NOAA Technical Memorandum NWS WR-209

STRATUS SURGE PREDICTION ALONG THE CENTRAL CALIFORNIA COAST

Peter Felsch
National Weather Service
Weather Service Forecast Office
San Francisco, California

Woodrow Whitlatch
San Jose State University
San Jose, California

December 1990

U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Weather Service

NOAA TECHNICAL MEMORANDA
National Weather Service, Western Region Subseries

The National Weather Service (NWS) Western Region (WR) Subseries provides an informal medium for the documentation and quick dissemination of results not appropriate, or not yet ready, for formal publication. The series is used to report on work in progress, to describe technical procedures and practices, or to relate progress to a limited audience. These Technical Memoranda will report on investigations devoted primarily to regional and local problems of interest mainly to personnel, and hence will not be widely distributed.

Papers 1 to 25 are in the former series, ESSA Technical Memoranda, Western Region Technical Memoranda (WRTM); papers 24 to 59 are in the former series, ESSA Technical Memoranda, Weather Bureau Technical Memoranda (WBTM). Beginning with 60, the papers are part of the series, NOAA Technical Memoranda NWS. Out-of-print memoranda are not listed.

Papers 2 to 22, except for 5 (revised edition), are available from the National Weather Service Western Region, Scientific Services Division, P.O. Box 11188, Federal Building, 125 South State Street, Salt Lake City, Utah 84147. Paper 5 (revised edition), and all others beginning with 25 are available from the National Technical Information Service, U.S. Department of Commerce, Sills Building, 5285 Port Royal Road, Springfield, Virginia 22161. Prices vary for all paper copies; microfiche are $3.50. Order by accession number shown in parentheses at end of each entry.

ESSA Technical Memoranda (WRTM)

2 Climatological Precipitation Probabilities. Compiled by Lucianne Miller, December 1965.
3 Western Region Pre- and Post-FP-3 Program, December 1, 1965, to February 20, 1966. Edward D. Diemer, March 1966.
5 Station Descriptions of Local Effects on Synoptic Weather Patterns. Philip Williams, Jr., April 1966 (Revised November 1967, October 1969). (PB-17800)
8 Interpreting the RAREP. Herbert P. Benner, May 1966 (Revised January 1967).
11 Some Electrical Processes in the Atmosphere. J. Latham, June 1966.
17 A Digitalized Summary of Radar Echoes within 100 Miles of Sacramento, California. J. A. Youngberg and L. B. Overaas, December 1966.
21 An Objective Aid for Forecasting the End of East Winds in the Columbia Gorge, July through October. D. John Coparanis, April 1967.
22 Derivation of Radar Horizons in Mountainous Terrain. Roger G. Pappas, April 1967.

ESSA Technical Memoranda, Weather Bureau Technical Memoranda (WBTM)

25 Verification of Operation Probability of Precipitation Forecasts, April 1966-March 1967. W. W. Dickey, October 1967. (PB-176240)
26 A Study of Winds in the Lake Mead Recreation Area. R. P. Augulis, January 1968. (PB-177830)
28 Weather Extremes. R. J. Schmidli, April 1968 (Revised March 1986). (PB86 177672/AS)
29 Small-Scale Analysis and Prediction. Philip Williams, Jr., May 1968. (PB178425)
30 Numerical Weather Prediction and Synoptic Meteorology. CPT Thomas D. Murphy, USAF, May 1968. (AD 673365)
31 Precipitation Detection Probabilities by Salt Lake ARTC Radars. Robert K. Belesky, July 1968. (PB 179084)
32 Probability Forecasting--A Problem Analysis with Reference to the Portland Fire Weather District. Harold S. Ayer, July 1968. (PB 179289)

36 Temperature Trends in Sacramento--Another Heat Island. Anthony D. Lentini, February 1969. (PB 183055)
37 Disposal of Logging Residues Without Damage to Air Quality. Owen P. Cramer, March 1969. (PB 183057)
39 Upper-Air Lows Over Northwestern United States. A.L. Jacobson, April 1969. PB 184296)
40 The Man-Machine Mix in Applied Weather Forecasting in the 1970s. L.W. Snellman, August 1969. (PB 185068)
43 Forecasting Maximum Temperatures at Helena, Montana. David E. Olsen, October 1969. (PB 185762)
44 Estimated Return Periods for Short-Duration Precipitation in Arizona. Paul C. Kangieser, October 1969. (PB 187763)
46 Applications of the Net Radiometer to Short-Range Fog and Stratus Forecasting at Eugene, Oregon. L. Yee and E. Bates, December 1969. (PB 190476)
47 Statistical Analysis as a Flood Routing Tool. Robert J.C. Burnash, December 1969. (PB 188744)
48 Tsunami. Richard P. Augulis, February 1970. (PB 190157)
49 Predicting Precipitation Type. Robert J.C. Burnash and Floyd E. Hug, March 1970. (PB 190962)
50 Statistical Report on Aeroallergens (Pollens and Molds) Fort Huachuca, Arizona, 1969. Wayne S. Johnson, April 1970. (PB 191743)
51 Western Region Sea State and Surf Forecaster's Manual. Gordon C. Shields and Gerald B. Burdwell, July 1970. (PB 193102)
52 Sacramento Weather Radar Climatology. R.G. Pappas and C. M. Veliquette, July 1970. (PB 193347)
54 A Refinement of the Vorticity Field to Delineate Areas of Significant Precipitation. Barry B. Aronovitch, August 1970.
55 Application of the SSARR Model to a Basin without Discharge Record. Vail Schermerhorn and Donal W. Kuehl, August 1970. (PB 194394)
56 Areal Coverage of Precipitation in Northwestern Utah. Philip Williams, Jr., and Werner J. Heck, September 1970. (PB 194389)
57 Preliminary Report on Agricultural Field Burning vs. Atmospheric Visibility in the Willamette Valley of Oregon. Earl M. Bates and David O. Chilcote, September 1970. (PB 194710)
58 Air Pollution by Jet Aircraft at Seattle-Tacoma Airport. Wallace R. Donaldson, October 1970. (COM 71 00017)
59 Application of PE Model Forecast Parameters to Local-Area Forecasting. Leonard W. Snellman, October 1970. (COM 71 00016)
60 An Aid for Forecasting the Minimum Temperature at Medford, Oregon, Arthur W. Fritz, October 1970. (COM 71 00120)
63 700-mb Warm Air Advection as a Forecasting Tool for Montana and Northern Idaho. Norris E. Woerner, February 1971. (COM 71 00349)
64 Wind and Weather Regimes at Great Falls, Montana. Warren B. Price, March 1971.
65 Climate of Sacramento, California. Tony Martini, April 1990. (Fifth Revision) (PB89 207781/AS)
66 A Preliminary Report on Correlation of ARTCC Radar Echoes and Precipitation. Wilbur K. Hall, June 1971. (COM 71 00829)
69 National Weather Service Support to Soaring Activities. Ellis Burton, August 1971. (COM 71 00956)
71 Western Region Synoptic Analysis-Problems and Methods. Philip Williams, Jr., February 1972. (COM 72 10433)
74 Thunderstorms and Hail Days Probabilities in Nevada. Clarence M. Sakamoto, April 1972. (COM 72 10554)
75 A Study of the Low Level Jet Stream of the San Joaquin Valley. Ronald A. Willis and Philip Williams, Jr., May 1972. (COM 72 10707)
76 Monthly Climatological Charts of the Behavior of Fog and Low Stratus at Los Angeles International Airport. Donald M. Gales, July 1972. (COM 72 11140)
77 A Study of Radar Echo Distribution in Arizona During July and August. John E. Hales, Jr., July 1972. (COM 72 11136)
78 Forecasting Precipitation at Bakersfield, California, Using Pressure Gradient Vectors. Earl T. Riddiough, July 1972. (COM 72 11146)
79 Climate of Stockton, California. Robert C. Nelson, July 1972. (COM 72 10920)
80 Estimation of Number of Days Above or Below Selected Temperatures. Clarence M. Sakamoto, October 1972. (COM 72 10021)
81 An Aid for Forecasting Summer Maximum Temperatures at Seattle, Washington. Edgar G. Johnson, November 1972. (COM 73 10150)
82 Flash Flood Forecasting and Warning Program in the Western Region. Philip Williams, Jr., Chester L. Glenn, and Roland L. Raetz, December 1972, (Revised March 1978). (COM 73 10251)
83 A comparison of Manual and Semiautomatic Methods of Digitizing Analog Wind Records. Glenn E. Rasch, March 1973. (COM 73 10669)
86 Conditional Probabilities for Sequences of Wet Days at Phoenix, Arizona. Paul C. Kangieser, June 1973. (COM 73 11264)
87 A Refinement of the Use of K-Values in Forecasting Thunderstorms in Washington and Oregon. Robert Y.G. Lee, June 1973. (COM 73 11276)
89 Objective Forecast Precipitation Over the Western Region of the United States. Julia N. Paegle and Larry P. Kierulff, September 1973. (COM 73 11946/3AS)
91 Arizona "Eddy" Tornadoes. Robert S. Ingram, October 1973. (COM 73 10465)
92 Smoke Management in the Willamette Valley. Earl M. Bates, May 1974. (COM 74 11277/AS)
93 An Operational Evaluation of 500-mb Type Regression Equations. Alexander E. MacDonald, June 1974. (COM 74 11407/AS)
94 Conditional Probability of Visibility Less than One-Half Mile in Radiation Fog at Fresno, California. John D. Thomas, August 1974. (COM 74 11555/AS)
95 Climate of Flagstaff, Arizona. Paul W. Sorenson, and updated by Reginald W. Preston, January 1987. (PB87 143160/AS)
96 Map type Precipitation Probabilities for the Western Region. Glenn E. Rasch and Alexander E. MacDonald, February 1975. (COM 75 10428/AS)
97 Eastern Pacific Cut-Off Low of April 21-28, 1974. William J. Alder and George R. Miller, January 1976. (PB 250 711/AS)
98 Study on a Significant Precipitation Episode in Western United States. Ira S. Brenner, April 1976. (COM 75 10719/AS)
99 A Study of Flash Flood Susceptibility-A Basin in Southern Arizona. Gerald Williams, August 1975. (COM 75 11360/AS)
102 A Set of Rules for Forecasting Temperatures in Napa and Sonoma Counties. Wesley L. Tuft, October 1975. (PB 246 902/AS)
103 Application of the National Weather Service Flash-Flood Program in the Western Region. Gerald Williams, January 1976. (PB 253 053/AS)
104 Objective Aids for Forecasting Minimum Temperatures at Reno, Nevada, During the Summer Months. Christopher D. Hill, January 1976. (PB 252 866/AS)
105 Forecasting the Mono Wind. Charles P. Ruscha, Jr., February 1976. (PB 254 650)
106 Use of MOS Forecast Parameters in Temperature Forecasting. John C. Plankinton, Jr., March 1976. (PB 254 649)
107 Map Types as Aids in Using MOS PoPs in Western United States. Ira S. Brenner, August 1976. (PB 259 594)
108 Other Kinds of Wind Shear. Christopher D. Hill, August 1976. (PB 260 437/AS)

109 Forecasting North Winds in the Upper Sacramento Valley and Adjoining Forests. Christopher E. Fontana, September 1976. (PB 273 677/AS)
110 Cool Inflow as a Weakening Influence on Eastern Pacific Tropical Cyclones. William J. Denney, November 1976. (PB 264 655/AS)
112 The MAN/MOS Program. Alexander E. MacDonald, February 1977. (PB 265 941/AS)
113 Winter Season Minimum Temperature Formula for Bakersfield, California, Using Multiple Regression. Michael J. Oard, February 1977. (PB 273 694/AS)
114 Tropical Cyclone Kathleen. James R. Fors, February 1977. (PB 273 676/AS)
116 A Study of Wind Gusts on Lake Mead. Bradley Colman, April 1977. (PB 268 847)
117 The Relative Frequency of Cumulonimbus Clouds at the Nevada Test Site as a Function of K-Value. R.F. Quiring, April 1977. (PB 272 831)
118 Moisture Distribution Modification by Upward Vertical Motion. Ira S. Brenner, April 1977. (PB 268 740)
119 Relative Frequency of Occurrence of Warm Season Echo Activity as a Function of Stability Indices Computed from the Yucca Flat, Nevada, Rawinsonde. Darryl Randerson, June 1977. (PB 271 290/AS)
121 Climatological Prediction of Cumulonimbus Clouds in the Vicinity of the Yucca Flat Weather Station. R.F. Quiring, June 1977. (PB 271 704/AS)
122 A Method for Transforming Temperature Distribution to Normality. Morris S. Webb, Jr., June 1977. (PB 271 742/AS)
124 Statistical Guidance for Prediction of Eastern North Pacific Tropical Cyclone Motion - Part I. Charles J. Neumann and Preston W. Leftwich, August 1977. (PB 272 661)
125 Statistical Guidance on the Prediction of Eastern North Pacific Tropical Cyclone Motion - Part II. Preston W. Leftwich and Charles J. Neumann, August 1977. (PB 273 155/AS)
126 Climate of San Francisco. E. Jan Null, February 1978. Revised by George T. Pericht, April 1988. (PB88 208624/AS)
127 Development of a Probability Equation for Winter-Type Precipitation Patterns in Great Falls, Montana. Kenneth B. Mielke, February 1978. (PB 281 387/AS)
128 Hand Calculator Program to Compute Parcel Thermal Dynamics. Dan Gudgel, April 1978. (PB 283 080/AS)
129 Fire whirls. David W. Goens, May 1978. (PB 283 866/AS)
130 Flash-Flood Procedure. Ralph C. Hatch and Gerald Williams, May 1978. (PB 286 014/AS)
131 Automated Fire-Weather Forecasts. Mark A. Mollner and David E. Olsen, September 1978. (PB 289 916/AS)
132 Estimates of the Effects of Terrain Blocking on the Los Angeles WSR-74C Weather Radar. R.G. Pappas, R.Y. Lee, B.W. Finke, October 1978. (PB 289767/AS)
133 Spectral Techniques in Ocean Wave Forecasting. John A. Jannuzzi, October 1978. (PB291317/AS)
134 Solar Radiation. John A. Jannuzzi, November 1978. (PB291195/AS)
135 Application of a Spectrum Analyzer in Forecasting Ocean Swell in Southern California Coastal Waters. Lawrence P. Kierulff, January 1979. (PB292716/AS)
136 Basic Hydrologic Principles. Thomas L. Dietrich, January 1979. (PB292247/AS)
137 LFM 24-Hour Prediction of Eastern Pacific Cyclones Refined by Satellite Images. John R. Zimmerman and Charles P. Ruscha, Jr., January 1979. (PB294324/AS)
138 A Simple Analysis/Diagnosis System for Real Time Evaluation of Vertical Motion. Scott Heflick and James R. Fors, February 1979. (PB294216/AS)
139 Aids for Forecasting Minimum Temperature in the Wenatchee Frost District. Robert S. Robinson, April 1979. (PB298339/AS)
140 Influence of Cloudiness on Summertime Temperatures in the Eastern Washington Fire Weather district. James Holcomb, April 1979. (PB298674/AS)
141 Comparison of LFM and MFM Precipitation Guidance for Nevada During Doreen. Christopher Hill, April 1979. (PB298613/AS)

NOAA Technical Memorandum NWS WR-209

STRATUS SURGE PREDICTION ALONG THE CENTRAL CALIFORNIA COAST

Peter Felsch
National Weather Service
Weather Service Forecast Office
San Francisco, California

Woodrow Whitlatch
San Jose State University
San Jose, California

December 1990

UNITED STATES
DEPARTMENT OF COMMERCE
Robert A. Mosbacher, Secretary

National Oceanic and
Atmospheric Administration
John A. Knauss, Under Secretary
and Administrator

National Weather Service
Elbert W. Friday, Jr., Assistant
Administrator for Weather Services

This publication has been reviewed
and is approved for publication by
Scientific Services Division,
Western Region

Ken Mielke

Kenneth B. Mielke, Chief
Scientific Services Division
Salt Lake City, Utah

TABLE OF CONTENTS

PAGE

TABLE OF FIGURES

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<=-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.

VI. REFERENCES

Dorman, C. E., 1985: Evidence of Kelvin waves in California's marine layer and related eddy generation. *Mon. Wea. Rev.*, **113** 827-839.

Mass, C. F., and M. D. Albright, 1986: Coastal southerlies and along shore surges of the west coast of North America: evidence of mesoscale topographically trapped response to topographic forcing. *Mon. Wea. Rev.* **115**: 1707-1738.

Western Regional Technical Attachment, 1969: Stratus Plume Details by Satellite. WRTA #69-24.

Jackson, B., 1983: Dealing with the Thermal Trough. Western Regional Technical Attachment #83-21.

Gilliland, R. P., 1980: The Structure and Development of the California Heat Trough. Masters Thesis, Department of Meteorology, San Jose State University, San Jose, California, 90 pp.

Panofsky, H. A., and G. W. Brier, 1968: Some Applications of Statistics to Meteorology. Pennsylvania State University Press, University Park, PA, 222 pp.

Neiberger, M. et al., 1961: Studies Over the Eastern Pacific Ocean in Summer Vol. 1: The Inversion over the Eastern Pacific Ocean. University of California Press, 94 pp.

Ellrod G., 1989: A Decision Tree Approach to Clear Air Turbulence Analysis Using Satellite and Upper Air Data, NOAA Technical Memorandum NESDIS 23, Washington, DC.

SAS Institute Inc, 1985: SAS Users Guide: Statistics, Version 5 Edition, Cary, NC, 1290 pp.

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.

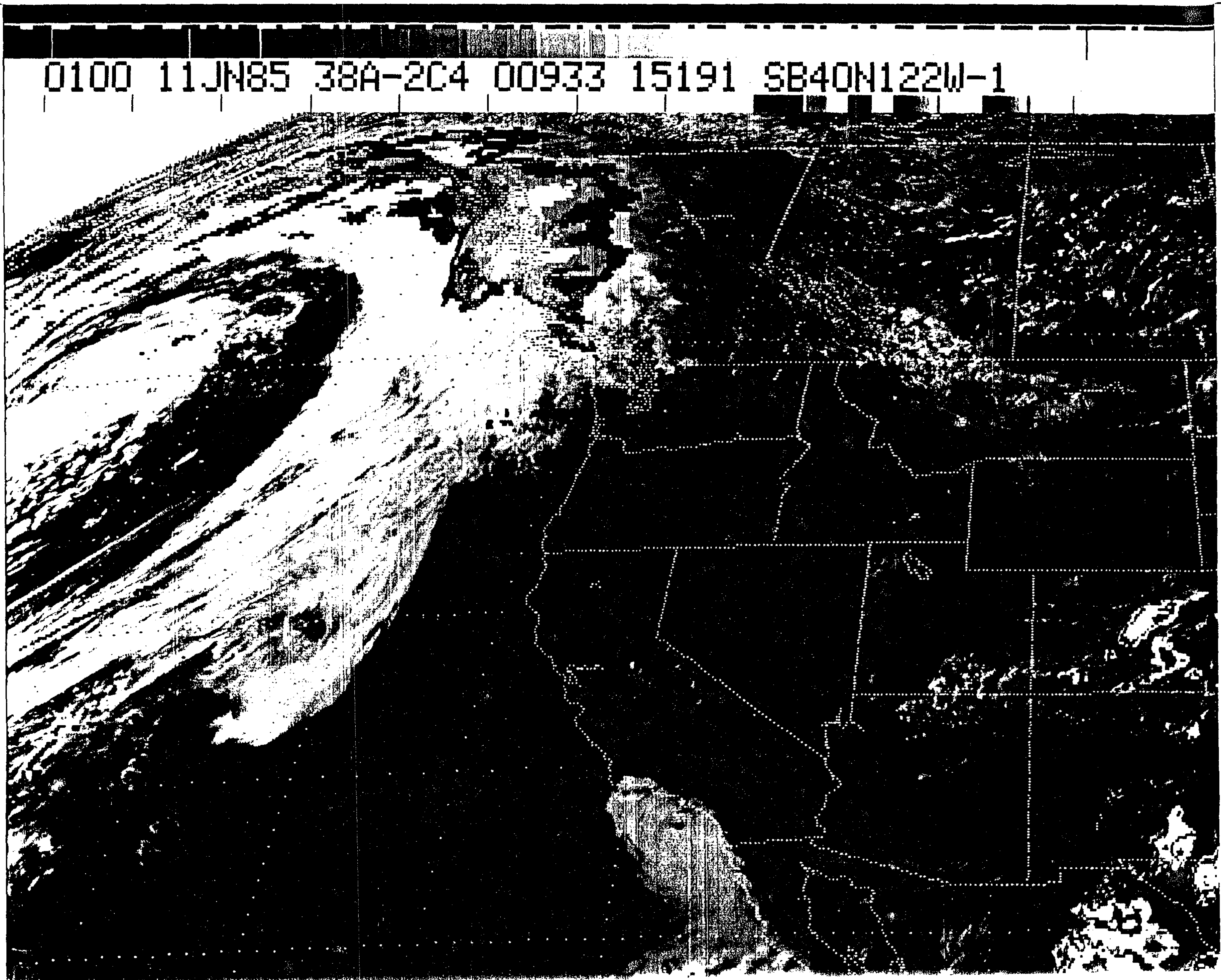
APPENDIX 2

Skill scores (S) were are 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:

$$E = Ri*Ci/T,$$

where Ri is the sum of the ith row and Ci is the sum of the ith column.

Figure 1A



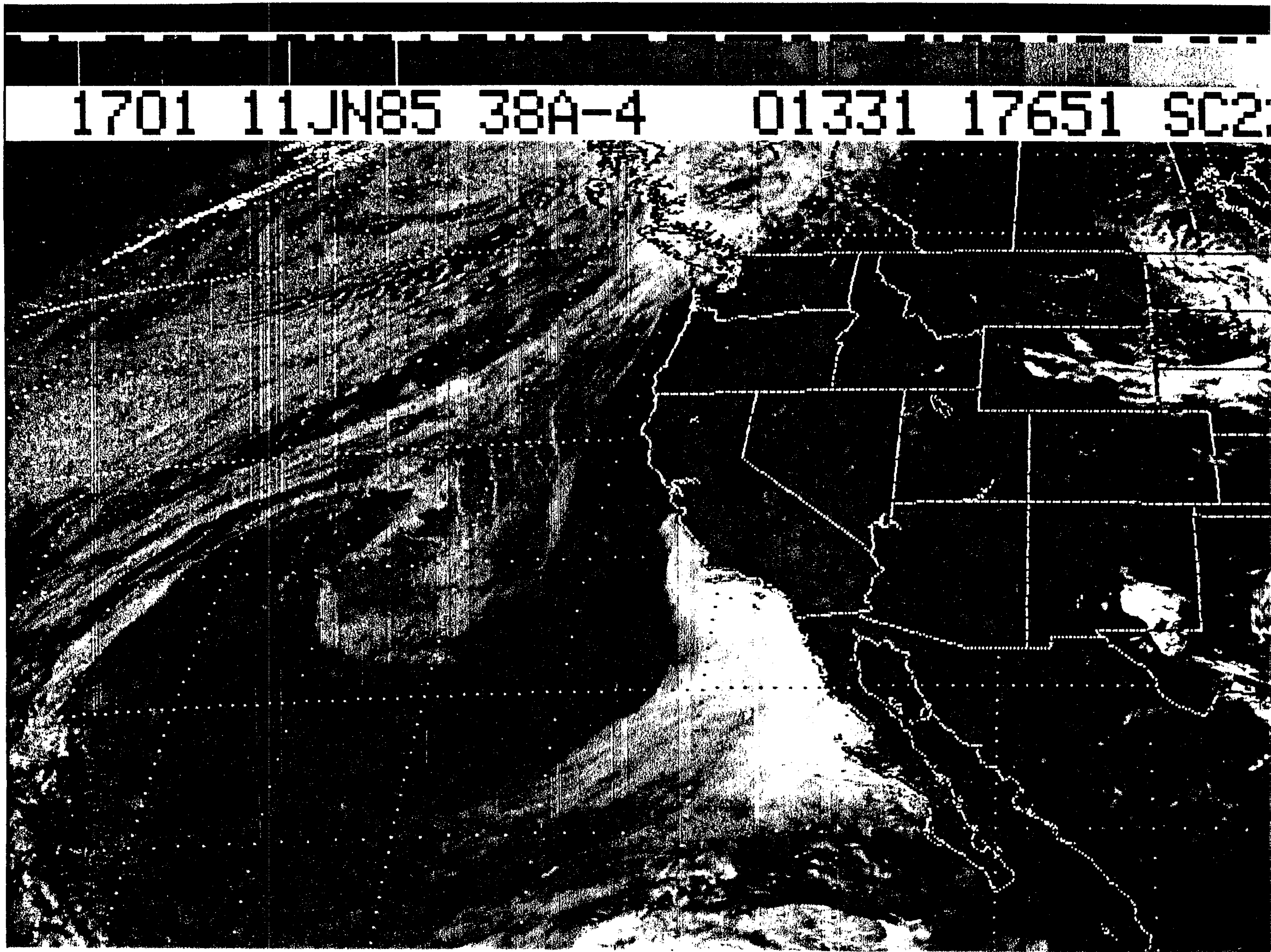
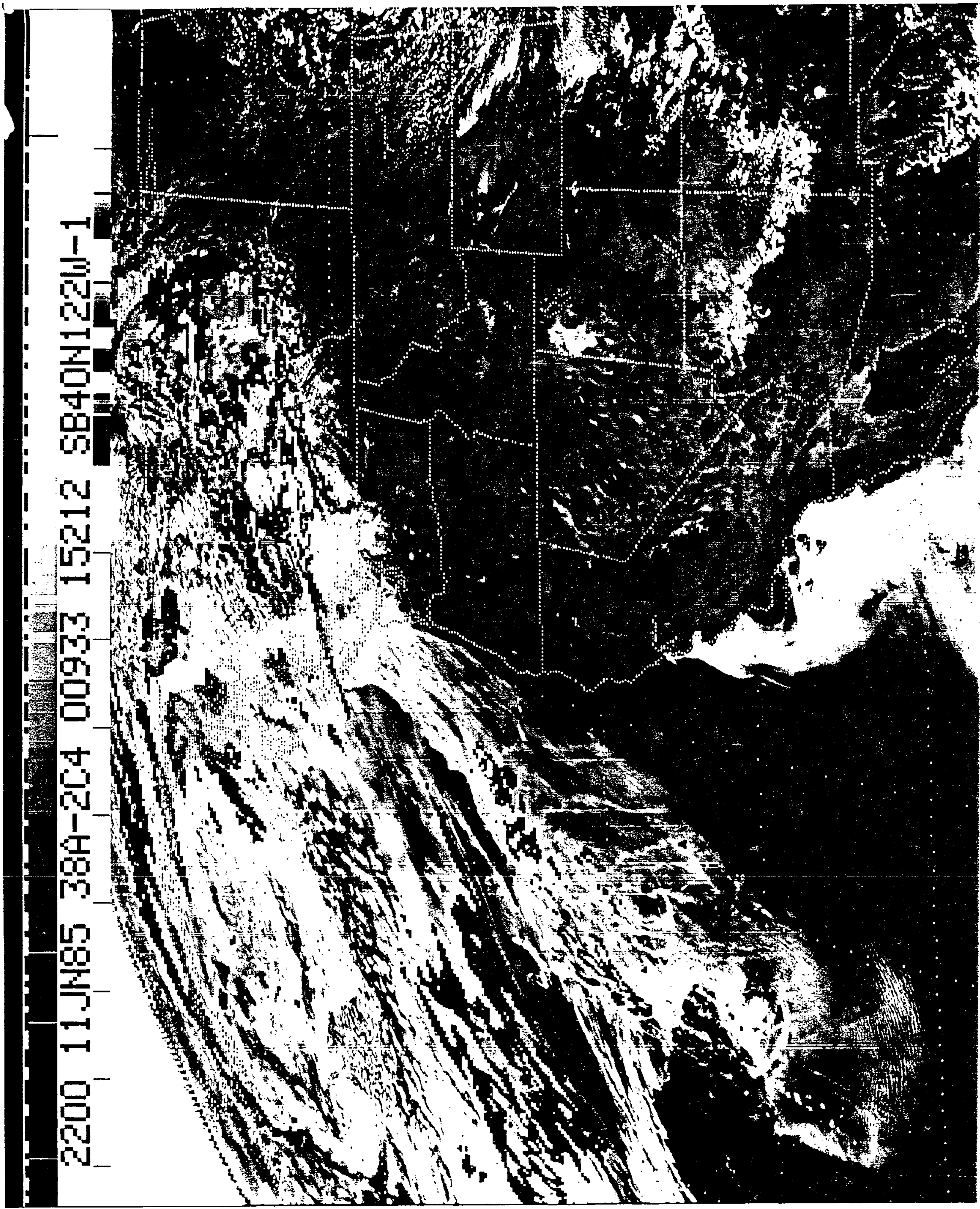


Figure 1B

Figure 1C



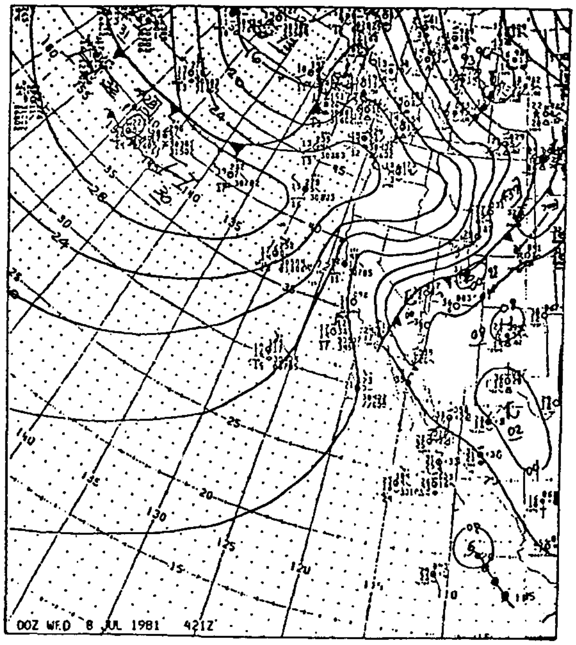


Figure 2.) Example of the the Surface Heat Trough Extending Coastward of Its Normal Position In Central California.

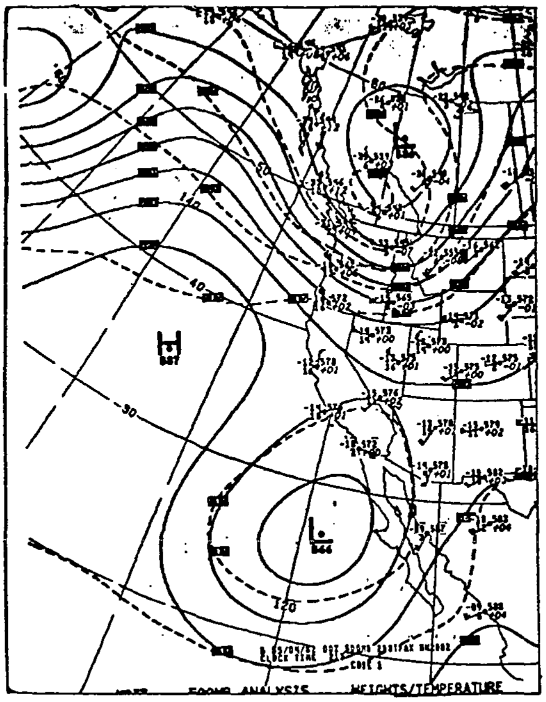


Figure 3.) Example of a 500mb Cutoff Low Circulation Observed Prior to Some Surge Events.

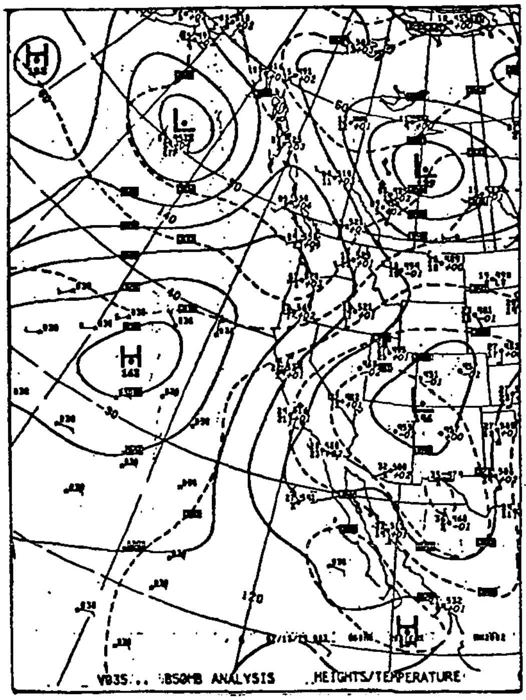


Figure 4.) Example of 850mb Pattern Associated With Short Wave Ridge Movement Across Northern California.

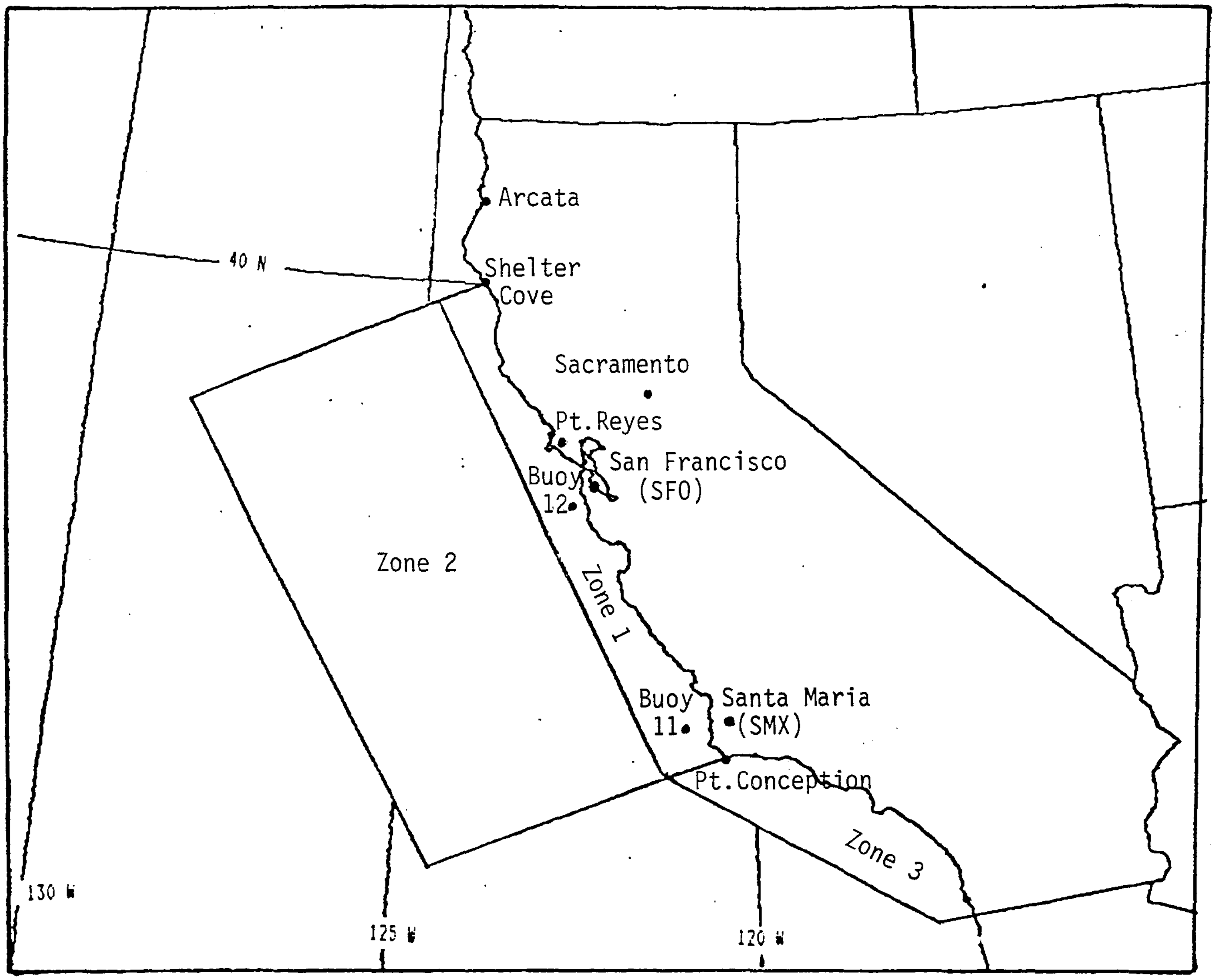


Figure 5.) Criteria for the Subjective Screening of Visible Band Satellite Images to Determine Potential Surge Events.

LEGEND

ZONE 1: A Continuous Stratus-Free Area 120 nmi Alongshore 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.

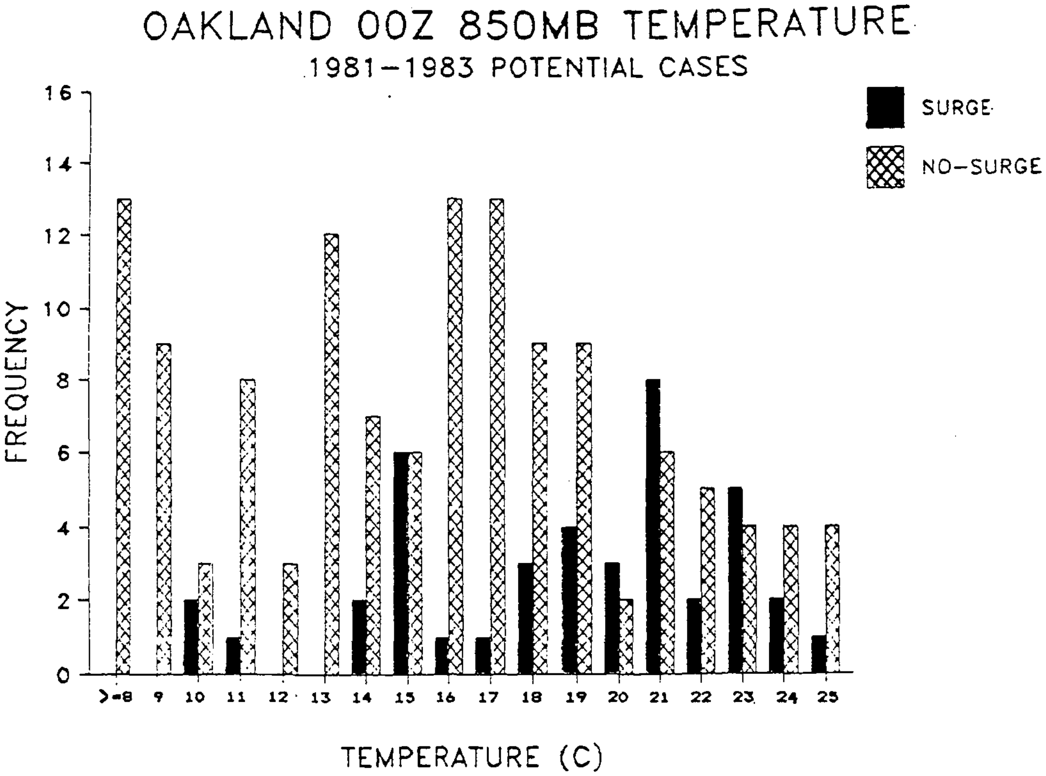


Figure 6.) Frequency Distribution (in 1 degree bins) of SURGE and NO SURGE Events as a Function of Oakland 850mb Temperature at 00Z; Development Dataset, 1981-1983.

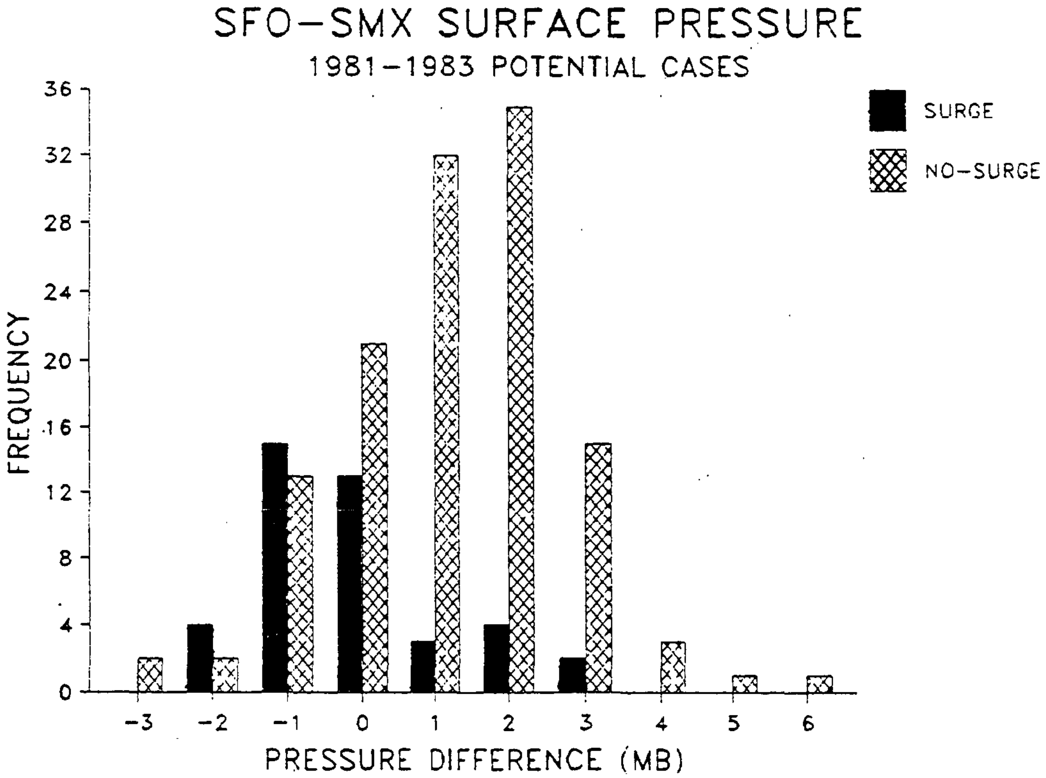


Figure 7.) Frequency Distribution (in 1 mb bins) of SURGE and NO SURGE Events as a Function of SFO-SMX Pressure Difference at 00Z.

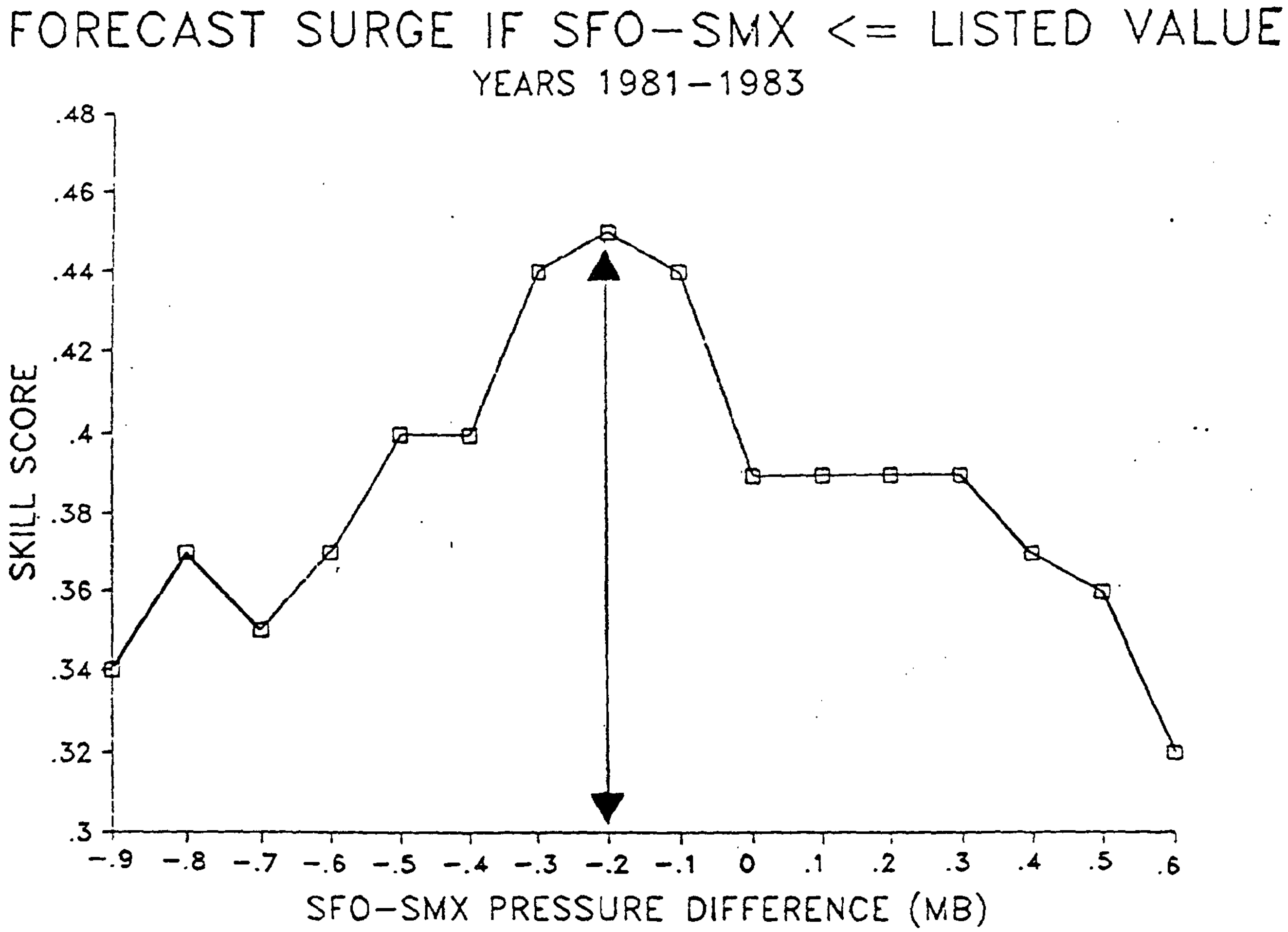


Figure 8.) Skill Scores Plotted as a Function of the Threshold Value of SFO-SMX Used to Forecast Surge Development.

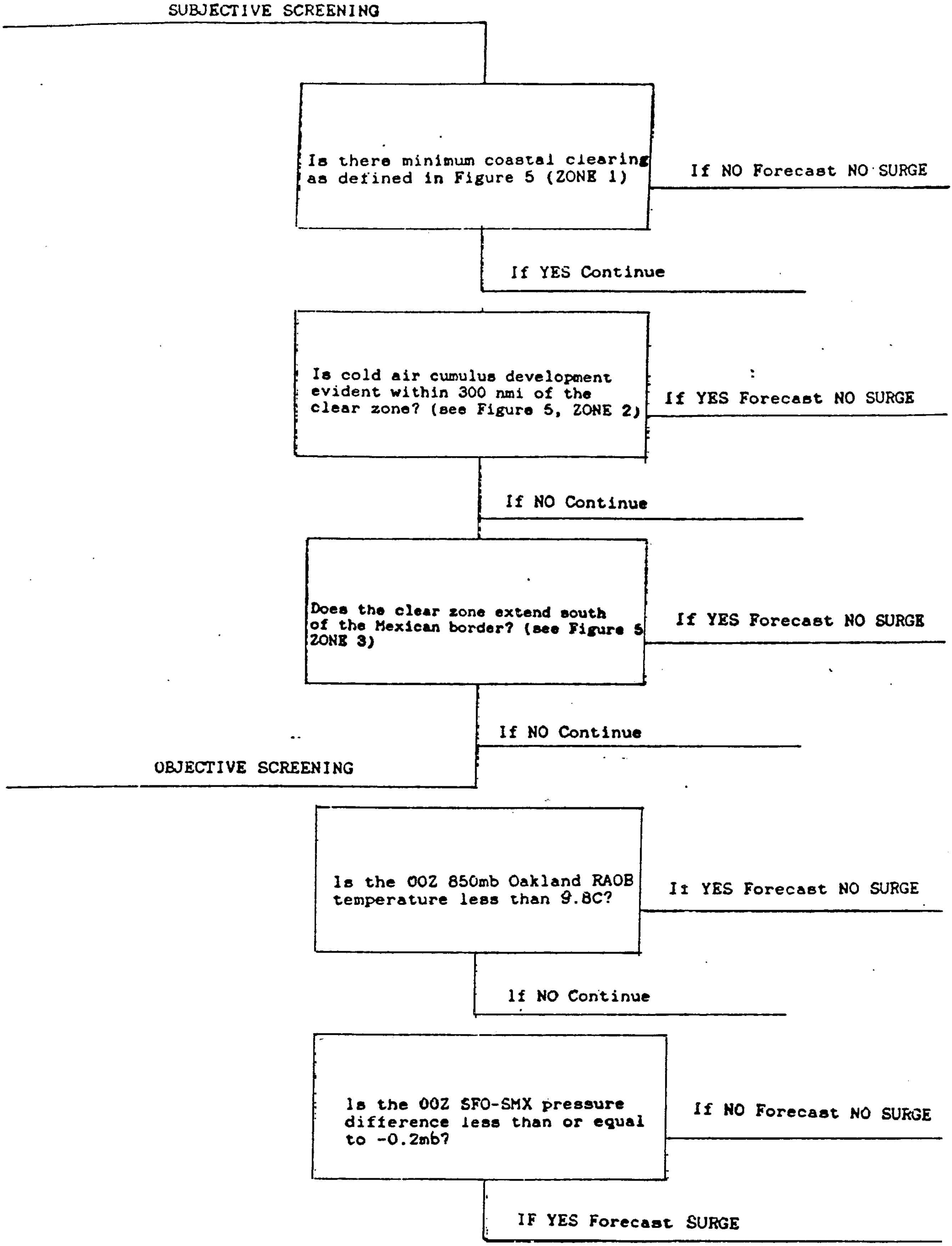


Figure 9.) Stratus Surge Forecast Flowchart.

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
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
COLUMN TOTALS	27	35	:	62

142 The Usefulness of Data from Mountaintop Fire Lookout Stations in Determining Atmospheric Stability. Jonathan W. Corey, April 1979. (PB298899/AS)
143 The Depth of the Marine Layer at San Diego as Related to Subsequent Cool Season Precipitation Episodes in Arizona. Ira S. Brenner, May 1979. (PB298817/AS)
144 Arizona Cool Season Climatological Surface Wind and Pressure Gradient Study. Ira S. Brenner, May 1979. (PB298900/AS)
146 The BART Experiment. Morris S. Webb, October 1979. (PB80 155112)
147 Occurrence and Distribution of Flash Floods in the Western Region. Thomas L. Dietrich, December 1979. (PB80 160344)
149 Misinterpretations of Precipitation Probability Forecasts. Allan H. Murphy, Sarah Lichtenstein, Baruch Fischhoff, and Robert L. Winkler, February 1980. (PB80 174576)
150 Annual Data and Verification Tabulation - Eastern and Central North Pacific Tropical Storms and Hurricanes 1979. Emil B. Gunther and Staff, EPHC, April 1980. (PB80 220486)
151 NMC Model Performance in the Northeast Pacific. James E. Overland, PMEL-ERL, April 1980. (PB80 196033)
152 Climate of Salt Lake City, Utah. Wilbur E. Figgins (Retired) and Alexander R. Smith. Fourth Revision, March 1989. (PB89 180624/AS)
153 An Automatic Lightning Detection System in Northern California. James E. Rea and Chris E. Fontana, June 1980. (PB80 225592)
154 Regression Equation for the Peak Wind Gust 6 to 12 Hours in Advance at Great Falls During Strong Downslope Wind Storms. Michael J. Oard, July 1980. (PB91 108367)
155 A Raininess Index for the Arizona Monsoon. John H. Ten Harkel, July 1980. (PB81 106494)
156 The Effects of Terrain Distribution on Summer Thunderstorm Activity at Reno, Nevada. Christopher Dean Hill, July 1980. (PB81 102501)
157 An Operational Evaluation of the Scofield/Oliver Technique for Estimating Precipitation Rates from Satellite Imagery. Richard Ochoa, August 1980. (PB81 108227)
158 Hydrology Practicum. Thomas Dietrich, September 1980. (PB81 134033)
159 Tropical Cyclone Effects on California. Arnold Court, October 1980. (PB81 133779)
160 Eastern North Pacific Tropical Cyclone Occurrences During Intraseasonal Periods. Preston W. Leftwich and Gail M. Brown, February 1981. (PB81 205494)
161 Solar Radiation as a Sole Source of Energy for Photovoltaics in Las Vegas, Nevada, for July and December. Darryl Randerson, April 1981. (PB81 224503)
162 A Systems Approach to Real-Time Runoff Analysis with a Deterministic Rainfall-Runoff Model. Robert J.C. Burnash and R. Larry Ferral, April 1981. (PB81 224495)
163 A Comparison of Two Methods for Forecasting Thunderstorms at Luke Air Force Base, Arizona. LTC Keith R. Cooley, April 1981. (PB81 225393)
164 An Objective Aid for Forecasting Afternoon Relative Humidity Along the Washington Cascade East Slopes. Robert S. Robinson, April 1981. (PB81 23078)
165 Annual Data and Verification Tabulation, Eastern North Pacific Tropical Storms and Hurricanes 1980. Emil B. Gunther and Staff, May 1981. (PB82 230336)
166 Preliminary Estimates of Wind Power Potential at the Nevada Test Site. Howard G. Booth, June 1981. (PB82 127036)
167 ARAP User's Guide. Mark Mathewson, July 1981, Revised September 1981. (PB82 196783)
168 Forecasting the Onset of Coastal Gales Off Washington-Oregon. John R. Zimmerman and William D. Burton, August 1981. (PB82 127051)
169 A Statistical-Dynamical Model for Prediction of Tropical Cyclone Motion in the Eastern North Pacific Ocean. Preston W. Leftwich, Jr., October 1981. (PB82195298)
170 An Enhanced Plotter for Surface Airways Observations. Andrew J. Spry and Jeffrey L. Anderson, October 1981. (PB82 153883)
171 Verification of 72-Hour 500-MB Map-Type Predictions. R.F. Quiring, November 1981. (PB82 158098)

172 Forecasting Heavy Snow at Wenatchee, Washington. James W. Holcomb, December 1981. (PB82 177783)
173 Central San Joaquin Valley Type Maps. Thomas R. Crossan, December 1981. (PB82 196064)
174 ARAP Test Results. Mark A. Mathewson, December 1981. (PB82 198103)
176 Approximations to the Peak Surface Wind Gusts from Desert Thunderstorms. Darryl Randerson, June 1982. (PB82 253089)
177 Climate of Phoenix, Arizona. Robert J. Schmidli, April 1969 (Revised December 1986). (PB87 142063/AS)
178 Annual Data and Verification Tabulation, Eastern North Pacific Tropical Storms and Hurricanes 1982. E.B. Gunther, June 1983. (PB85 106078)
179 Stratified Maximum Temperature Relationships Between Sixteen Zone Stations in Arizona and Respective Key Stations. Ira S. Brenner, June 1983. (PB83 249904)
180 Standard Hydrologic Exchange Format (SHEF) Version I. Phillip A. Pasteries, Vernon C. Bissel, David G. Bennett, August 1983. (PB85 106052)
181 Quantitative and Spacial Distribution of Winter Precipitation along Utah's Wasatch Front. Lawrence B. Dunn, August 1983. (PB85 106912)
182 500 Millibar Sign Frequency Teleconnection Charts - Winter. Lawrence B. Dunn, December 1983. (PB85 106276)
183 500 Millibar Sign Frequency Teleconnection Charts - Spring. Lawrence B. Dunn, January 1984. (PB85 111367)
184 Collection and Use of Lightning Strike Data in the Western U.S. During Summer 1983. Glenn Rasch and Mark Mathewson, February 1984. (PB85 110534)
185 500 Millibar Sign Frequency Teleconnection Charts - Summer. Lawrence B. Dunn, March 1984. (PB85 111359)
186 Annual Data and Verification Tabulation eastern North Pacific Tropical Storms and Hurricanes 1983. E.B. Gunther, March 1984. (PB85 109635)
187 500 Millibar Sign Frequency Teleconnection Charts - Fall. Lawrence B. Dunn, May 1984. (PB85 110930)
188 The Use and Interpretation of Isentropic Analyses. Jeffrey L. Anderson, October 1984. (PB85 132694)
189 Annual Data & Verification Tabulation Eastern North Pacific Tropical Storms and Hurricanes 1984. E.B. Gunther and R.L. Cross, April 1985. (PB85 1878887AS)
190 Great Salt Lake Effect Snowfall: Some Notes and An Example. David M. Carpenter, October 1985. (PB86 119153/AS)
191 Large Scale Patterns Associated with Major Freeze Episodes in the Agricultural Southwest. Ronald S. Hamilton and Glenn R. Lussky, December 1985. (PB86 144474AS)
192 NWR Voice Synthesis Project: Phase I. Glen W. Sampson, January 1986. (PB86 145604/AS)
193 The MCC - An Overview and Case Study on Its Impact in the Western United States. Glenn R. Lussky, March 1986. (PB86 170651/AS)
194 Annual Data and Verification Tabulation Eastern North Pacific Tropical Storms and Hurricanes 1985. E.B. Gunther and R.L. Cross, March 1986. (PB86 170941/AS)
195 Radid Interpretation Guidelines. Roger G. Pappas, March 1986. (PB86 177680/AS)
196 A Mesoscale Convective Complex Type Storm over the Desert Southwest. Darryl Randerson, April 1986. (PB86 190998/AS)
197 The Effects of Eastern North Pacific Tropical Cyclones on the Southwestern United States. Walter Smith, August 1986. (PB87 106258AS)
198 Preliminary Lightning Climatology Studies for Idaho. Christopher D. Hill, Carl J. Gorski, and Michael C. Conger, April 1987. (PB87 180196/AS)
199 Heavy Rains and Flooding in Montana: A Case for Slantwise Convection. Glenn R. Lussky, April 1987. (PB87 185229/AS)
200 Annual Data and Verification Tabulation Eastern North Pacific Tropical Storms and Hurricanes 1986. Roger L. Cross and Kenneth B. Mielke, September 1987. (PB88 110895/AS)
201 An Inexpensive Solution for the Mass Distribution of Satellite Images. Glen W. Sampson and George Clark, September 1987. (PB88 114038/AS)
202 Annual Data and Verification Tabulation Eastern North Pacific Tropical Storms and Hurricanes 1987. Roger L. Cross and Kenneth B. Mielke, September 1988. (PB88 101935/AS)
203 An Investigation of the 24 September 1986 "Cold Sector" Tornado Outbreak in Northern California. John P. Monteverdi and Scott A. Braun, October 1988. (PB89 121297/AS)
204 Preliminary Analysis of Cloud-To-Ground Lightning in the Vicinity of the Nevada Test Site. Carven Scott, November 1988. (PB89 128649/AS)
205 Forecast Guidelines For Fire Weather and Forecasters -- How Nighttime Humidity Affects Wildland Fuels. David W. Goens, February 1989. (PB89 162549/AS)
206 A Collection of Papers Related to Heavy Precipitation Forecasting. Western Region Headquarters, Scientific Services Division. August 1989. (PB89 230833/AS)
207 The Las Vegas McCarran International Airport Microburst of August 8, 1989. Carven A. Scott, June 1990. (PB90-240268)
208 Meteorological Factors Contributing to the Canyon Creek Fire Blowup, September 6 and 7, 1988, June 1990. (PB90-245085)

NOAA SCIENTIFIC AND TECHNICAL PUBLICATIONS

The National Oceanic and Atmospheric Administration was established as part of the Department of Commerce on October 3, 1970. The mission responsibilities of NOAA are to assess the socioeconomic impact of natural and technological changes in the environment and to monitor and predict the state of the solid Earth, the oceans and their living resources, the atmosphere, and the space environment of the Earth.

The major components of NOAA regularly produce various types of scientific and technical information in the following kinds of publications.

PROFESSIONAL PAPERS--Important definitive research results, major techniques, and special investigations.

CONTRACT AND GRANT REPORTS--Reports prepared by contractors or grantees under NOAA sponsorship.

ATLAS--Presentation of analyzed data generally in the form of maps showing distribution of rainfall, chemical and physical conditions of oceans and atmosphere, distribution of fishes and marine mammals, ionospheric conditions, etc.

TECHNICAL SERVICE PUBLICATIONS--Reports containing data, observations, instructions, etc. A partial listing includes data serials; prediction and outlook periodicals; technical manuals, training papers, planning reports, and information serials; and miscellaneous technical publications.

TECHNICAL REPORTS--Journal quality with extensive details, mathematical developments, or data listings.

TECHNICAL MEMORANDUMS--Reports of preliminary, partial, or negative research or technology results, interim instructions, and the like.

Information on availability of NOAA publications can be obtained from:

NATIONAL TECHNICAL INFORMATION SERVICE

U. S. DEPARTMENT OF COMMERCE

5285 PORT ROYAL ROAD

SPRINGFIELD, VA 22161