



NOAA Technical Memorandum NWS WR-209

**STRATUS SURGE PREDICTION ALONG
THE CENTRAL CALIFORNIA COAST**

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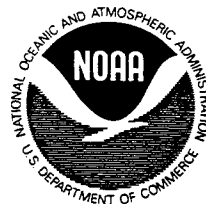
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ABSTRACT

A stratus surge is defined as the apparent movement of a narrow band of stratus from south to north along the west coast of the United States. It is considered to be an anomalous mesoscale event during the summer season because macroscale winds are predominantly from the northwest. A simple forecast scheme to predict the initiation of stratus surges along the central California coast has been developed and tested. The first part of the forecast scheme is based on a subjective screening of satellite images to determine the potential for a surge event. If that potential is high, an objective evaluation of the 850 mb Oakland RAOB temperature and San Francisco-Santa Maria sea level pressure difference is made to produce a final SURGE or NO SURGE forecast.

The forecast technique was developed using three years of data and tested independently on a fourth year. The subjective portion was effective in eliminating non-surge events. The objective portion resulted in skill scores of 0.48 for the development years and 0.56 for the test year. All data used to make the forecast are part of the incoming NWS data stream. The technique is easy to apply and should serve as a basis for the development of similar useful methods for other locations along the coast.

STRATUS SURGE PREDICTION ALONG THE CENTRAL CALIFORNIA COAST

I. INTRODUCTION

During the summer, the central California coast commonly experiences fair afternoon skies followed by the overnight development of stratus due to advection or in situ processes, which are triggered by very subtle changes in synoptic and/or mesoscale forces. A particularly difficult problem for the local forecaster is the prediction of the onset of stratus after one or more days of offshore flow and clear skies. One example is a unique type of onset known as a "stratus surge" which occurs when a narrow (mesoscale) band of marine stratus progresses northward along the coastline. A visible satellite image sequence showing the life cycle of a well-developed stratus surge along the central California coast is presented in Figure 1. Stratus surge events, considered anomalies because summer season coastal winds are predominantly northwesterly, act as mesoscale weather fronts as they progress along the coast. Their passage is marked by rising surface pressures, shifting winds, falling temperatures, and abrupt changes in ceilings and visibilities.

This study presents a climatology of stratus surge events and a forecast technique to predict events initiated along the central California coast. A brief review of past stratus surge studies along the west coast of the United States is discussed in section 2. The climatological study and a conceptual model are documented in section 3. The forecast scheme is developed and tested in section 4. Conclusions and recommendations for further study are presented in section 5.

II. BACKGROUND

Satellite images of northward progressing coastal stratus along the California coast were first documented by the National Weather Service (Western Regional Technical Attachment 69-24), but no

attempt was made to define or explain the phenomena. Jackson (1983) observed that the northward movement of stratus frequently appeared when the California heat trough extended to the coast, west of its normal inland position (see also Gilliland, 1980). Dorman (1985) presented a case study of a May 1982 event that progressed from Pt. Conception to Cape Mendocino over a three-day period and suggested that northward progressing "stratus surges" were due to coastally trapped Kelvin Waves.

Mass and Albright (1986) analyzed a "very strong" surge that progressed from central California to Vancouver Island. This event was synoptically forced. They hypothesized that an upper-level low circulation over southern California caused the cool marine layer to deepen in the south, reversing the mesoscale pressure gradient along the coastline, and triggering the surge event. At low levels, a narrow zone of ageostrophic downgradient flow developed and progressed northward. The width of this zone was limited because geostrophic balance was impeded by the presence of the coastal mountain barrier. Mass and Albright (1986) reanalyzed the Dorman case study and showed that the Kelvin wave hypothesis was not consistent with observational evidence.

Although the Dorman (1985) and Mass and Albright (1986) studies revealed some very important mechanisms for stratus surge initiation and progression, those studies involved two strong and particularly well-defined cases. In an attempt to generalize their results and apply them to the local forecast problem, an effort was made to define a large sample of stratus surges and to characterize them using available meteorological data.

III. CLIMATOLOGICAL STUDY AND CONCEPTUAL MODEL

In a preliminary unpublished investigation, one of the authors (Felsch) studied twenty-three well-defined stratus surges that developed along the California coast during the summer months (May through October) over the ten-year period 1975-1985. These surges were identified using visible band satellite images. The average surge identified in this study had a life span of 72 hours, and event durations ranged from 14 to 144 hours. Eleven of the 23 events did not progress north of the California-Oregon border.

Surface and upper-air pressure patterns from synoptic charts prior to surge initiation were summarized in the preliminary study. A common surface pressure pattern featured the axis of the California heat trough aligned from the northwest corner of California through the Central Valley, coastward of its normal summer season position (Figure 2). Two upper-air circulation patterns that could result in the westward shift of the surface heat trough were associated with the development of surge events. One pattern, observed prior to 11 of the 23 events, featured an upper-level low circulation over, or to the south of, the central California coast (Figure 3). For the remaining cases, the axis of an upper-level, short-wave ridge was aligned northeast to southwest across northern California. At 850 mb, this synoptic pattern results in ridging over northern California and troughing over the southern coastal area (Figure 4). Both upper-air patterns can produce low-level offshore flow and a shallow marine layer (low inversion) to the north, and a deeper marine layer (higher inversion) to the south. During these conditions, a mesoscale alongshore pressure gradient conducive to localized southerly flow can result.

A noteworthy observation in the preliminary study was that all surge events identified began during the nighttime hours, i.e., after the last available visible satellite image of the day and before the first visible image the next morning. The mesoscale pressure gradient during the nighttime hours is important to the nocturnal initiation of surges. After sunset, radiative cooling of the land reduces the land-sea temperature differential, thereby relaxing the macroscale pressure gradient. Macroscale northwest winds, which are sustained by the large-scale pressure gradient, also subside. A surge can develop when an alongshore mesoscale pressure gradient exists, featuring higher surface pressures to the south.

Based on this climatology and case study analyses of Dorman (1985) and Mass and Albright (1986) a conceptual model of the stratus surge emerges: Prior to surge development, the upper-level ridging exists over northern California. The surface heat trough is displaced coastward from its normal position. This pattern is related to lower than normal sea level pressures, a low inversion, and clear skies along the central California coast. At the same time, the marine inversion in the south has risen, establishing a localized reversal of the normal pressure gradient. During the nighttime hours, the mesoscale pressure gradient is enhanced by the relaxation of the large-scale gradient and low-level convergence. Ageostrophic southerly flow is initiated at the location of the steepest slope of the inversion. The sloping inversion moves northward in a flow field analogous to a dynamic head. The stratus signature of the surge event appears as the inversion rises locally to a height above the lifting condensation level.

IV. FORECAST MODEL DEVELOPMENT AND TESTING

Drawing on previous studies and the conceptual model described above, a semi-objective forecast technique was developed to predict the initiation of stratus surge events along the central California coastline during the stratus season. A "stratus surge" for this forecast scheme is defined as the northward progression of a narrow band of stratus along the central California coast between Pt. Conception and Pt. Reyes (Figure 5). The progression must be at least 60 nautical miles (nmi) in the 24 hour period after 00Z. SURGE and NO SURGE forecasts are verified using satellite images.

The forecast scheme was developed using the results of an evaluation of satellite images, and surface and upper-air meteorological observations from the months May through October over a three year period (1981-1983). The technique is composed of two parts, one subjective and one objective. In the subjective portion, the 00Z (or latest afternoon) visible satellite image is screened to determine if the potential for stratus surge development exists. Once a potential event is identified, the objective part of the scheme evaluates data from the 00Z Oakland sounding and the 00Z sea level pressure distribution along the coast to make a SURGE or NO SURGE forecast.

In the subjective screening of satellite images, it was assumed that a surge would not develop if stratus was observed along the entire central California coastline at 00Z. A potential stratus surge was identified if the 00Z satellite image showed a stratus free zone extending at least 60 nmi offshore and 120 nmi alongshore south of Shelter Cove (Figure 5), but not extending south beyond the Mexican border. Furthermore, the stratus free zone could not be bounded to the west by cold air

cumulus clouds within 300 nmi of the coast (eliminating strong, post-frontal northwest flow situations). The subjective criteria are described graphically in Figure 5.

For the 525 days during the model development period that satellite images were available, 170 were classified as "potential" surge days based on a review of the 00Z images. Stratus surges developed in the study area on 41 days (24%). No surges were observed on the days identified as having "no potential". Consistent with the findings of the climatology discussed earlier, all surge events developed during the nighttime hours.

The objective portion of the forecast technique was developed using predictors which provided some objective description of the marine inversion strength and alongshore sea level pressure field at the beginning of the forecast period. One restriction was that the predictor had to be a routine National Weather Service observation that was generally available for the model development years, and is still part of the current NWS data stream. A preliminary objective forecast scheme was developed using multiple predictors including:

- 00Z surface pressure readings for Arcata, San Francisco, Santa Maria, Sacramento, buoy 11 and buoy 12.
- 00Z alongshore and across-shore pressure gradients derived from the above listed stations.
- 00Z Oakland raob mandatory level temperature, wind and pressure surface height (850, 700, and 500 mb).

A forecast model using ten of the parameters listed above was developed and tested. This initial modeling effort demonstrated forecasting skill. However,

a model constructed using just two of the most promising predictors (the Santa Maria to San Francisco pressure difference [DPSFSM] and the Oakland 850 mb temperature [T850]) resulted in nearly identical stratus surge forecasting skill. Since the two-parameter objective model had the same skill as the ten-parameter model, and would be much easier to implement in an operational mode, it was chosen for this application.

Frequency distributions of T850 and DPSFSM for all potential surge days are shown in Figures 6 and 7. T850 data were available for 164 of the 170 potential surge event days. Data for the missing dates were estimated by interpolating between the previous and following 00Z T850's. 00Z DPSFSM data were available for 133 cases. Missing data were estimated statistically using the Buoy 11-Buoy 12 pressure difference, a process described in Appendix 1 and shown in Figure 5. The T850 histogram shows that surges did not occur at the low end of the temperature range, i.e., when the inversion was too high, too weak, or non-existent. Surge and non-surge events were fairly evenly distributed at the higher temperatures. The pressure difference histogram presented in Figure 7 shows a near normal distribution of surge events. The mode is slightly negative, that is, surface pressures was higher at Santa Maria than San Francisco. For the non-surge cases, peak frequencies of DPSFSM occurred when the 00Z San Francisco surface pressure was slightly higher than observed at Santa Maria.

Based on the frequency distributions discussed above, a two-step procedure was developed to objectively forecast surge initiation for the 170 potential cases. The first step consisted of making a NO SURGE forecast when the 00Z T850 was below 9.8C, the level below which no surge events were observed. As a result of this test, 22 of the 170 cases were eliminated as potential events.

The second step of the objective portion of the forecast method consisted of making a SURGE or NO SURGE forecast for the remaining potential events based on the value of DPSFSM at 00Z. The pattern shown in Figure 7 suggests that there was an optimum San Francisco-Santa Maria pressure difference threshold value above which surges were likely to develop, and below which surges were unlikely to develop. Skill scores were calculated to determine the optimum threshold value to be used to predict surge development. The method used to calculate skill score is presented in Appendix 2. Results of the skill score computations, presented in Figure 8, indicate that forecasting skill was optimized if surges were forecast when the 00Z DPSFSM was less than or equal to -0.2 mb.

A contingency table showing the results of SURGE and NO SURGE forecasts made for the model development data set using $DPSFSM \leq -0.2$ mb as the predictor for surge development is presented in Table 1. Over 68 percent (28 of 41) of the surge events and 79 percent (85 of 107) of the non-surge events were correctly forecast. The contingency table also shows that the probability of surge development when SURGE was forecast was 56 percent (28 of 50). The probability of surge development when a NO SURGE forecast was made was 13 percent (13 of 98). These results indicate that the greatest strength of the objective portion of this forecast scheme is the ability to identify non-surge events. Very likely this is due to stronger measurable macroscale (synoptic) influences in the non-surge events and poorly measured mesoscale influences in the surge cases.

The model was tested using data from the months of May through October, 1984. Satellite images were available for 177 days during that period. Using the subjective screening technique, 67 potential surge cases were identified.

Satellite images indicated surges developed within 24 hours on 27 (40 percent) of the potential surge days. All surges began during the nighttime hours. In no cases were surges identified within 24 hours of 00Z when the subjective screening tests resulted in a NO SURGE forecast.

The 67 cases were further screened using the objective portion of the model. Five of the potential cases were eliminated as NO SURGE cases on the basis of the T850 criteria. All were correct forecasts. Of the remaining cases, the DPSFSM criteria resulted in 27 SURGE forecasts and 35 NO SURGE forecasts. For the test data set 74 percent of the SURGE forecasts and 80 percent of the NO SURGE forecasts verified. Based on the contingency table presented in Table 2, a skill score of .54 was attained, somewhat higher than calculated for the development period. Similar to the forecast verification pattern for the development years, the test year results show that the probability of accurately predicting non-surge events was higher than for surge events.

A summary of the instructions for implementing the stratus surge forecast model developed here is presented in a flowchart format in Figure 9. One feature of the model is that the user may exit the model any time a NO SURGE forecast is made. In this respect, this semi-objective forecast scheme has many of the characteristics of a decision tree forecast technique in which a logical series of questions branch out toward the solution of a problem. Ellrod (1989) suggests that the decision tree approach is well-suited for problems involving both subjective and objective criteria.

V. CONCLUSIONS AND RECOMMENDATIONS

Past case studies of stratus surge events along the California coast by Dorman

(1985) and Mass and Albright (1986), and the climatological review, proved to be useful tools for developing a method to forecast that phenomena. The semi-objective forecast technique developed here verified well using an independent data set. It provides the forecaster with a simple and easy-to-implement prediction method, and offers some guidance for the future development of better techniques.

The subjective and objective portions of this model give some indication of both the macroscale and mesoscale atmospheric conditions necessary for stratus surge initiation. In summary, those conditions allow the marine layer to the south to rise, while the marine layer to the north remains shallow, resulting in a weakening or reversal of the normal pressure gradient. Surges were consistently observed to develop during the nighttime hours when the macroscale northwest gradient weakens or reverses due to radiative cooling of the land, increasing the importance of the alongshore mesoscale gradient with higher surface pressure values developing to the south. A majority of surges were observed when the surface pressure was higher at Santa Maria than San Francisco at 00Z, but a reversal of this pressure gradient was not a necessary condition for surge development. Since these stations are approximately 175 nmi apart, it is probable that the spatial scale used to define the pressure gradient in the model is too large to identify some mesoscale events.

Alongshore pressure tendency and/or pressure gradient tendency, not evaluated in this forecast scheme, may provide additional skill in forecasting surges if included in the objective screening step. It may also be possible to improve forecast skill by including computer model 12 or 24 hour forecasts of surface pressure patterns. Model output 500 mb vorticity advection patterns may also have predictor value for forecasting the marine

layer depth, in response to changes in upper-level dynamics:

No attempt was made to forecast the northward extent of the stratus surge or predict the duration of events which may be as important as forecasting the event itself. This deserves further study. Also, eddies have been observed to form at the leading edge of a stratus surge when it encounters coastal headlands. Further study of this phenomenon may lead to a better understanding of the stratus surge life cycle and the effect that topographic features along the coast have on surge duration.

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APPENDIX 1

Although DPSFSM data were available for most of the model development and test years there were some missing data. In order to evaluate this parameter for all potential surge days identified in the subjective portion of the model, a method was developed to estimate DPSFSM based on the pressure gradient between BUOY 12 and BUOY 11 (DP1211). These buoys are located approximately 30 miles offshore near the northern and southern boundaries of the study area (Figure 5). BUOY 11 is located directly west of Santa Maria and BUOY 12 is located about 20 miles south-southwest of San Francisco Airport. Available 00Z pressure gradient data from both sources (sample size=285) were statistically analyzed using a General Linear Models procedure (SAS 1985). A good correlation was found between DPSFSM and DP1211 (R-SQUARE=0.75) and the equation to estimate the 00Z DPSFSM using the observed 00Z DP1211 and the slope and intercept output by GLM was:

$$\text{DPSFS} = \text{DP1211} * .7807 - 0.943$$

This equation was used to estimate missing alongshore pressure differences.

APPENDIX 2

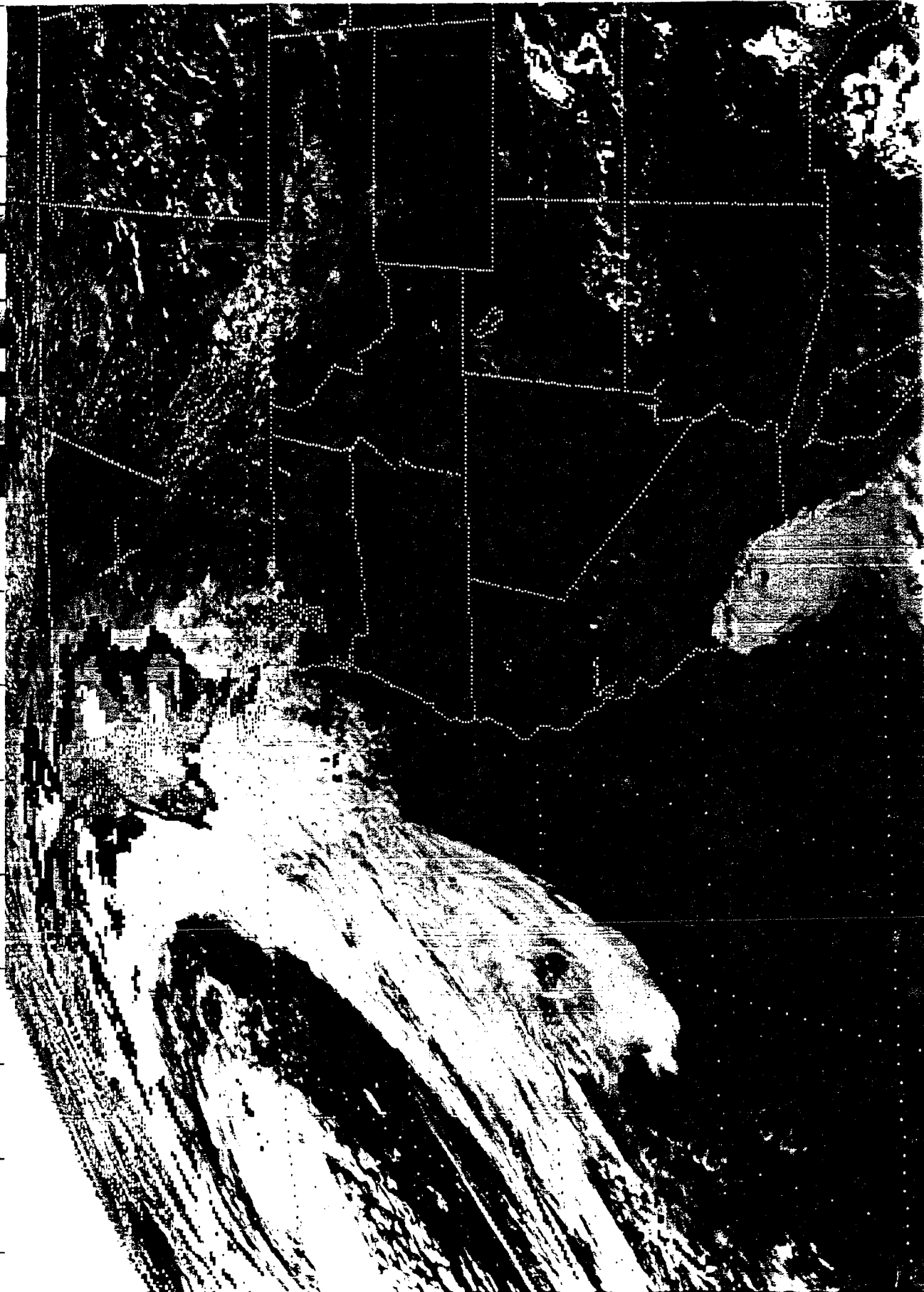
Skill scores (S) were defined as: $S = (R - E) / (T - E)$, where R is the number of correct forecasts, T is the total number of forecasts, and E is the number of forecasts expected to be correct (Panofsky and Brier 1968). S has a value of zero if the number of correct forecasts equals the number of expected correct forecasts, and approaches unity as forecast skill increases. In a purely chance forecast situation, such as a coin flip, the value of E is one-half of T. Since surge events were only observed on about one-fourth of the potential surge days, E was calculated using the margin totals of the contingency tables as suggested by Panofsky and Brier (1968). The expected number of correct forecasts was therefore calculated using:

$$E = \sum R_i * C_i / T,$$

where R_i is the sum of the i th row and C_i is the sum of the i th column.

Figure 1A

0100 11JN85 38A-204 00933 15191 SB40N122W-1



1701 11JN85 38A-4 01331 17651 9C2

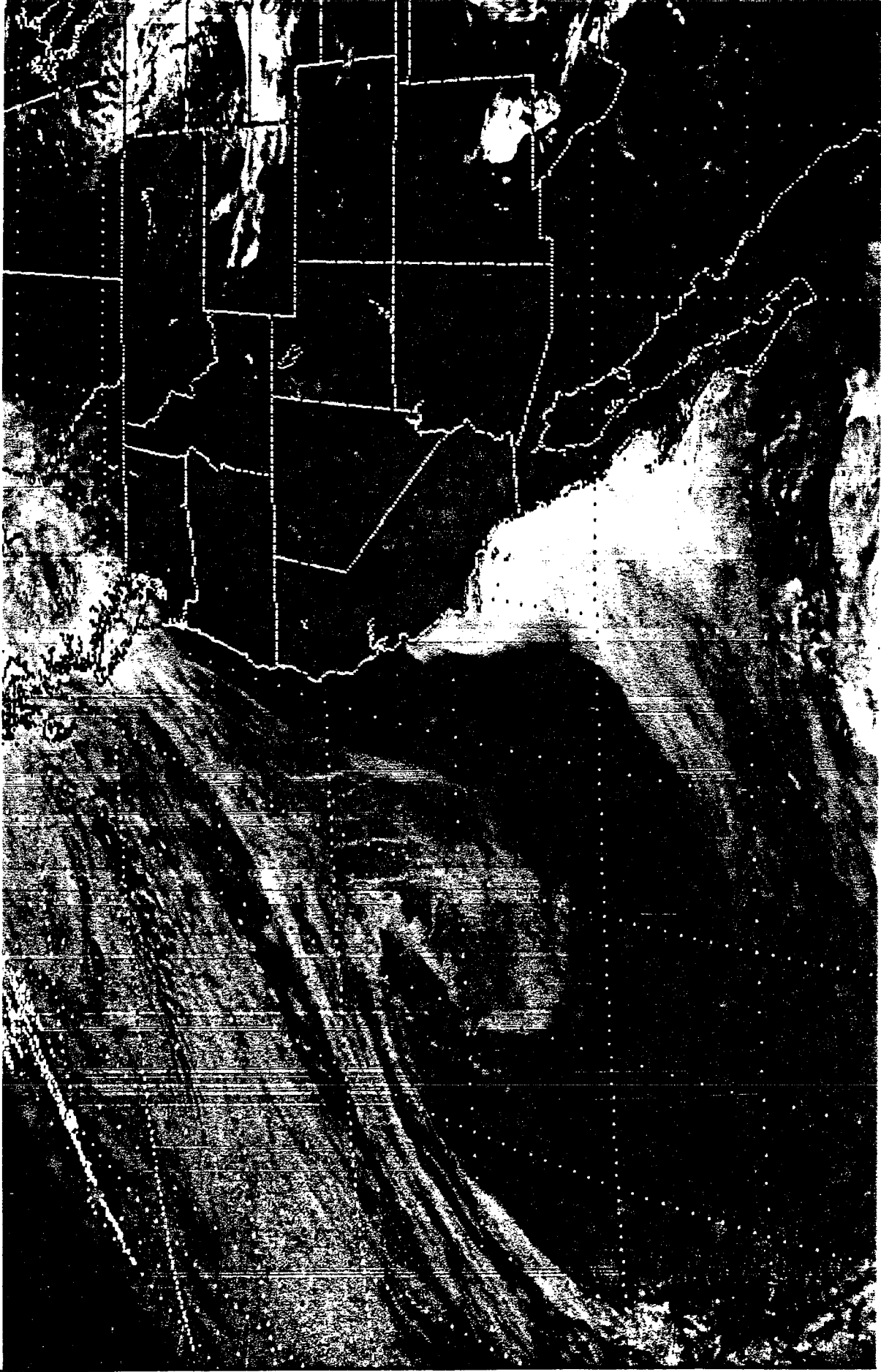
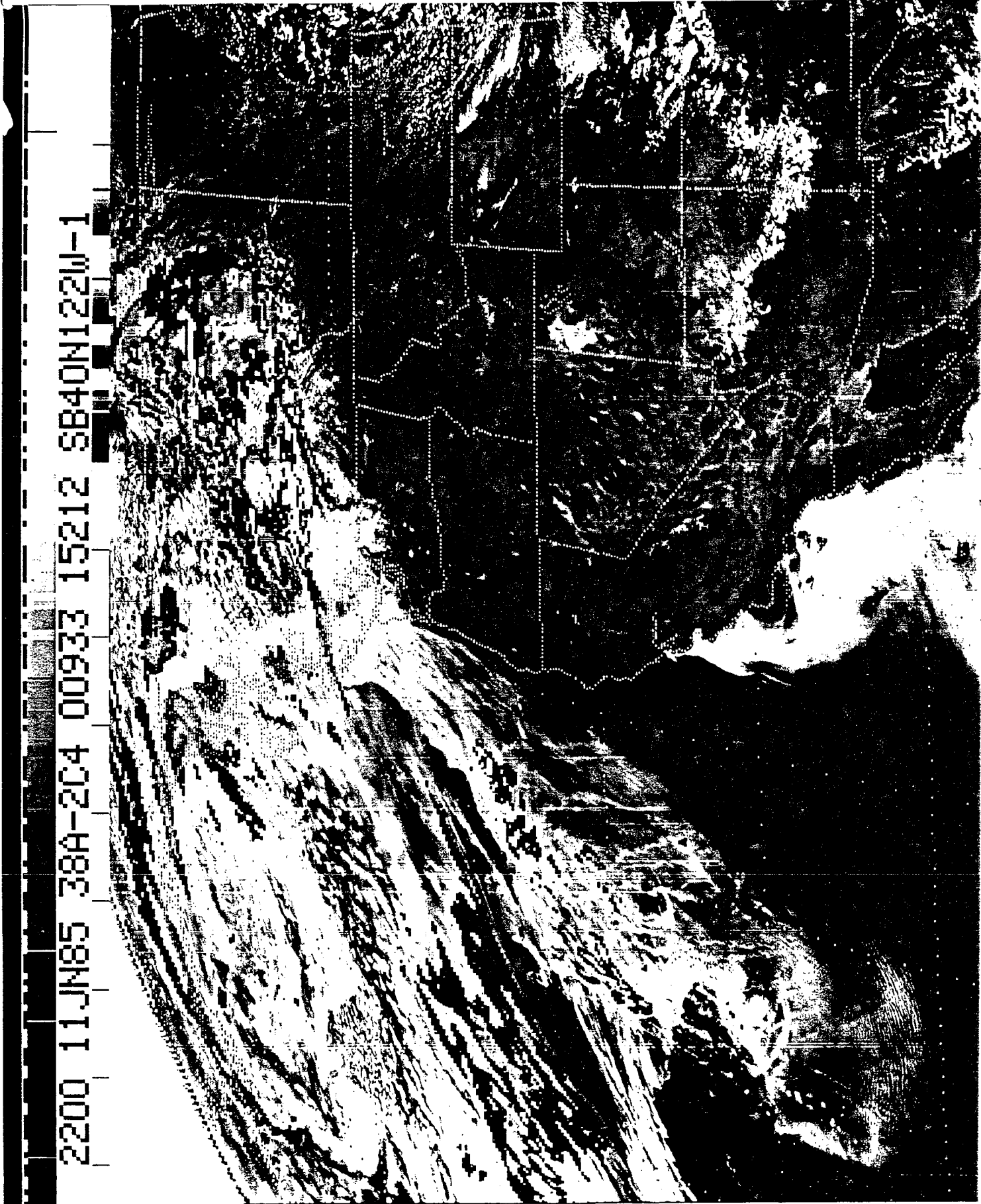


Figure 1B

Figure 1C



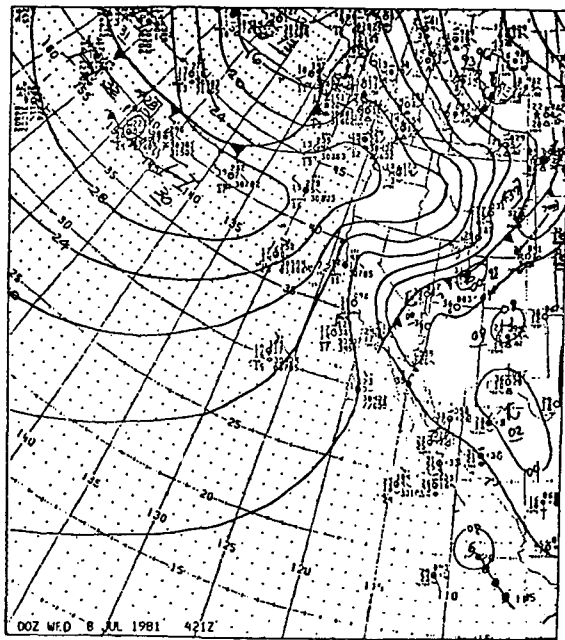


Figure 2.) Example of the the Surface Heat Trough Extending Coastward of Its Normal Position In Central California.

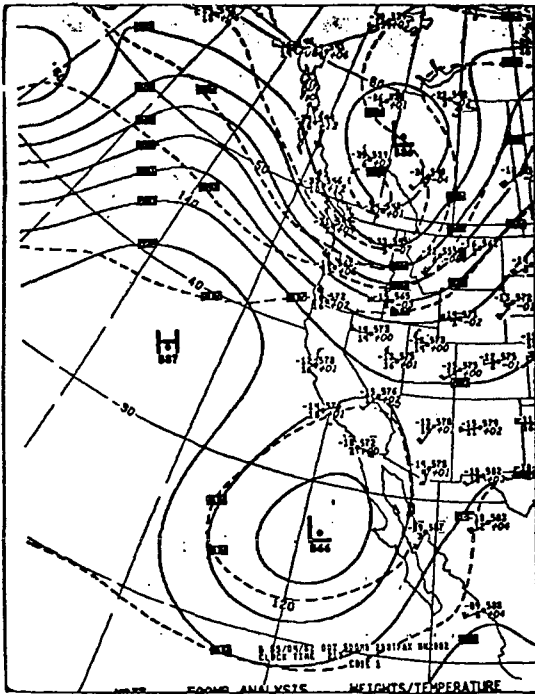


Figure 3.) Example of a 500mb Cutoff Low Circulation Observed Prior to Some Surge Events.

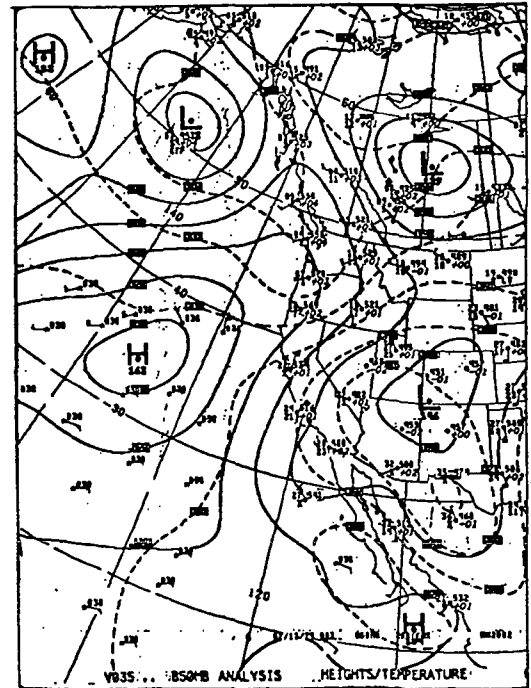


Figure 4.) Example of 850mb Pattern Associated With Short Wave Ridge Movement Across Northern California.

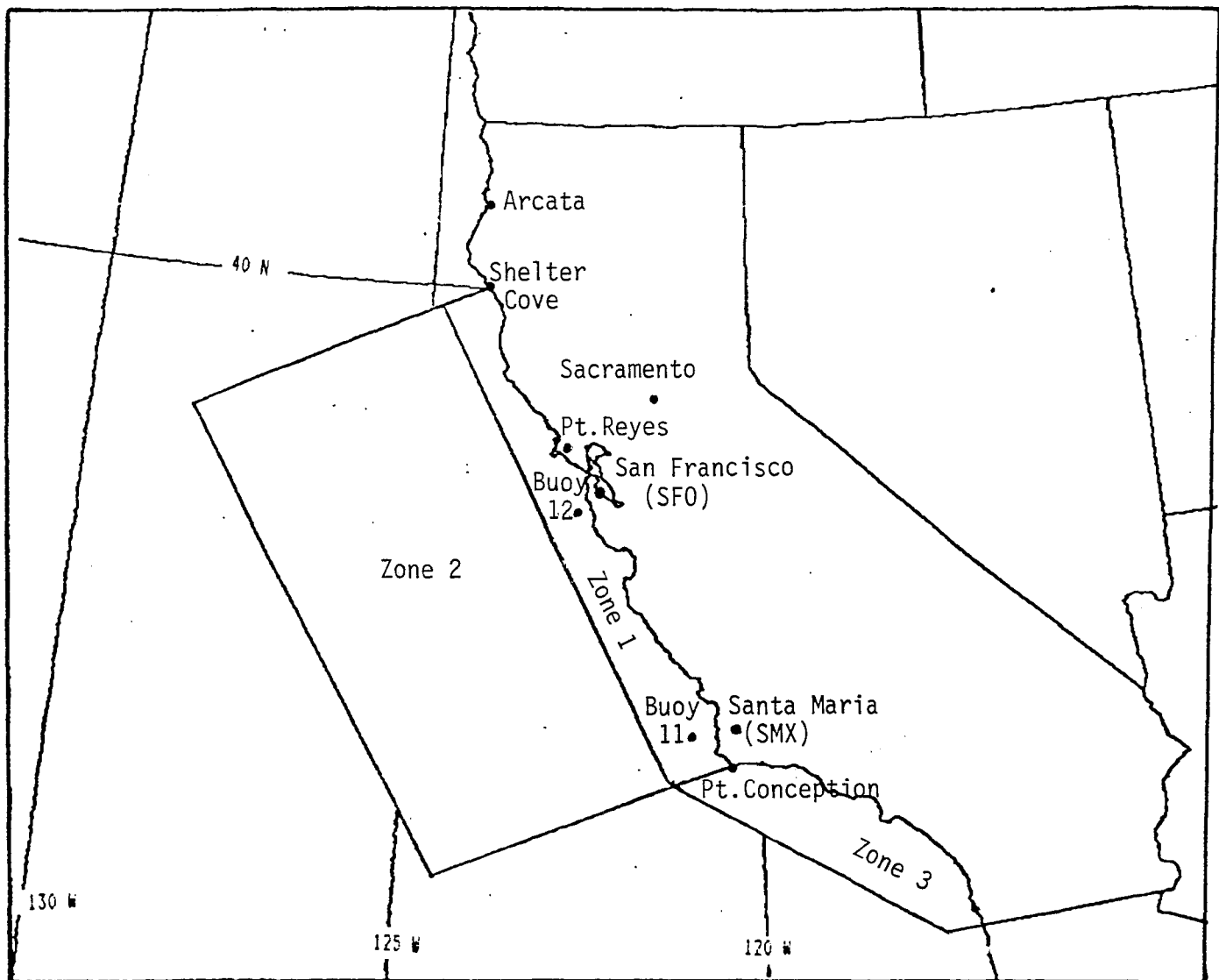


Figure 5.) Criteria for the Subjective Screening of Visible Band Satellite Images to Determine Potential Surge Events.

LEGEND

- ZONE 1: A Continuous Stratus-Free Area 120 nmi Along-shore and 60 nmi Offshore Must Be Observed in This Zone at 00Z or There is NO Surge Potential.
- ZONE 2: If Cold Air Cumulus Are Observed in This Zone at 00Z There is NO Surge Potential.
- ZONE 3: If the Stratus-Free Area Extends South of the Mexican Border There is NO Surge Potential.

OAKLAND 00Z 850MB TEMPERATURE
1981-1983 POTENTIAL CASES

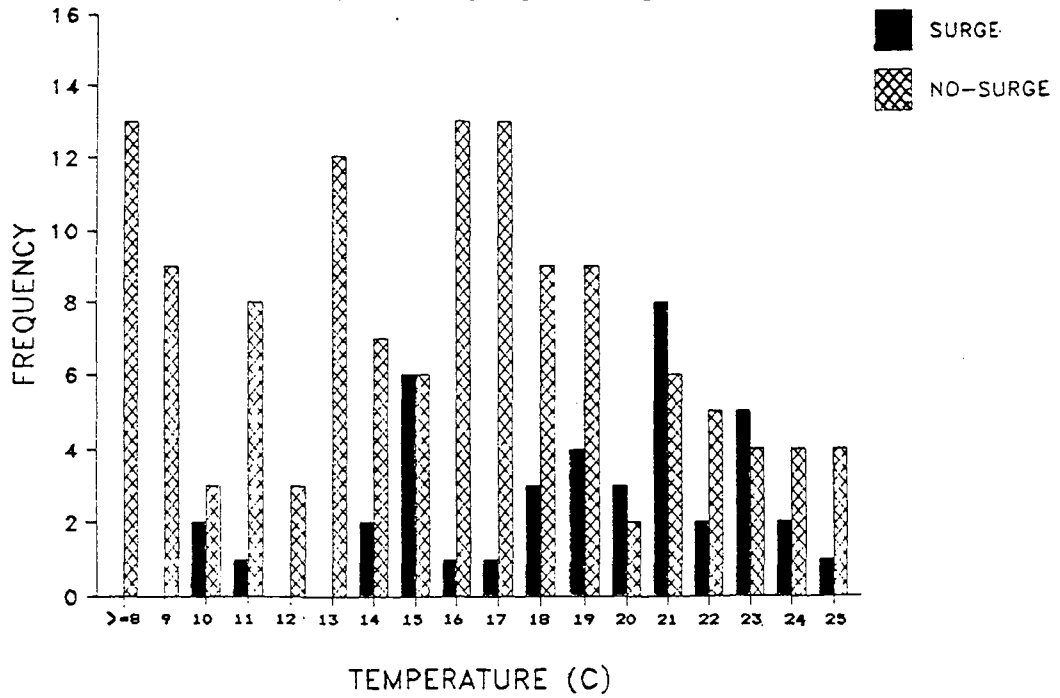


Figure 6.) Frequency Distribution (in 1 degree bins) of SURGE and NO SURGE Events as a Function of Oakland 850mb Temperature at 00Z; Development Dataset, 1981-1983.

SFO-SMX SURFACE PRESSURE
1981-1983 POTENTIAL CASES

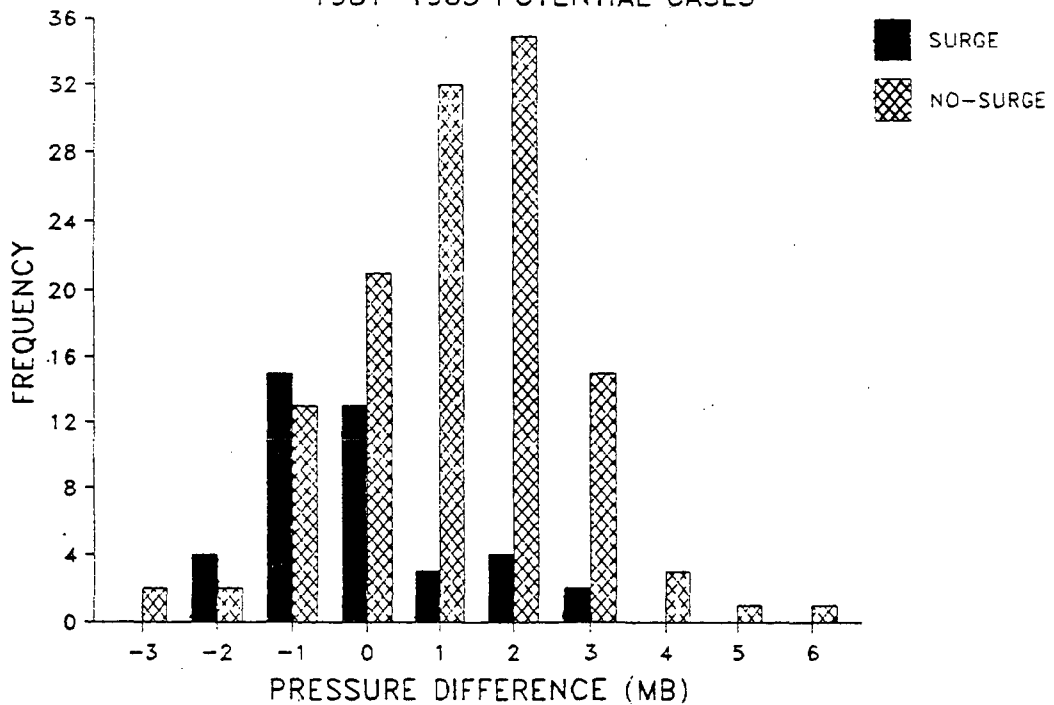


Figure 7.) Frequency Distribution (in 1 mb bins) of SURGE and NO SURGE Events as a Function of SFO-SMX Pressure Difference at 00Z.

FORECAST SURGE IF SFO-SMX \leq LISTED VALUE
YEARS 1981-1983

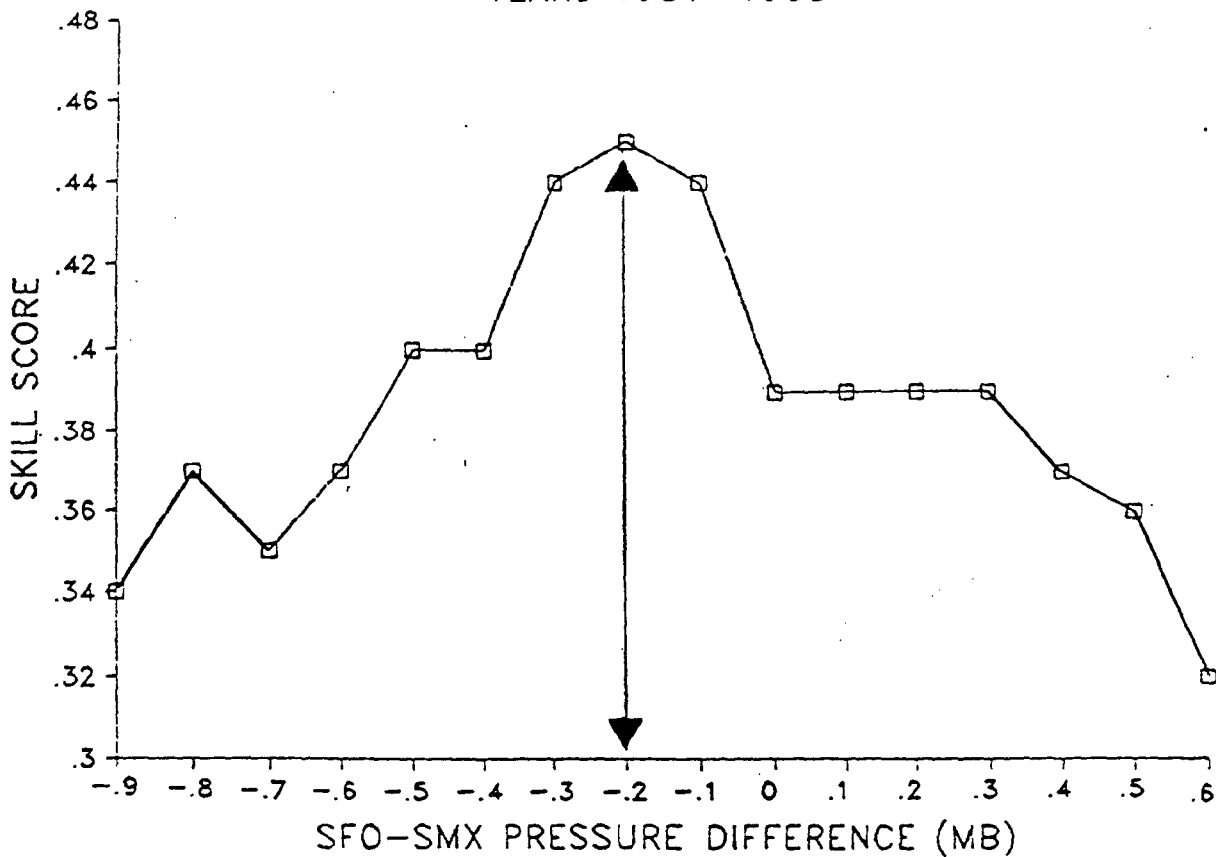


Figure 8.) Skill Scores Plotted as a Function of the Threshold Value of SFO-SMX Used to Forecast Surge Development.

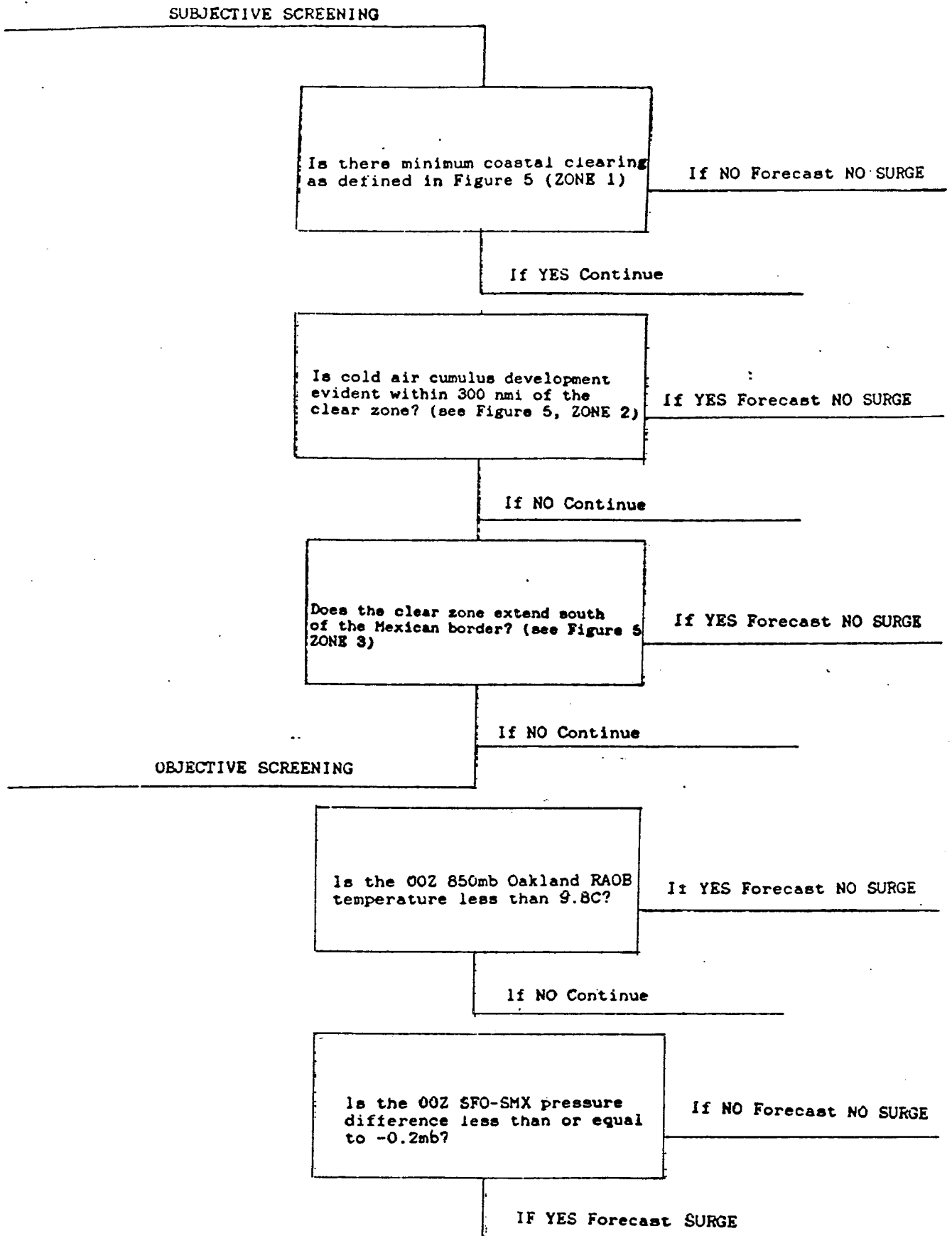


Figure 9.) Stratus Surge Forecast Flowchart.

TABLE 1

CONTINGENCY TABLE FOR DEVELOPMENT YEARS
1981-1983

FORECAST TEST: IF DPSFSM<=-0.2MB FORECAST SURGE

	FORECAST SURGE	FORECAST NO SURGE	:	ROW TOTALS
OBSERVED SURGE	28	13	:	41
OBSERVED NO SURGE	22	85	:	107
<hr style="border-top: 1px dashed black;"/>				
COLUMN TOTALS	50	98	:	148

TABLE 2

CONTINGENCY TABLE FOR TEST YEAR
1984

FORECAST TEST: IF DPSFSM<=-0.2MB FORECAST SURGE

	FORECAST SURGE	FORECAST NO SURGE	:	ROW TOTALS
OBSERVED SURGE	20	7	:	27
OBSERVED NO SURGE	7	28	:	35
<hr style="border-top: 1px dashed black;"/>				
COLUMN TOTALS	27	35	:	62

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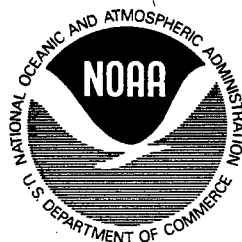
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