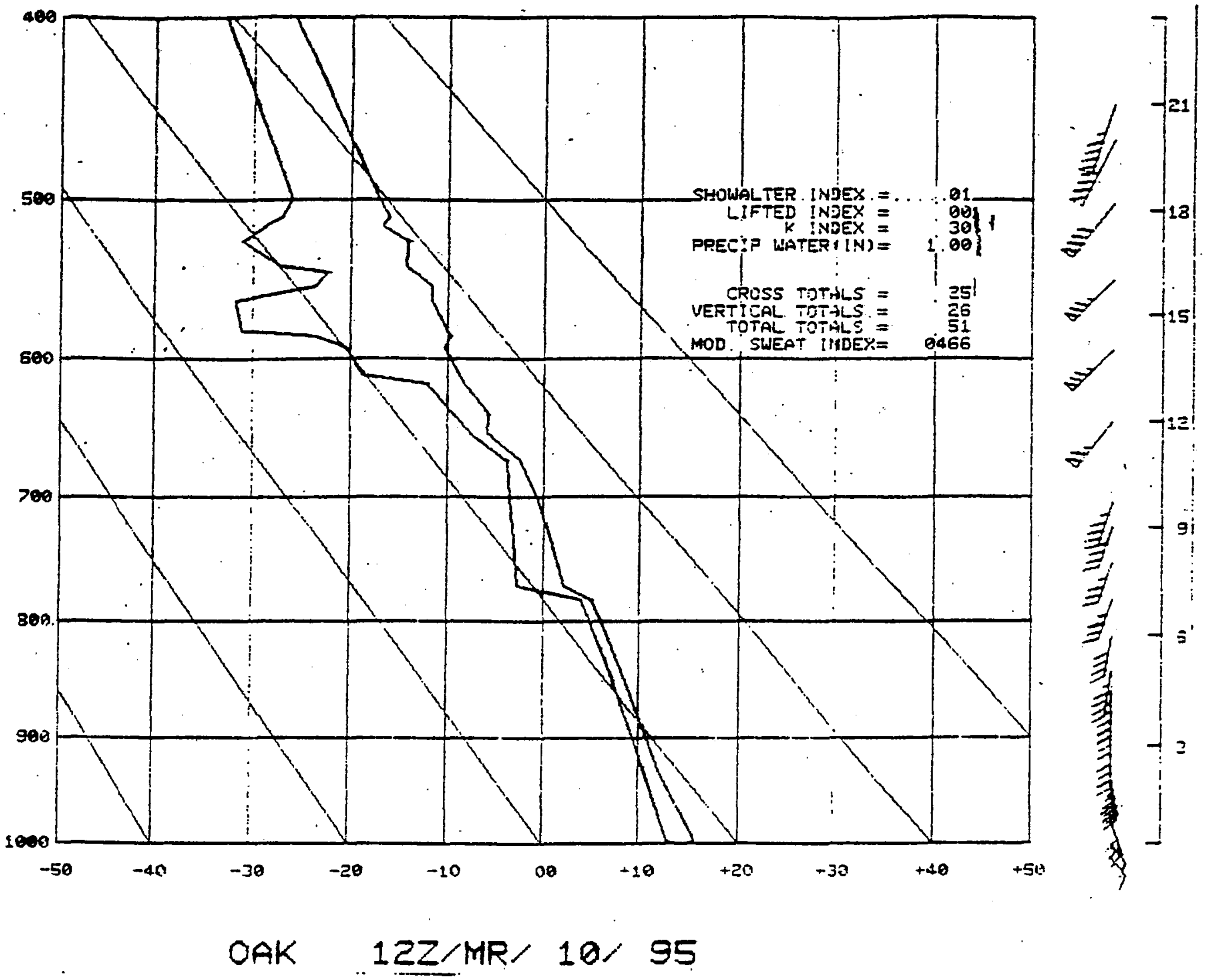

Figure 2. Sounding from Oakland, California for 12Z on March 10, 1995. The normal precipitable water for this date is 0.46 inches.

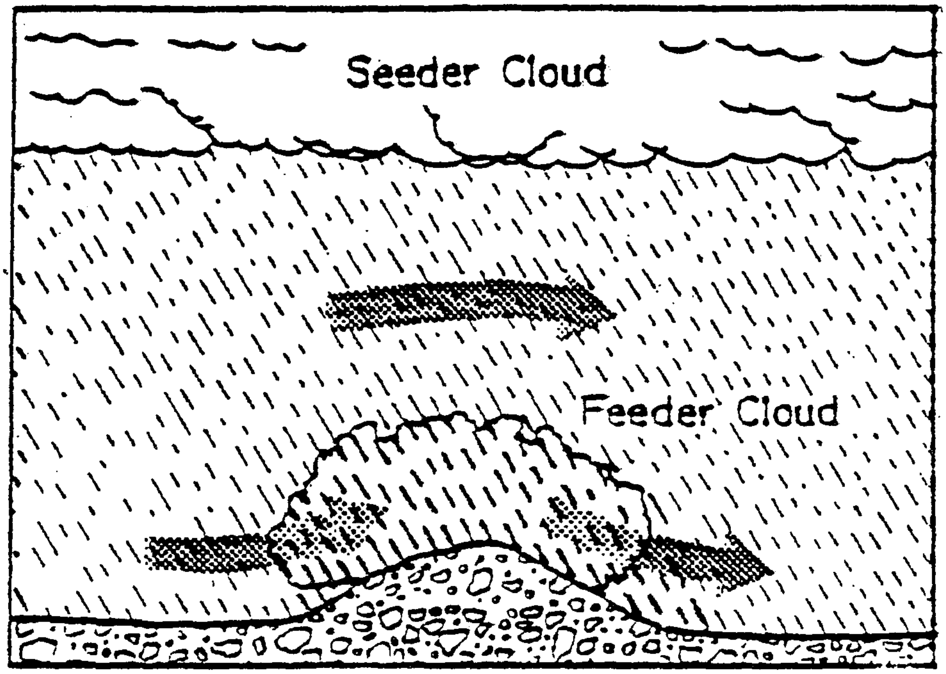

Figure 3. Seeder-feeder mechanism for the enhancement of orographic precipitation (Klemp, 1992).