

NOAA Technical Memorandum NWS WR-114



WES - see p 11

TROPICAL CYCLONE KATHLEEN

James R. Fors

National Weather Service Western Region
Salt Lake City, Utah

February 1977

NOAA LIBRARY SEATTLE

noaa

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 23 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.

Papers 1 to 23, except for 5 (revised edition) and 10, 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 84111. Papers 5 (revised edition), 10, and all others beginning with 24 are available from the National Technical Information Service, U. S. Department of Commerce, Sills Building, 5285 Port Royal Road, Springfield, Virginia 22151. Prices vary for all paper copy; \$2.25 microfiche. Order by accession number shown in parentheses at end of each entry.

ESSA Technical Memoranda

- WRTM 1 Some Notes on Probability Forecasting. Edward D. Diemer, September 1965. (Out of print.)
WRTM 2 Climatological Precipitation Probabilities. Compiled by Lucianne Miller, December 1965.
WRTM 3 Western Region Pre- and Post-FP-3 Program, December 1, 1965, to February 20, 1966. Edward D. Diemer, March 1966.
WRTM 4 Use of Meteorological Satellite Data. March 1966.
WRTM 5 Station Descriptions of Local Effects on Synoptic Weather Patterns. Philip Williams, Jr., April 1966 (revised November 1967, October 1969). (PB-17800)
WRTM 6 Improvement of Forecast Wording and Format. C. L. Glenn, May 1966.
WRTM 7 Final Report on Precipitation Probability Test Programs. Edward D. Diemer, May 1966.
WRTM 8 Interpreting the RAREP. Herbert P. Benner, May 1966 (revised January 1967). (Out of print.)
WRTM 9 A Collection of Papers Related to the 1966 NMC Primitive-Equation Model. June 1966. (Out of print.)
WRTM 10 Sonic Boom. Loren Crow (6th Weather Wing, USAF, Pamphlet), June 1966. (Out of print.) (AD-479365)
WRTM 11 Some Electrical Processes in the Atmosphere. J. Latham, June 1966.
WRTM 12 A Comparison of Fog Incidence at Missoula, Montana, with Surrounding Locations. Richard A. Dightman, August 1966. (Out of print.)
WRTM 13 A Collection of Technical Attachments on the 1966 NMC Primitive-Equation Model. Leonard W. Snellman, August 1966. (Out of print.)
WRTM 14 Application of Net Radiometer Measurements to Short-Range Fog and Stratus Forecasting at Los Angeles. Frederick Thomas, September 1966.
WRTM 15 The Use of the Mean as an Estimate of "Normal" Precipitation in an Arid Region. Paul C. Kangieser, November 1966. (Out of print.)
WRTM 16 Some Notes on Acclimatization in Man. Edited by Leonard W. Snellman, November 1966.
WRTM 17 A Digitalized Summary of Radar Echoes Within 100 Miles of Sacramento, California. J. A. Youngberg and L. B. Overaas, December 1966.
WRTM 18 Limitations of Selected Meteorological Data. December 1966.
WRTM 19 A Grid Method for Estimating Precipitation Amounts by Using the WSR-57 Radar. R. Granger, December 1966. (Out of print.)
WRTM 20 Transmitting Radar Echo Locations to Local Fire Control Agencies for Lightning Fire Detection. Robert R. Peterson, March 1967. (Out of print.)
WRTM 21 An Objective Aid for Forecasting the End of East Winds in the Columbia Gorge, July through October. D. John Coparanis, April 1967.
WRTM 22 Derivation of Radar Horizons in Mountainous Terrain. Roger G. Pappas, April 1967.
WRTM 23 "K" Chart Applications to Thunderstorm Forecasts Over the Western United States. Richard E. Hambidge, May 1967.

ESSA Technical Memoranda, Weather Bureau Technical Memoranda (WBTM)

- WBTM 24 Historical and Climatological Study of Grinnell Glacier, Montana. Richard A. Dightman, July 1967. (Out of print.) (PB-178071)
WBTM 25 Verification of Operational Probability of Precipitation Forecasts, April 1966-March 1967. W. W. Dickey, October 1967. (PB-176240)
WBTM 26 A Study of Winds in the Lake Mead Recreation Area. R. P. Augulis, January 1968. (PB-177830)
WBTM 27 Objective Minimum Temperature Forecasting for Helena, Montana. D. E. Olsen, February 1968. (PB-177827)
WBTM 28 Weather Extremes. R. J. Schmidli, April 1968 (revised July 1968). (PB-178928)
WBTM 29 Small-Scale Analysis and Prediction. Philip Williams, Jr., May 1968. (PB-178425)
WBTM 30 Numerical Weather Prediction and Synoptic Meteorology. Capt. Thomas D. Murphy, U.S.A.F., May 1968. (AD-673365)
WBTM 31 Precipitation Detection Probabilities by Salt Lake ARTC Radars. Robert K. Belesky, July 1968. (PB-179084)
WBTM 32 Probability Forecasting--A Problem Analysis with Reference to the Portland Fire Weather District. Harold S. Ayer, July 1968. (PB-179289)
WBTM 33 Objective Forecasting. Philip Williams, Jr., August 1968. (Out of print.) (AD-680425)
WBTM 34 The WSR-57 Radar Program at Missoula, Montana. R. Granger, October 1968. (Out of print.) (PB-180292)
WBTM 35 Joint ESSA/FAA ARTC Radar Weather Surveillance Program. Herbert P. Benner and Delvon B. Smith, December 1968 (revised June 1970). (AD-681857)
WBTM 36 Temperature Trends in Sacramento--Another Heat Island. Anthony D. Lentini, February 1969. (Out of print.) (PB-183055)
WBTM 37 Disposal of Logging Residues Without Damage to Air Quality. Owen P. Cramer, March 1969. (PB-183057)
WBTM 38 Climate of Phoenix, Arizona. R. J. Schmidli, P. C. Kangieser, and R. S. Ingram, April 1969. (Out of print.) (PB-184295)
WBTM 39 Upper-Air Lows Over Northwestern United States. A. L. Jacobson, April 1969. (PB-184296)
WBTM 40 The Man-Machine Mix in Applied Weather Forecasting in the 1970s. L. W. Snellman, August 1969. (PB-185068)
WBTM 41 High Resolution Radiosonde Observations. W. S. Johnson, August 1969. (PB-185673)
WBTM 42 Analysis of the Southern California Santa Ana of January 15-17, 1966. Barry B. Aronovitch, August 1969. (PB-185670)
WBTM 43 Forecasting Maximum Temperatures at Helena, Montana. David E. Olsen, October 1969. (PB-185762)
WBTM 44 Estimated Return Periods for Short-Duration Precipitation in Arizona. Paul C. Kangieser, October 1969. (PB-187763)
WBTM 45/1 Precipitation Probabilities in the Western Region Associated with Winter 500-mb Map Types. Richard A. Augulis, December 1969. (PB-188248)

NOAA Technical Memorandum NWS WR-114

TROPICAL CYCLONE KATHLEEN

James R. Fors
Scientific Services Division
Western Region Headquarters
Salt Lake City, Utah

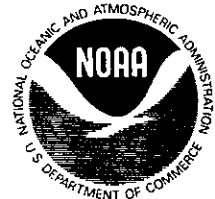
February 1977

PROPERTY OF
NOAA Library E/OC43
7600 Sand Point Way NE
Seattle WA 98115-0070

UNITED STATES
DEPARTMENT OF COMMERCE
Juanita M. Kreps, Secretary

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION
Robert M. White, Administrator

NATIONAL WEATHER
SERVICE
George P. Cressman, Director



CONTENTS

	<u>Page</u>
Table and Figures	iv
Abstract	1
I. Introduction	1
II. Tropical Cyclone Kathleen	2
III. Past History of Southern California Tropical Storms	4
A. Northern California Storm of September 12 - 14, 1918	4
B. The Tehachapi Storm of September 30, 1932	4
C. The Southern California Tropical Storm of September 25, 1939	4
IV. Climatology	5
A. Speed	5
B. Track	5
V. Synoptic Situation	6
VI. Forecasts and Guidance	7
A. Official Forecasts	7
B. Objective Track Guidance	7
C. Objective Precipitation Guidance	8
VII. Speed	9
A. Upper-Level Flow	9
B. Fujiwhara Effect	9
VIII. Intensity	10
A. Speed	10

CONTENTS (Continued)

Page

	B. Gulf of California	11
	C. Sea-Surface Temperatures	11
	D. Nonelliptic Upper-Tropospheric Flow	11
IX.	Conclusions	12
X.	Acknowledgments	12
XI.	References	12

TABLE AND FIGURES

Page

Table 1.	Average speed and average maximum speed of eastern Pacific tropical storms based on a 1965 through 1971 sample	5
Figure 1.	The track of Tropical Cyclone Kathleen as determined by satellite observation of the eye of the storm	15
Figure 2.	Two mile, infrared satellite picture	16
Figure 3.	72-hour precipitation totals for the period from 1200Z on September 9 to 1200Z on September 12 . .	17
Figure 4.	Tracks of the three previous tropical cyclones . .	18
Figure 5.	Mean eastern Pacific tropical cyclone trajectories	18
Figure 6.	Climatology of the twelve-hour movement of eastern Pacific tropical cyclones for the period of September 1 - 15	19
Figure 7.	500-mb initial analysis for 0000Z on September 9, 1976	20
Figure 8a.	36-hour barotropic 500-mb forecast valid September 10, 1976	20
Figure 8b.	36-hour PE 500-mb forecast valid 1200Z on September 10, 1976	20
Figure 8c.	36-hour LFM 500-mb forecast valid 1200Z on September 10, 1976	20
Figure 9.	500-mb verifying analysis valid 1200Z on September 10, 1976	20
Figure 10a.	36-hour PE 500-mb forecast valid 1200Z on September 11, 1976	21
Figure 10b.	48-hour LFM 500-mb forecast valid 1200Z on September 11, 1976	21
Figure 10c.	500-mb verifying analysis valid 1200Z on September 11, 1976	21
Figure 11.	Starting from the initial position and time as shown, the 12-, 24-, and 48-hour forecasts made at that time by the San Francisco WSFO are shown	22
Figure 12a.	Vector error of 12-hour San Francisco forecasts . .	22
Figure 12b.	Vector error of 24-hour San Francisco forecasts . .	22

TABLE AND FIGURES (Continued)		<u>Page</u>
Figure 13.	Objective track guidance provided by SANBAR and MFM based on data from 1200Z on the 9th	23
Figure 14.	Objective track guidance provided by EPANALOG based on data from 1200Z on the 9th	23
Figure 15a.	MFM forecast of precipitation amounts for the period from 1800Z on the 10th to 0000Z on the 11th	24
Figure 15b.	Same as 15a, except for the period from 0000Z to 0600Z on the 11th	24
Figure 15c.	Same as 15a, except for the period from 0600Z to 1200Z on the 11th	24
Figure 15d.	Same as 15a, except for the period from 1800Z on the 11th to 0000Z on the 12th	24
Figure 16.	LFM 12-, 24-, 36-, and 48-hour precipitation forecasts of 12-hour precipitation amounts are shown in A, B, C, and D, respectively	25
Figure 17a.	12-hour observed precipitation amounts ending at 0000Z on the 11th	26
Figure 17b.	Same as 17a, except ending at 1200Z on the 11th	26
Figure 17c.	Same as 17a, except ending at 0000Z on the 12th	26
Figure 17d.	Same as 17a, except ending at 1200Z on the 12th	26
Figure 18a.	Deep layer mean wind analysis for the 9th, 1200Z	27
Figure 18b.	Same as 18a, except for 10th, 00Z	27
Figure 18c.	Same as 18a, except for 10th, 12Z	27
Figure 18d.	Same as 18a, except for 11th, 00Z	27
Figure 19.	Plot of the relative positions of the cut-off low and Kathleen as described in the text	28
Figure 20.	Sea-surface temperature anomalies in degrees Celsius for September 9	29
Figure 21.	Sea-surface temperature anomalies in degrees Celsius for September 14	29
Figure 22.	Sea-surface temperature normals in degrees Celsius for September	29
Figure 23.	200-mb winds in knots at 1200Z, September 10th	29

TROPICAL CYCLONE KATHLEEN

James R. Fors
Scientific Services Division
National Weather Service Western Region

ABSTRACT. Tropical Cyclone Kathleen moved through the western United States on September 10 - 12, 1976. The storm caused 5 deaths in the United States, more than 150 million dollars in damage, localized rain amounts of greater than 10 inches, and sustained winds in excess of 50 knots.

There have been three other significant tropical cyclones that have hit California in the last 60 years (i.e., 1918, 1932, 1939). Kathleen was different from any of these in regard to track and intensity. Kathleen's track was not unusual in a climatological sense after 1200Z on the 9th; however, the intensity at landfall and the speed of movement were unusual. Kathleen moved in excess of 30 knots before landfall. The objective guidance was fairly good in forecasting the direction of movement but was too slow on the speed of movement even though the National Meteorological Center's (NMC) operational numerical weather prediction models did a good job in forecasting the synoptic scale features pertinent to Kathleen. This rapid speed of movement was largely due to the upper level steering flow but the Fujiwhara effect would have been a useful forecast model in this data-sparse region.

The objective precipitation guidance was of limited help in forecasting heavy rain situations. The Limited Fine Mesh (LFM) model forecasts were somewhat better in overall Quantitative Precipitation Forecast (QPF) guidance than the Movable Fine Mesh (MFM) model forecasts.

Kathleen maintained her intensity unusually far north. Her rapid speed of movement; above-normal sea-surface temperatures; advection of warm, moist air from the Gulf of California, and nonelliptic upper-tropospheric flow are suggested as possible mechanisms in maintaining her intensity.

I. INTRODUCTION

Tropical Cyclone Kathleen moved through the western United States on September 10 - 12, 1976. The storm caused 5 deaths in the United States,

more than 150 million dollars in damage, localized rain amounts of greater than 10 inches, and winds in excess of 50 knots. It was the first major tropical cyclone to hit the western United States since 1939.

This paper looks at Kathleen from several different viewpoints. First, the history of the storm is reviewed in relation to its movement, associated weather, and related damage. Second, the history of several previous tropical cyclones striking the western United States is presented along with the climatology of eastern Pacific tropical cyclones pertinent to Kathleen. Third, the synoptic situation, pertinent forecasts and the objective guidance available are presented. Fourth, the speed of movement of the storm is discussed in relation to the upper level steering flow and the Fujiwhara (1923) effect. Finally, the intensity as related to its speed of movement; sea-surface temperature patterns; advection of warm, moist air from the Gulf of California, and upper-level wind fields is discussed.

II. TROPICAL CYCLONE KATHLEEN

Kathleen began as a tropical disturbance 300 miles southwest of Acapulco, Mexico, on September 6, 1976, 0000Z (Figure 1). Since the positions in Figure 1 are estimates of the location of the eye from satellite pictures, there is some degree of uncertainty in the exact location of Kathleen at any given time. The path of the actual storm is certainly smoother than is shown in Figure 1. Moving northwest, the disturbance was upgraded to a tropical depression at 0600Z on the 7th when it was near 15N, 109W. Showing little movement, the winds were estimated at 35 knots by 0000Z on the 8th and the depression was upgraded to Tropical Storm Kathleen. Kathleen began her north-northwest track by 1200Z on the 8th. Winds on Socorro Island increased to 50 knots as Kathleen passed 60 miles west of the island at 0300Z on the 9th.

The storm was upgraded to hurricane intensity with winds estimated at 70 knots at 0000Z on the 10th. At 0046Z an Air Force reconnaissance aircraft located the center near 25.3N, 114.8W. This fix is almost a full degree of longitude west of the position shown in Figure 1. However, within the accuracy claimed by each source, the positions do agree. Maximum surface winds were located in a band about 70 nautical miles (nmi) east of the center and estimated to be 80 knots. This may be due to a funneling effect caused by the terrain of Baja. A 986-mb central pressure was reported. A second penetration (from the southwest) one hour later estimated maximum surface winds of 55 knots about 50 nmi west of the center. Heavy rain and turbulence were reported. Kathleen was downgraded to a tropical storm at 0600Z on the 10th.

Kathleen never developed a discernible eye on the satellite pictures and was often difficult to locate precisely. Large amounts of moisture, in the form of cirrus, can be seen advecting into southern California and Arizona at 0415Z on the 9th (Figure 2). Thus, large amounts of moisture were available when the storm moved through these areas.

Moving rapidly northward at 30 - 33 knots, Kathleen crossed the western tip of the Point Eugenia Peninsula and then moved onshore 220 miles south of San Diego at 1130Z on the 10th. Kathleen crossed into southern California and was centered near Imperial at 1800Z on the 10th. The storm continued its northward track and was located 140 miles southeast of Reno, Nevada, by 0600Z on the 11th. The center was difficult to follow after this, but wind and rain continued to spread northward into Idaho and Montana.

The first rain associated with Kathleen over the southern California desert areas began early on September 9th. Moderate rain began that evening at Imperial and continued for 5 hours. Flash-flood watches were issued for southern California, most of Arizona and Utah, parts of southern and western Nevada and for the Sierra Nevadas from Yosemite southward.

At 1800Z on the 10th, Imperial, California, reported a surface pressure of 997.3 millibars. Yuma, Arizona, reported a wind gust of 76 miles per hour. One death was reported in Yuma when a tree fell on a trailer. As the storm continued northward into Nevada, a cut-off low which had been located off the southern California coast began to move into California. It crossed over California, southern Nevada, and into Utah. Additional precipitation was caused by this system in southern California with some areas receiving heavy precipitation from the cut-off low.

Kathleen continued into Idaho and Montana on the 11th and 12th causing high winds and isolated heavy precipitation. Winds of up to 50 miles per hour were reported in Idaho. Boise, Idaho, set a new record of 1.74 inches for a 24-hour precipitation amount in the month of September.

Precipitation amounts from 1200Z on the 9th to 1200Z on the 12th are shown in Figure 3. These totals do not include some extreme values but indicate the general trend of precipitation. On the average more than 3 inches of rain fell in southern California. Notice the rain minimum in eastern California and southwest Nevada. This may be largely due to the blocking of the Sierra Nevadas but other local effects may be important. A second precipitation maxima is evident as the storm entered the mountainous regions of Idaho and Montana.

Heavy amounts of rain were reported over the southern California mountain and desert areas. Kathleen left a total of 10.78 inches on Mount Wilson north of Los Angeles, 14.50 inches on San Gorgonio Mountain northwest of Palm Springs, and 10.13 inches on Mount Laguna east of San Diego. Palm Desert, which normally receives only 2 inches of rain a year, received 3.57 inches.

Hardest hit by the storm was the desert town of Ocotillo located about 25 miles west of El Centro near the California-Mexico border. Witnesses reported that a wall of water one-half-mile wide and 4 to 6 feet deep came through Ocotillo destroying 70 percent of the homes. At least 100 people were evacuated and 3 deaths occurred.

Agricultural losses in the Imperial Valley exceeded 60 million dollars. In the San Joaquin Valley of central California, a large portion of the raisin crop was destroyed along with late varieties of fruit and nuts.

The loss has been estimated in excess of 100 million dollars (some of the information in this section has been summarized from the San Francisco post-storm report (Gunther, 1976)).

III. PAST HISTORY OF SOUTHERN CALIFORNIA TROPICAL CYCLONES

Kathleen was certainly a rare event but not completely without precedent. Three significant tropical cyclones in the last 60 years have preceded Kathleen into California (see Figure 4, historical information from Weaver, 1962). Kathleen's track differs from all three previous storms. It should be noted that all four occurred in the month of September.

A. Northern California Storm of September 12 - 14, 1918

This storm crossed the west coast of the United States farther north than any storm on record. By the time of landfall its surface circulation had been dissipated by the cool sea surface. However, low or middle level convergence continued as a general two-day rain occurred over central and northern California. Near record surface dew points of 64° - 66° F. persisted at San Francisco and Sacramento through most of the storm period.

Heavy precipitation oriented in a north-south axis coincided with reported thunderstorm activity. A heavy area of precipitation near Red Bluff occurred in a thunderstorm on the morning of the 14th dropping 4.70 inches of rain in a three-hour period.

B. The Tehachapi Storm of September 30, 1932

This storm moved up the Gulf of California and weakened rapidly upon landfall. Rainfall from the upper circulation amounted to less than 1/2 inch over southern California and the southern San Joaquin Valley.

A downpour occurred near Tehachapi with 4.38 inches of rain recorded. Property damage and loss of life were reported downstream at Bakersfield.

C. The Southern California Tropical Storm of September 25, 1939

The storm was reported to have a 971-mb center pressure and 60-knot winds while located near 22°N/117°W on the morning of the 22nd. Its track was made possible by a strong ridge over the western United States and another offshore, separated by an inverted trough extending along the coast at the surface and aloft.

The storm hit the coast near San Pedro with 37-knot winds and a central pressure of 998 mb on the morning of the 25th. Damage was estimated at 1.5 million dollars. The surface circulation quickly dissipated as the center moved into the rugged mountain terrain.

The large amount of moisture available was indicated by a surface dew point of 66°F. at Los Angeles and San Diego. Los Angeles received 5.42 inches of rain. Higher amounts were associated with terrain features. Mount Wilson received over 11 inches. In contrast to the 1918 storm, little convective activity was reported.

There are two main differences between Kathleen and these storms. Kathleen came in with much stronger winds than any previous tropical cyclone, and Kathleen maintained more intensity after landfall with record rains and strong winds reported into Idaho.

IV. CLIMATOLOGY

The possibility of obtaining useful information from the climatology of eastern Pacific tropical cyclones should not be overlooked. Even for the rare event, the climatology may be useful as a guide or bound on the forecast.

A. Speed

Kathleen moved north-northwest quite rapidly after 1800Z on the 9th reaching speeds of greater than 30 knots. This is Kathleen's most unusual and striking feature, especially when compared with the average speed and average maximum speed of eastern Pacific Tropical cyclones shown in Table I. Kathleen's speed is even more unusual since the average speed for storms moving between 340° - 360° (like Kathleen) is less than 9 knots (Hansen, 1972). For the period of record since satellite data became available, Kathleen's rate of movement was record setting. This is an important factor in understanding Kathleen's behavior.

TABLE I

Average speed and average maximum speed of eastern Pacific tropical storms based on a 1965 through 1971 sample (Hansen, 1972).

SPEED

Median	10.3 knots
Standard deviation	3.0 knots

MAXIMUM SPEED

Mean	13.4 knots
Standard deviation	2.3 knots

B. Track

Eastern Pacific tropical storms tend to either move westward or recurve into Mexico (see Figure 5, Hansen, 1972). Storms that occur before September generally move to the west, while storms which occur in September and October have a greater tendency to recurve (Hansen, 1972).

The climatology for the first two weeks of September based on 1965 through 1974 data is shown in Figure 6. Kathleen followed the climatological track quite well after 1200Z on the 9th. Based on this climatology,

recurvature would not be expected. However, Kathleen did not follow climatology very well before this as the usual track is toward the west.

Most of the storms that have followed a track similar to Kathleen have occurred in the first two weeks of September with a maximum frequency around September 10th (Baum, 1975). However, climatology indicates that these storms dissipate shortly after landfall (Baum, 1975).

Climatology would not have been useful in forecasting the speed of movement of Kathleen; however, it may have been a useful tool in forecasting the track after 1200Z on the 9th.

V. SYNOPTIC SITUATION

There are three key factors in the synoptic flow pattern that are important in the forecasting of Kathleen's track (see Figure 7). These features are the cut-off low off the California coast, the building high-pressure ridge over New Mexico and the short wave approaching the coast from the Gulf of Alaska.

Key questions that needed to be answered on a synoptic scale were:

- 1) Would the cut-off low and high-pressure ridge continue and maintain strong flow from the south?
- 2) Would the ridge weaken and allow the storm to recurve into Mexico?
- 3) When would the cut-off low eject into southern California?

The 36-hour LFM, PE, and Barotropic 500-mb forecasts valid at 1200Z on the 10th show flow from the south throughout the critical time when Kathleen was moving toward landfall (see Figure 8a, b, c). The verification for 1200Z on the 10th is shown in Figure 9. The LFM forecast appears to be the best in forecasting the strongest gradient in the region of Baja. The PE gradient is weaker and the Barotropic indicates the strongest flow to be farther off the coast. However, all three forecasts show the correct trend.

These same charts also answer the second question. All three forecasts show a strengthening and westward building of the ridge allowing little chance for recurvature.

The final concern was whether the cut-off low would eject north of Kathleen bringing westerly flow that would steer Kathleen into Mexico. The 48-hour LFM and the 36-hour PE 500-mb forecast valid at 1200Z on the 11th do not show the cut-off low moving on to the California coast until the 11th (Figure 10). The 500-mb analysis for this time shows that the forecasts verified quite well. The forecasts were correct in maintaining the southerly flow over California and Arizona until Friday evening or early Saturday.

It is apparent that the synoptic scale models did a good job in forecasting the large-scale features associated with Kathleen. Therefore, they should not have significantly contributed to the error in the track forecast of Kathleen.

VI. FORECASTS AND GUIDANCE

A. Official Forecasts

The forecast 12-, 24-, and 48-hour positions of Kathleen for successive observed locations are shown in Figure 11. The forecasts were inconsistent until after 1800Z on the 9th when a northerly track was finally forecast. Although the later forecasts indicated the direction of movement well, the indicated speed of movement was too slow. The last forecast storm bulletin was issued at 1200Z on the 10th.

The problem in forecasting the speed of movement is made more clear by looking at the 12- and 24-hour forecast vector errors shown in Figure 12. They emphasize that the forecast movement was near track but consistently too slow. Kathleen's unusual speed was the main forecast problem.

B. Objective Track Guidance

Several types of objective guidance based on statistical and physical models are available to use when forecasting the track of a tropical storm. SANBAR (an acronym for Sanders' Barotropic Model (Sanders, 1968)) and NMC's MFM are two physical models used. Their guidance based on data from 1200Z on the 9th is shown in Figure 13.

SANBAR is based upon simple vorticity advection averaged throughout the troposphere. Thus, this model gives a good indication of the movement due to the upper level steering flow. SANBAR forecast the track almost perfectly as far as direction is concerned but was much too slow on the speed of movement. This indicates that the upper level flow was important in determining the direction of movement but that the simplified physics of vorticity advection was not sufficient to move it rapidly enough. It is also possible that the initial analysis for SANBAR may have been poor.

The MFM is a physically complex baroclinic model with a grid spacing on the order of 60 Km (Technical Procedures Bulletin (TPB) 160, 1976). It can be run in either a track mode or a precipitation mode. The model was run in the track mode based on 1200Z data on the 9th. It forecast a track almost directly to the north. The MFM direction of movement wasn't as good as SANBAR but it was better on the speed; however, the MFM was still much too slow. NMC has indicated that the direction forecast by the MFM should be given more weight than the speed of movement (TPB 160, 1976).

EPANALOG is an objective forecasting routine that is based on the analog technique. The position of the storm and its past 12-hour movement are compared to previous storms that have occurred within some given distance of the present storm. A most probable track is computed based on the movement of these past storms. The guidance provided by EPANALOG based

on data from 1200Z on the 9th is shown in Figure 14. Because of the peculiarities of eastern Pacific tropical storms and the low number of cases available as a base, this type of guidance is not very useful for storms that move north or north-northwest (Jarrell, 1975). Therefore, for a storm like Kathleen EPANALOG guidance should be rejected. Attempts are being made to correct this bias in the analog technique.

C. Objective Precipitation Guidance

The MFM model was run in a precipitation mode based on data from 1200Z on the 10th. A 48-hour forecast was made with 6-hourly precipitation amounts output every 6 hours. The forecast for 12, 18, 24, and 36 hours along with the observed 6-hourly precipitation are shown in Figure 15.

The MFM tended to overforecast the precipitation amounts. The large "bull's-eyes" of over 7 inches in a six-hour period forecast through the first 12 hours are certainly out of line. The tendency to overforecast extends throughout the 48-hour period. Experience with the MFM would probably allow a proper interpretation and "toning down" of the precipitation amounts. However, as presented, the amounts forecast are very misleading.

A more serious problem lies in the misleading forecast of where the precipitation would occur. The precipitation forecast for Arizona by 18 hours was completely erroneous. By 24 hours the MFM failed to forecast the precipitation associated with the cut-off low moving into California and the precipitation moving into Idaho. The 36-hour forecast is again misleading by indicating precipitation for Wyoming and western Utah rather than Idaho and Montana.

It is apparent that the MFM forecasts were misleading in amounts and patterns and of little value in preparing flash-flood forecasts. The failure of the MFM QPF is undoubtedly related to inadequate handling of terrain effects. Rather smooth terrain is used in the MFM. In the western United States, accurate forecasting of orographic precipitation is essential to any precipitation forecasting model. However, one should not draw too many conclusions from a sample of one.

The LFM 12-, 24-, 36-, and 48-hour precipitation forecasts of 12-hour precipitation amounts initialized from the same data as the MFM are shown in Figure 16. The observed 12-hour precipitation amounts are given in Figure 17.

The LFM precipitation forecasts were superior to the MFM forecasts. Precipitation in southern California was underforecast for the first 12 hours and overforecast for the last 36 hours. However, the amounts forecast were more realistic than those from the MFM. The underforecast of precipitation in the first 12 hours is a problem and may be due to Kathleen being such a small feature in relationship to the LFM grid.

The pattern of precipitation forecast by the LFM is quite good through 24 hours although at 12 hours it had the heaviest precipitation too far north. At 24 hours, it keeps precipitation in California and spreads it

into Nevada. This verified quite well. The LFM did not forecast the precipitation in Idaho and Montana at 36 hours. By 48 hours it does forecast a small area of precipitation in Idaho that did verify quite well. However, the large area in Nevada and southern Utah is erroneous.

Neither the LFM nor MFM gave good QPF guidance in this case. More work is needed on forecasting precipitation in mountainous regions.

VII. SPEED

A. Upper-Level Flow

Kathleen's speed of movement was a source of serious forecast error. One explanation for Kathleen's speed is the strong north-south flow between the cut-off low and the high-pressure ridge. The deep-layer mean wind (V_d) analysis computed from the NMC operational analysis package of the ten levels, 1000 mb through 100 mb, for the period of Kathleen is shown in Figure 18. The deep layer mean wind is defined as:

$$V_d = (75V_{1000} + 150V_{850} + 175V_{700} + 150V_{500} + 100V_{400} + 75V_{300} + 50V_{250} + 50V_{200} + 50V_{150} + 25V_{100}) / 900.$$

The darkened symbol represents the position of Kathleen and the heavy wind barb attached represents the best track instantaneous storm motion. These maps were prepared from data routinely received at the National Hurricane Center.

These maps show that Kathleen's rapid movement corresponds to her entering a strongly confluent area with values of V_d between 30 and 35 knots. Kathleen followed this deep-layer mean-wind pattern very well. This would have been an excellent forecast tool in this case, if it had been available to the forecaster.

B. Fujiwhara Effect

Analyses and data like that shown in Figure 18 are not always available. In data-sparse regions, the Fujiwhara effect has often proven to be a useful model in forecasting the movement of a tropical cyclone. In the case of Kathleen, it would have worked well in forecasting the speed and the direction of movement.

When two low-pressure centers come in close proximity (700 nm), they tend to interact and dumbbell about each other in what is called the Fujiwhara effect (Brand, 1970). In the case of Kathleen, there would appear to be an interaction between the cut-off low off the California coast and Kathleen resulting in rather strong southerly steering winds. To test this hypothesis, the positions of Kathleen and the cut-off low were determined every six hours using still satellite pictures and time-lapse movies of these pictures. A straight line was constructed

connecting the positions of the two lows for 6-hour time steps. The length of the line (in degrees of latitude) and the angle which it makes with true north were measured. Using these two values, the relative positions of the two systems were plotted on a polar graph. See Figure 19. The striking result is the classical Fujiwhara pattern. When their relative movements are considered, the two lows approached each other and dumbbelled about each other. The Fujiwhara model can also be related to the acceleration of Kathleen. Since the cut-off low was the larger, more massive feature, it would be expected to move only a small amount when applying this type of Fujiwhara model. The less-massive Kathleen would be accelerated northward in a "crack-the-whip" fashion. The interaction can be visualized as being similar to an athlete spinning the weight about himself in the hammer throw. Thus, the Fujiwhara effect in the case of a cut-off low and a hurricane would alert forecasters to possible rapid acceleration of the hurricane. In retrospect, this was true for Kathleen.

This Fujiwhara-type model is suggested as a useful forecasting tool. By extrapolating the spiral inward and having an idea of where the cut-off low will move, a good forecast can be made of the movement of the storm. A cut-off low in the vicinity of a hurricane may signal that a rapid acceleration may occur.

VIII. INTENSITY

Kathleen maintained her intensity much farther north than normal. Four possible mechanisms for maintaining Kathleen's intensity are considered here: 1) the relationship between intensity and speed of movement; 2) advection of warm, moist air from the Gulf of California; 3) the relationship between intensity and sea-surface temperature, and 4) the relationship between intensity and nonelliptic upper tropospheric flow.

A. Speed

Snellman (1969) has shown that tropical storms which move rapidly tend to decrease slowly in intensity while those that move more slowly tend to decay faster. These conclusions are based on a careful study of hurricane Carol, 1954, and hurricane Diane, 1955. The premise is that the storm begins to decay as colder air is entrained into the center of the storm. If the storm moves rapidly with respect to the cold air (i.e., air with temperature 16° C. or lower at 850 mb and lower than 22° C. at the surface), the cold air cannot reach the center of the storm and its intensity is maintained. In contrast, cold air can be readily entrained into the center of a slow-moving storm and weaken it.

Kathleen was an unusually fast-moving storm so that this result may be applicable. A careful study of the trajectories of air parcels and temperature fields is needed to determine the validity of this point.

A rapid speed of movement may also be important in relation to the effect of terrain on a storm. Normally, the rugged terrain of northern Baja is enough to dissipate most storms. However, the rapid movement did not allow the terrain a very long period of time to disrupt the flow. Thus, a well-defined upper-level circulation could be maintained well inland.

B. Gulf of California

Hales (1973) has shown that the Gulf of California is an important moisture source in the southwestern United States in the fall. Figure 18 shows that strong, southerly flow off the Gulf of California into southern California and Arizona was prevalent before Kathleen reached southern California. Since the sea-surface temperatures in the Gulf of California range between 85° - 90° F. at this time of year, this very warm, moist air may have contributed to Kathleen's maintaining or possibly increasing her intensity as she moved into southern California.

C. Sea-Surface Temperatures

It is well known that tropical storm intensity is related to sea-surface temperature. Sea-surface temperature anomalies were determined for the period just before and just after Kathleen using satellite-derived, sea-surface temperatures.

The anomaly pattern for the period before Kathleen is shown in Figure 20. The normals for September are shown in Figure 22. The strong positive anomaly of 3.6° C. is very large. Such unusually warm water would be important in allowing Kathleen to move so strongly into Baja, rather than weaken over the colder water. Denney (1976) discusses the importance of warm inflow into the right side of a storm to maintain its intensity. This fact is also illustrated by Snellman (1961). Kathleen had unusually warm water on her right flank for this time of year, and this may have contributed to Kathleen's unusual intensity.

Figure 21 shows the anomaly pattern for the period shortly after Kathleen. The water temperatures have been lowered considerably due to upwelling associated with Kathleen's strong surface wind field.

D. Nonelliptic Upper-Tropospheric Flow

After a tropical storm leaves the ocean and moves over land, its dynamics in the lower levels and in the boundary layer are far different. It is no longer a tropical storm in the true sense. Yet, in the case of Kathleen significant rain and winds continued into Montana. Therefore, there must have been a continuation of some of the dynamics to maintain the system.

Several papers by Paegle and Paegle (1974, 1976a, 1976b) have discussed the occurrence and dynamics of strongly divergent upper-tropospheric flows associated with nonelliptic regions with respect to the balance equation. MacDonald (1976) showed that this type of upper-tropospheric pattern has been associated with family outbreaks of tornadoes and with hurricane Camille. It was also apparently associated with the Big Thompson Flood (Paegle, private communication). ✓

A strongly divergent upper-tropospheric flow of this kind is apparent in the 200-mb analysis in the vicinity of southern California on the morning of the 12th (Figure 23). Perhaps this kind of dynamic process,

established while still over the water, helped to maintain the intensity of the storm into Montana. This aspect of the storm warrants further study.

IX. CONCLUSIONS

Kathleen was the most destructive tropical cyclone to strike the western United States this century. Kathleen's speed of movement was her most significant feature. This rapid acceleration and resulting high speed was the cause of most of the forecast problems. The acceleration of movement was due to a strengthening upper-level steering flow. The storm's rapid acceleration of movement can also be understood by using a model based upon the Fujiwhara effect.

The synoptic scale forecast models did a good job of forecasting the synoptic-scale features associated with Kathleen. However, the objective track guidance available did not do very well in forecasting the speed of movement but did do a good job in forecasting the direction of movement.

The quantitative precipitation guidance provided by the LFM and MFM was not satisfactory. The MFM was poor and misleading. The LFM guidance was somewhat more useful but not detailed enough to forecast heavy rain areas.

Unusually warm sea-surface temperatures on Kathleen's right flank associated with rapid movement may have been important in maintaining Kathleen's intensity so strongly into Baja. Also, warm, moist air advected off the Gulf of California may have helped feed the storm into southern California. Finally, a nonelliptic region in relationship to the balance equation in the upper-tropospheric flow was associated with Kathleen and may have helped the storm to maintain its intensity into Montana.

X. ACKNOWLEDGMENTS

The author wishes to thank the staff of the San Francisco Weather Service Forecast Office for their help and time provided in the collection of data for this paper. Also, a special note of thanks to Larry Breaker (Satellite Field Services Station - San Francisco) and Forrest Miller (National Marine Fisheries Service - La Jolla) for the sea-surface temperature data.

Acknowledgment is also made of Mr. Hazen Bedke's (Regional Director, National Weather Service Western Region) suggesting the study and for the guidance and encouragement provided by other members of the Scientific Services Division staff.

XI. REFERENCES

Baum, R. A., and Rasch, G. E., 1975; Digitized Eastern Pacific Tropical Cyclone Tracks. NOAA Technical Memorandum, NWS WR-101, National

MFM

Oceanic and Atmospheric Administration, U. S. Department of Commerce, National Weather Service Western Region, 189 pp.

Brand, S., 1970: Interaction of Binary Tropical Cyclones of the Western North Pacific Ocean. Journal of Applied Meteorology, 9, 433-441.

Cooley, D. S., 1976: The Movable Fine Mesh (MFM)--A New Operational Forecast Model. Technical Procedures Bulletin No. 160, Technical Procedures Branch, National Oceanic and Atmospheric Administration, U. S. Department of Commerce, Silver Spring, Maryland, 5 pp.

Denney, W. J., 1976: Cool Inflow as a Weakening Influence on Eastern Pacific Tropical Cyclones. NOAA Technical Memorandum, NWS WR-110, National Oceanic and Atmospheric Administration, U. S. Department of Commerce, National Weather Service Western Region, 4 pp.

Fujiwhara, S., 1923: On the Growth and Decay of Vortical Systems. Quarterly Journal, Vol. 49, Royal Meteorological Society, 75-104.

Gunther, E. B., 1976: Post-Storm Report: Tropical Cyclone Kathleen. Eastern Pacific Hurricane Center, National Oceanic and Atmospheric Administration, U. S. Department of Commerce, National Weather Service Western Region, 4 pp.

Hales, J. E., 1973: Southwestern United States Summer Monsoon Source--Gulf of Mexico or Pacific Ocean? NOAA Technical Memorandum, NWS WR-84, National Oceanic and Atmospheric Administration, U. S. Department of Commerce, National Weather Service Western Region, 26 pp.

Hansen, L. E., 1972: The Climatology and Nature of Tropical Cyclones of the Eastern North Pacific Ocean. Master's Thesis, Naval Postgraduate School, Monterey, California, 178 pp.

Jarrell, J. D., Mauck, C. J., and Renard, R. J., 1975: The Navy's Analog Scheme for Forecasting Tropical Cyclone Motion Over the Northeastern Pacific Ocean. Technical Paper No. 6-75, Environmental Prediction Research Facility, Naval Postgraduate School, Monterey, California, 27 pp.

MacDonald, A. E., 1976: On a Type of Strongly Divergent Balanced Flow. Monthly Weather Review (in press).

Paegle, J., and Paegle, J. N., 1974: An Efficient and Accurate Approximation of the Balance Wind with Application to Nonelliptic Data. Monthly Weather Review, 102, 838-846.

Paegle, J., and Paegle, J. N., 1976: On Geopotential Data and Ellipticity of the Balance Equation: A Data Study. Monthly Weather Review, 104, 1279-1288.

Paegle, J., and Paegle, J. N., 1976: On the Realizability of Strongly Divergent Supergradient Flows. Journal of Atmospheric Sciences, 33, 2300-2307.

- Renard, J. R., and Bowman, W. N., 1976: The Climatology and Forecasting of Eastern North Pacific Ocean Tropical Cyclones. Technical Paper No. 7-76, Environmental Prediction Research Facility, Naval Postgraduate School, Monterey, California, 79 pp.
- Robinson, M. K., 1973: Atlas of Monthly Mean Sea Surface and Subsurface Temperatures in the Gulf of California, Mexico. San Diego Society of Natural History, San Diego, California, Figure 50.
- Sanders, F., and Burpee, R. W., 1968: Experiments in Barotropic Hurricane Track Forecasting. Monthly Weather Review, 7, 313-323.
- Snellman, L. W., 1961: On the Relationship Between Intensity and Speed of Hurricanes after Recurvature. Report No. 50, Proceedings of the Second Technical Conference on Hurricanes, 27-33.
- Weaver, R. L., 1962: Meteorology of Hydrologically Critical Storms in California. Hydrometeorological Report No. 37, Environmental Science Services Administration, U. S. Department of Commerce, Weather Bureau, 196-203.

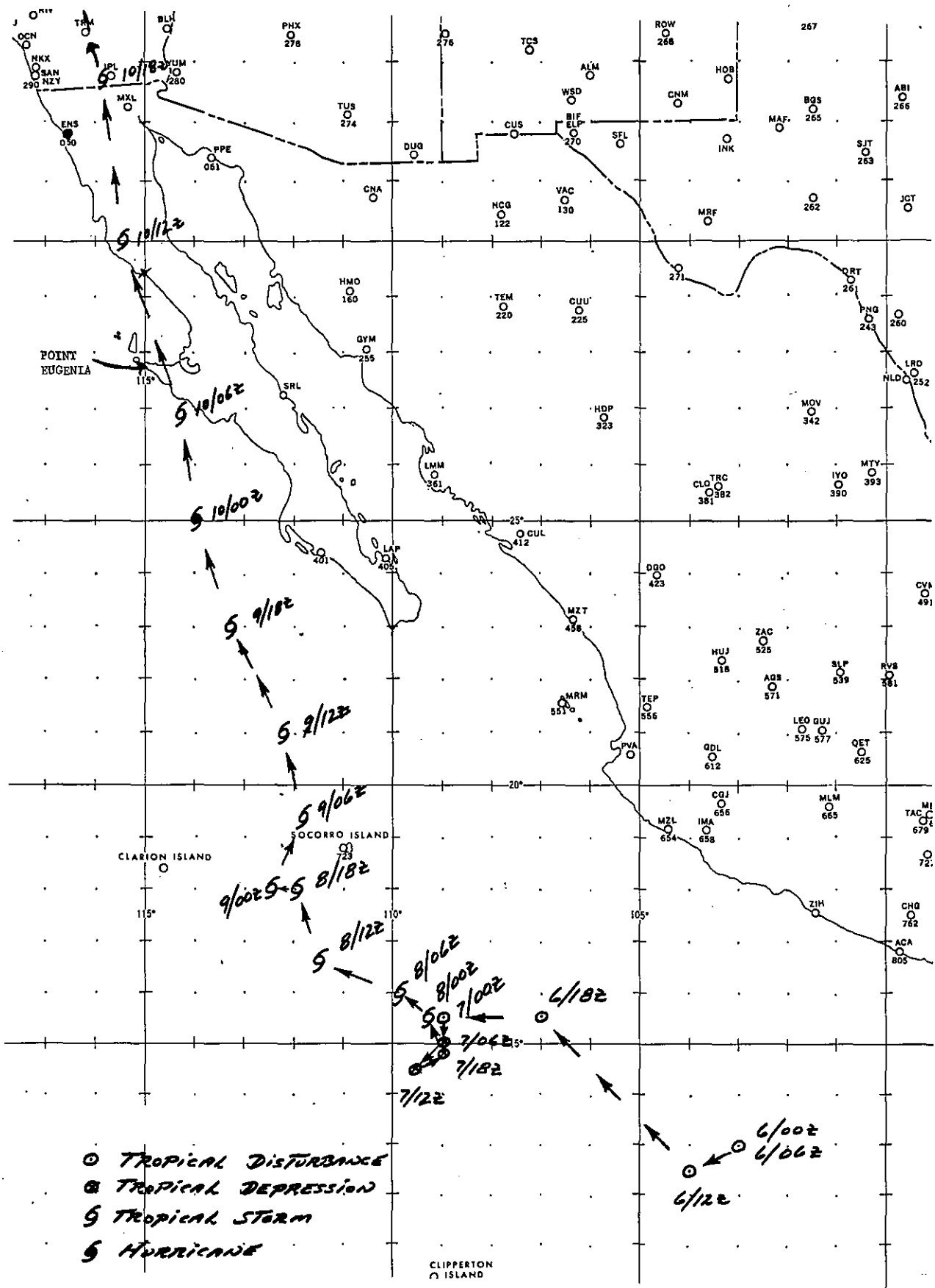


Figure 1. The track of Tropical Cyclone Kathleen as determined by satellite observation of the eye of the storm.

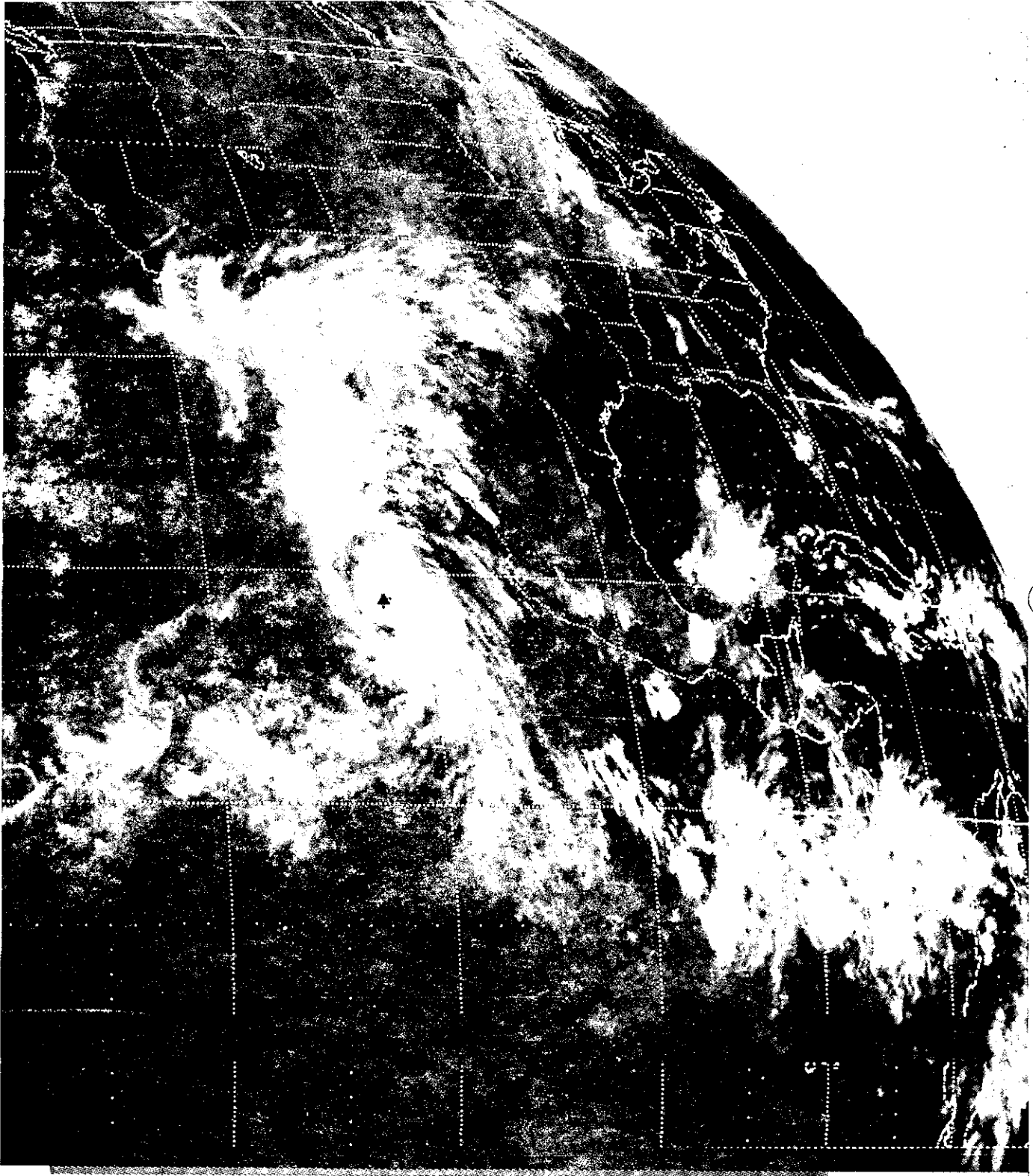


Figure 2. Two-mile, infrared satellite picture for 0415Z, September 9, 1976. Kathleen's approximate position is indicated by "▲".

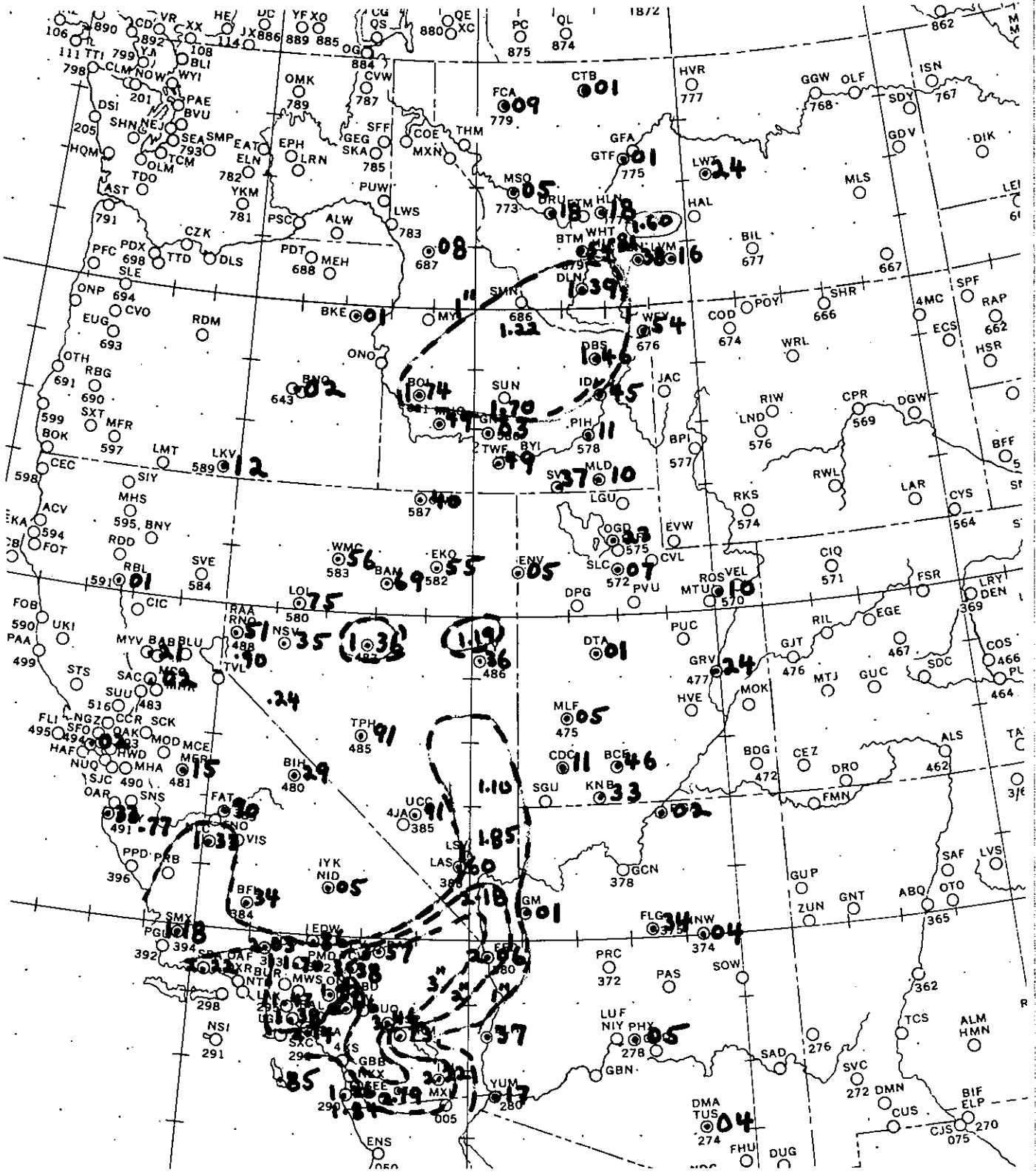


Figure 3. 72-hour precipitation totals for the period from 1200Z on September 9 to 1200Z on September 12. The contour interval is 1 inch.

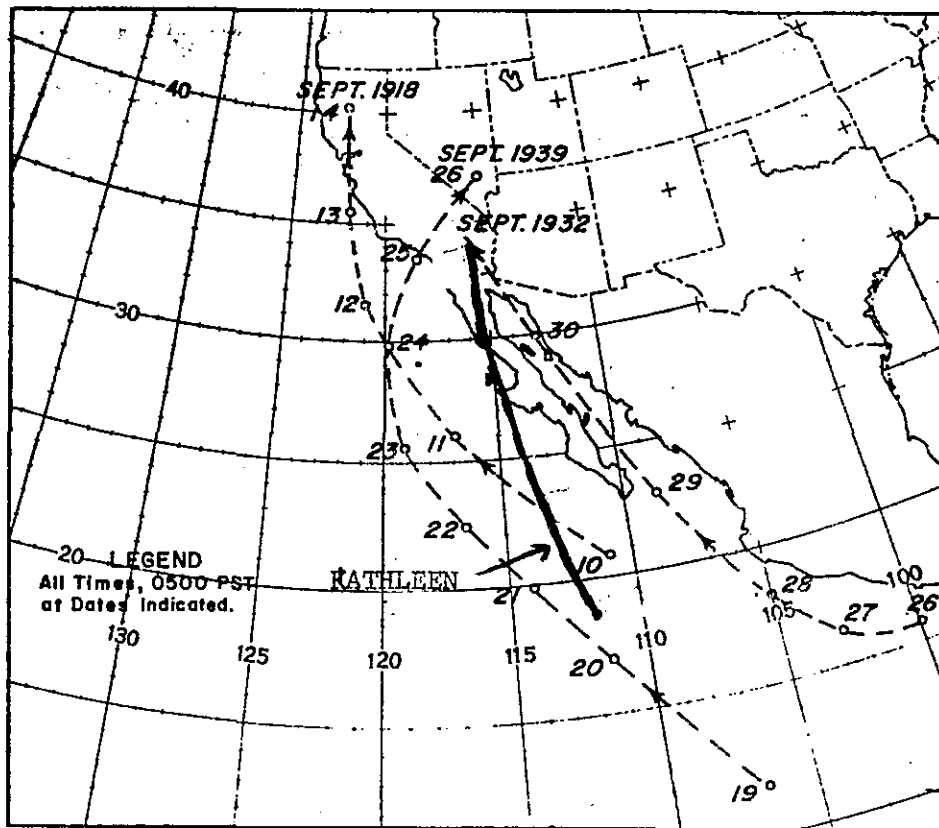


Figure 4. Tracks of the three previous tropical cyclones that have significantly affected the west coast of the United States this century (Weaver, 1962). Kathleen's track is shown for comparison.

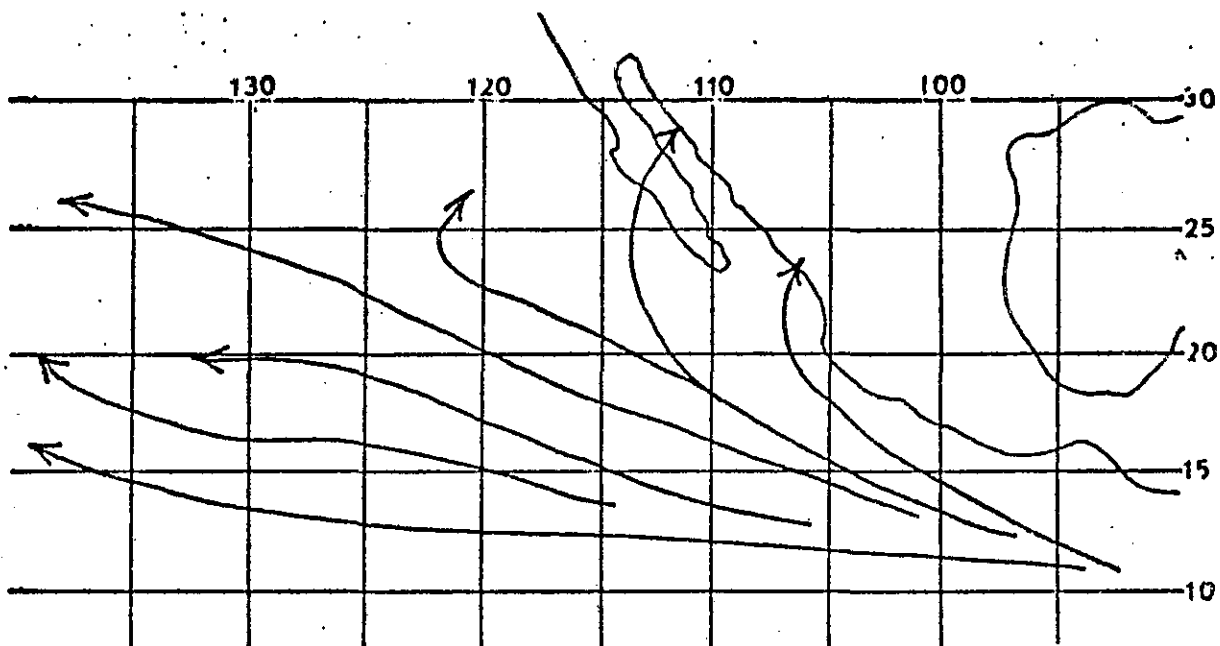


Figure 5. Mean Eastern Pacific tropical cyclone trajectories (Hansen, 1972).

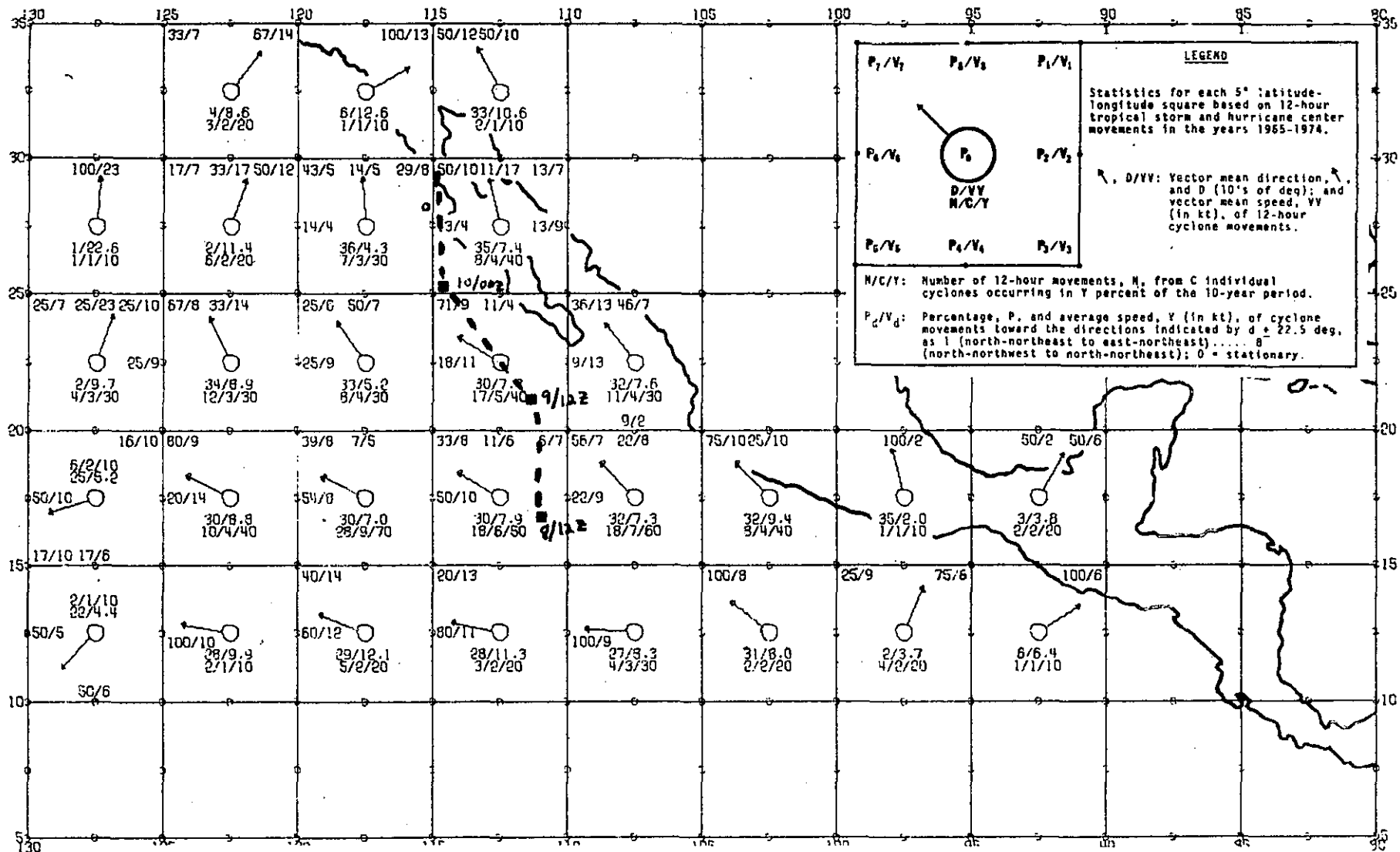


Figure 6. Climatology of the twelve-hour movement of eastern Pacific tropical cyclones for the period of September 1-15. See legend for the meaning of the figures (Renard, 1976). Kathleen's track is dashed in for comparison.

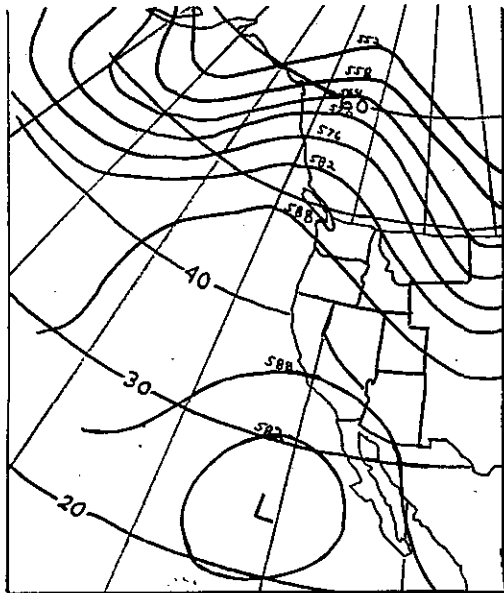


Figure 7. 500-mb initial analysis for 0000Z on September 9, 1976.

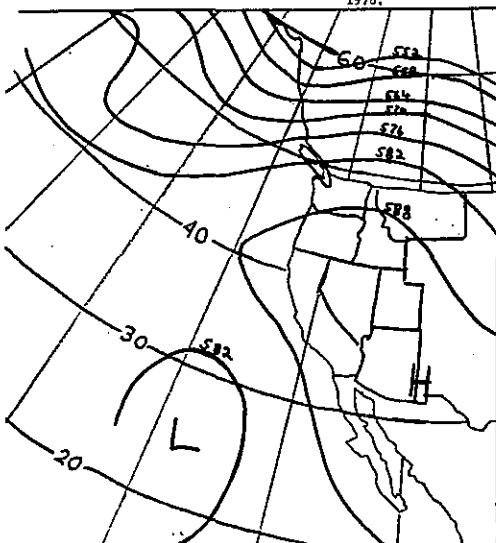


Figure 8a. 36-hr Barotropic 500-mb forecast valid 1200Z on September 10, 1976.

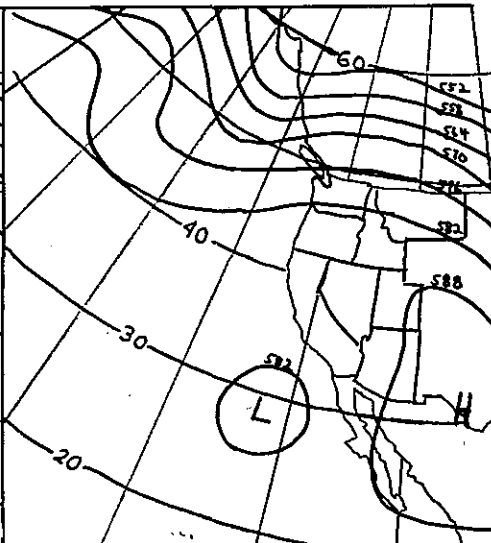


Figure 8b. 36-hr PE 500-mb forecast valid 1200Z on September 10, 1976.

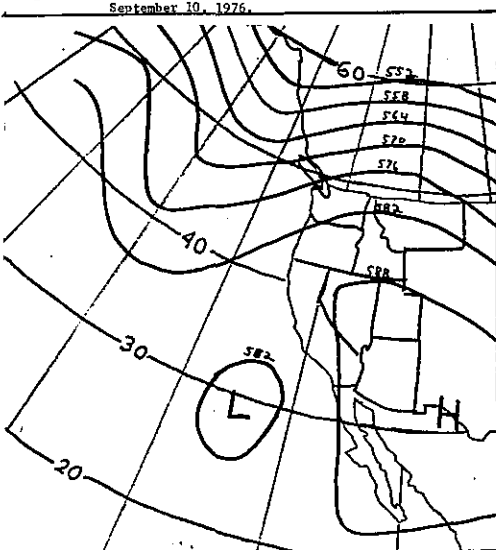


Figure 8c. 36-hour LFM 500-mb forecast valid 1200Z on September 10, 1976.

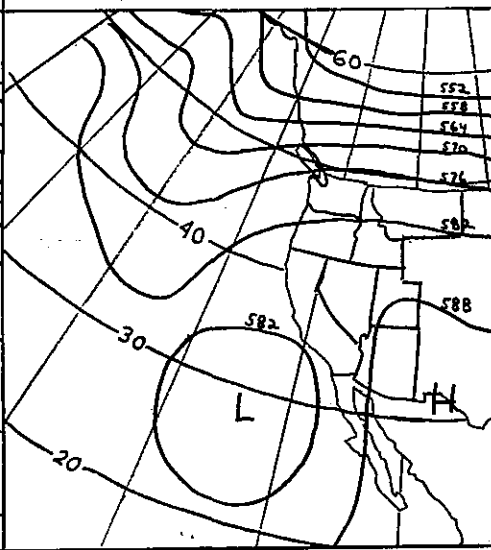


Figure 9. 500-mb verifying analysis valid 1200Z on September 10, 1976.

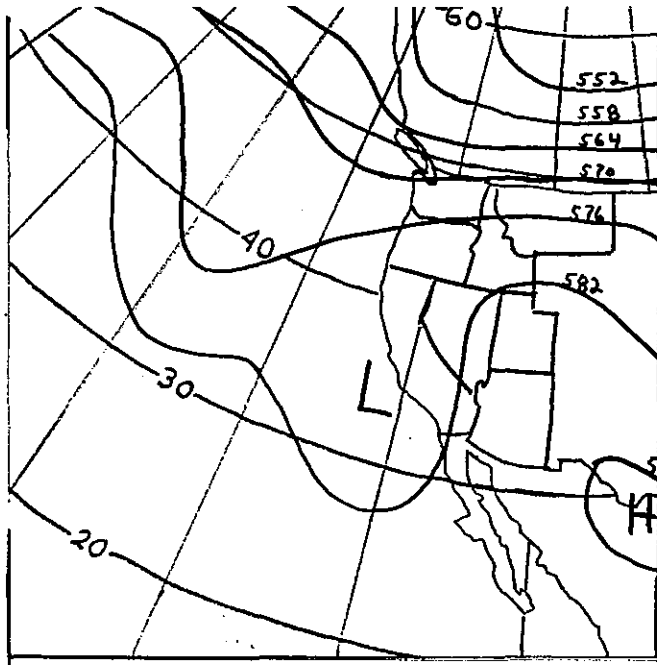


Figure 10a. 36-hr PE 500-mb forecast valid 1200Z on September 11, 1976.

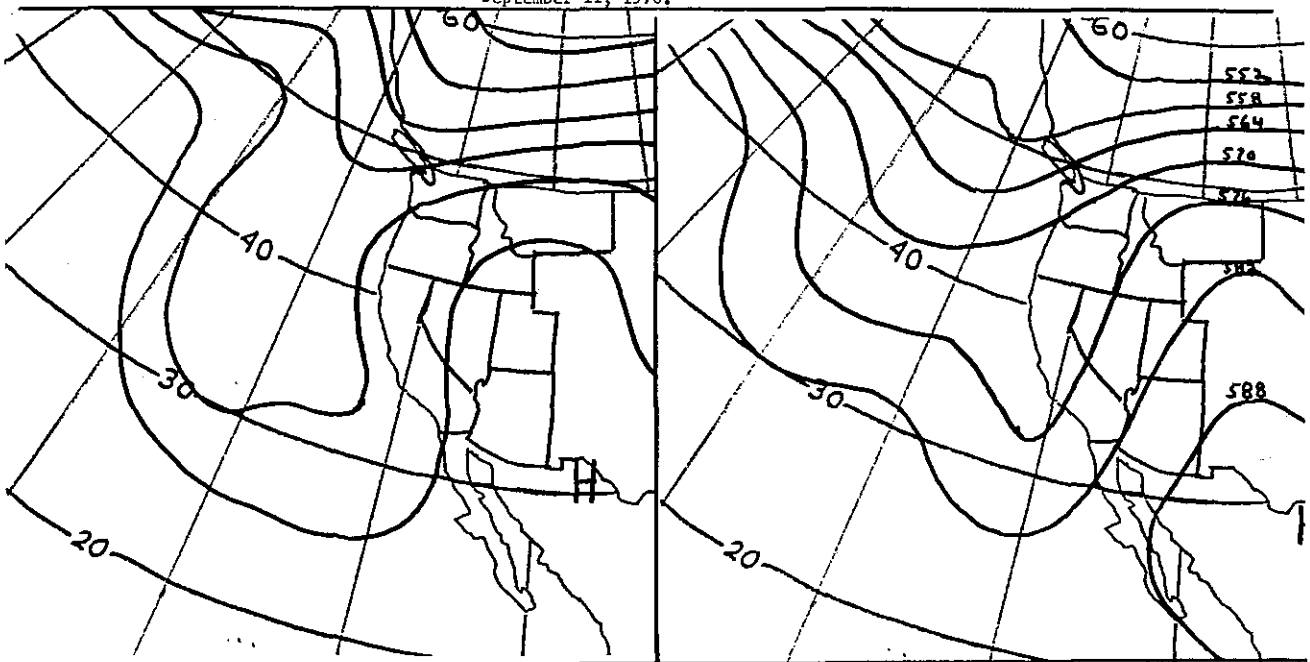


Figure 10b. 48-hr LFM 500-mb forecast valid 1200Z on September 11, 1976.

Figure 10c. 500-mb verifying analysis valid 1200Z on September 11, 1976.

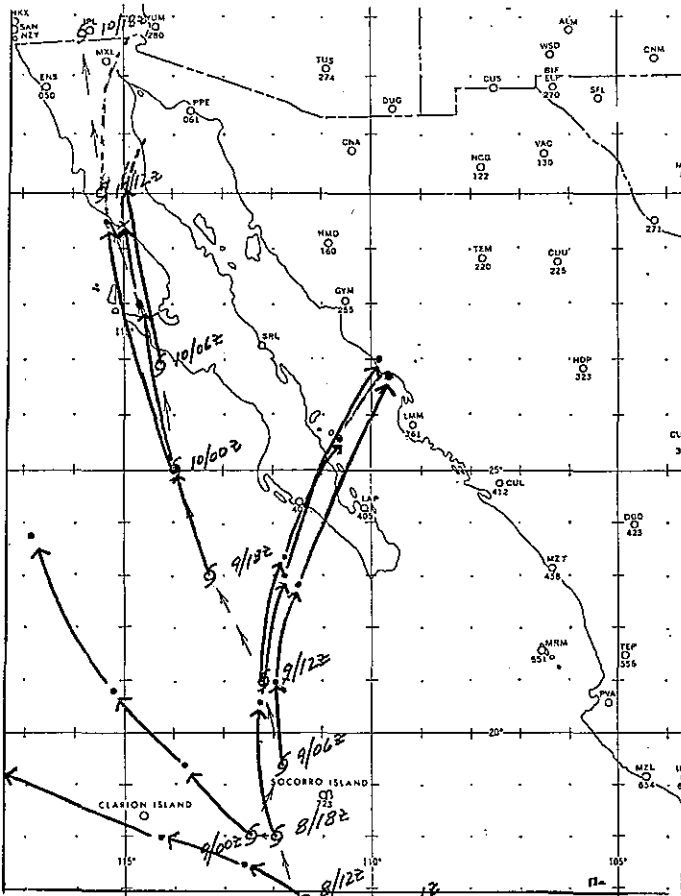


Figure 11. Starting from the initial position and time as shown, the 12-, 24- and 48-hour forecasts made at that time by the San Francisco WSEF are shown.

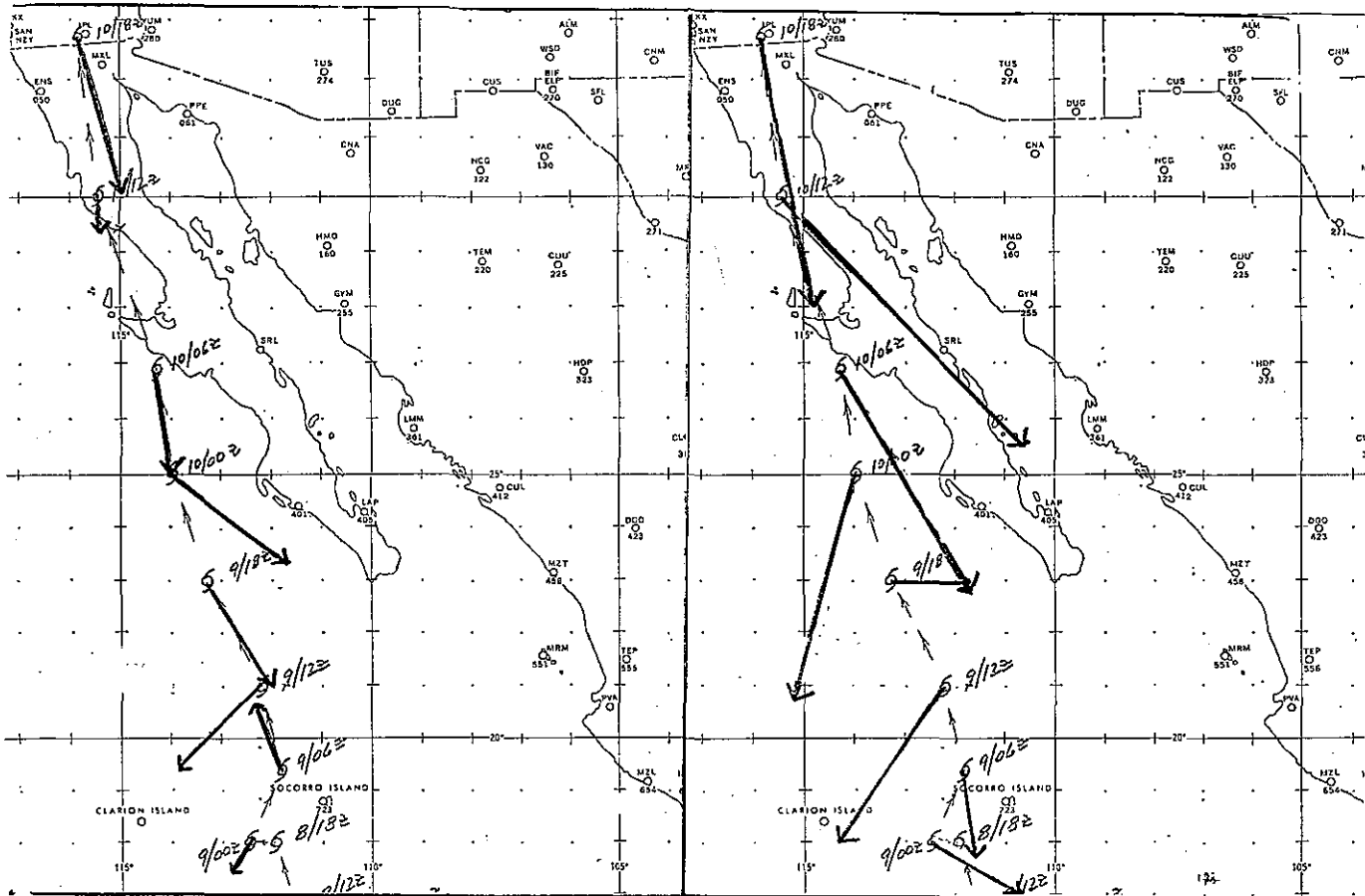


Figure 12a. Vector error of 12-hour San Francisco forecasts.

-22- Figure 12b. Vector error of 24-hour San Francisco forecasts.

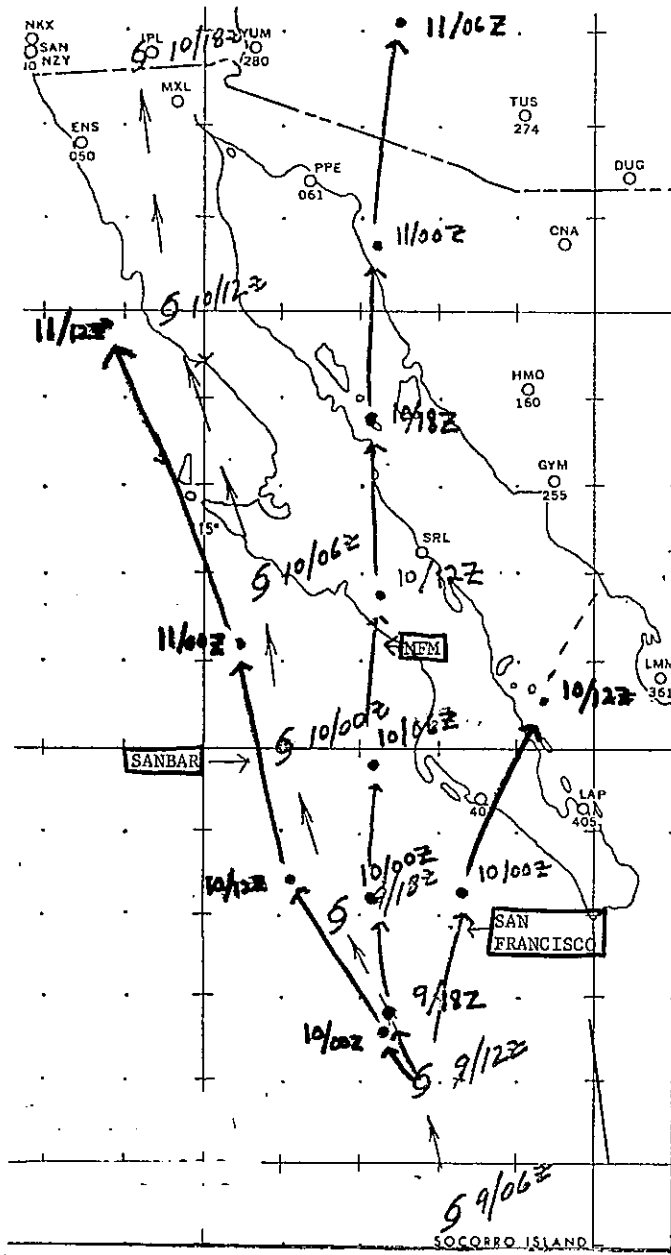


Figure 13. Objective track guidance provided by SANBAR and the MFM based on data from 1200Z on the 9th. The official forecast is shown for comparison.

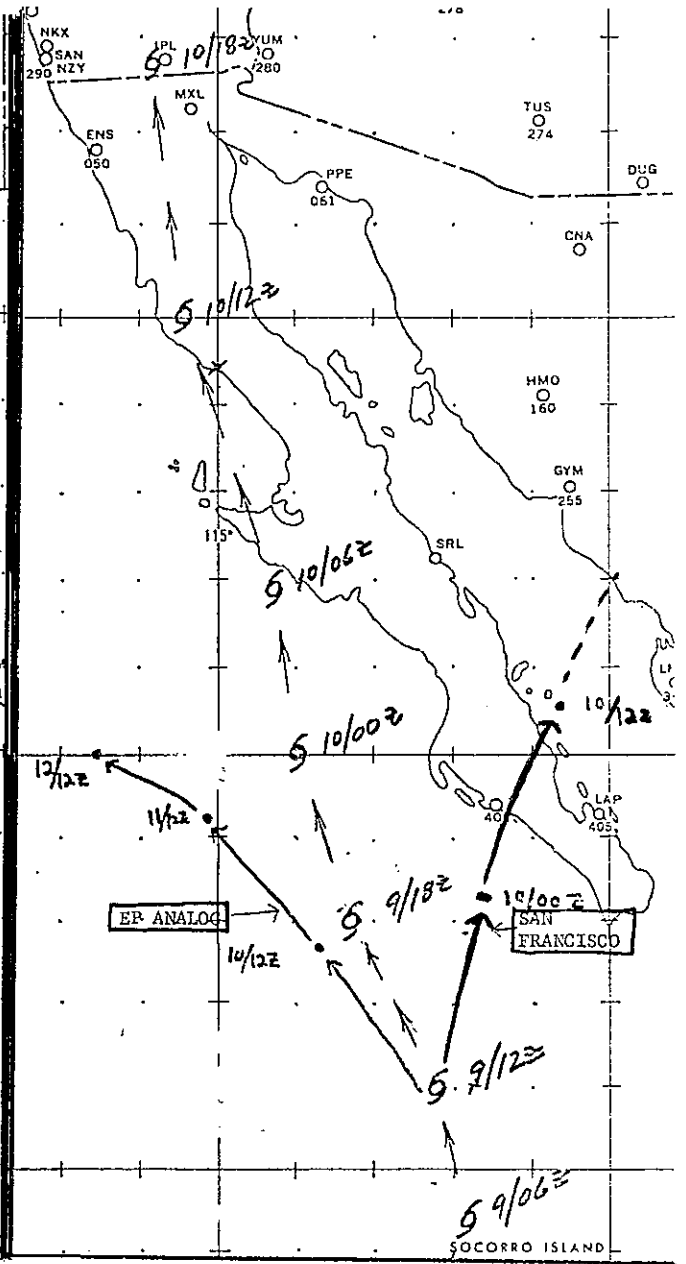


Figure 14. Objective track guidance provided by EPANALOG based on data from 1200Z on the 9th. The official forecast is shown for comparison.

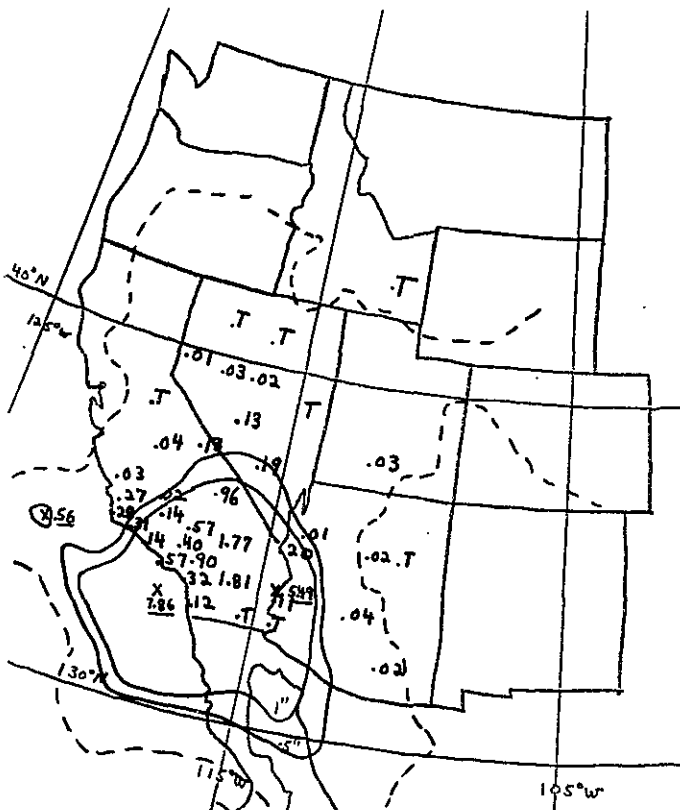


Figure 15a. NFM forecast of precipitation amounts for the period from 1800Z on the 10th to 0000Z on the 11th. The .5 inch and 1 inch contours are shown. The dashed line indicates the general area where precipitation was forecast. The forecast location of maximum precipitation is marked by "x" and the amount forecast is underlined. The verifying precipitation amounts are also shown.

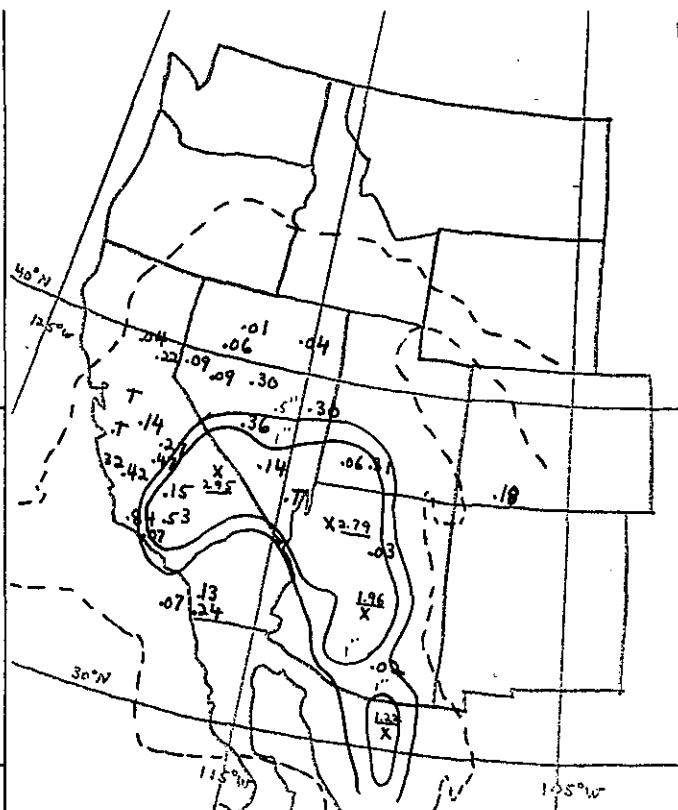


Figure 15b. Same as 15a except for the period from 0000Z to 0600Z on the 11th.

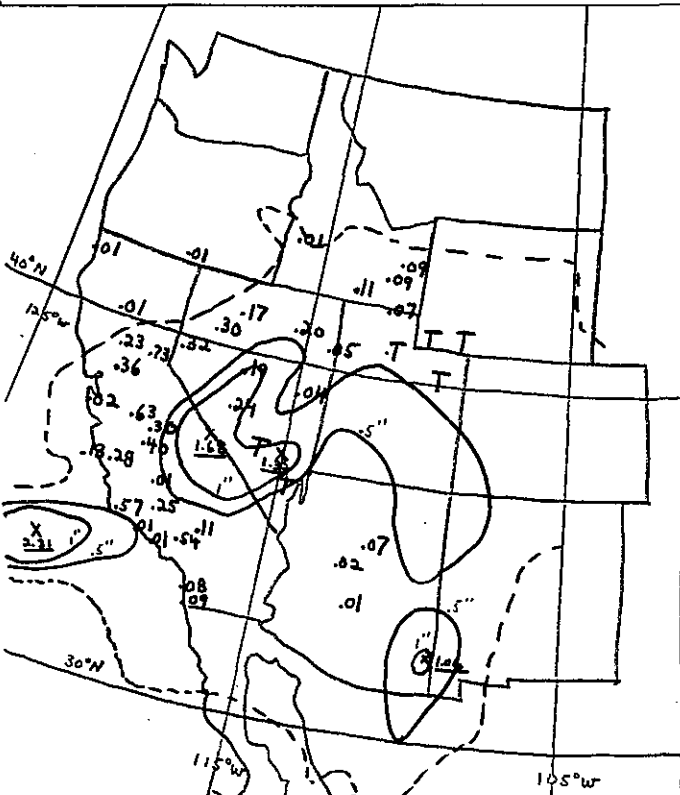


Figure 15c. Same as 15a, except for the period from 0600Z to 1200Z on the 11th.

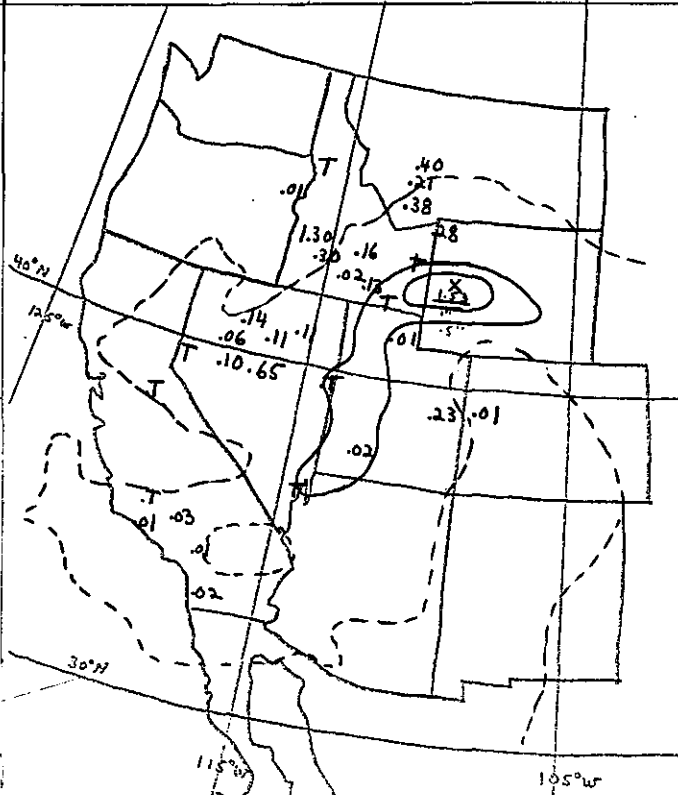
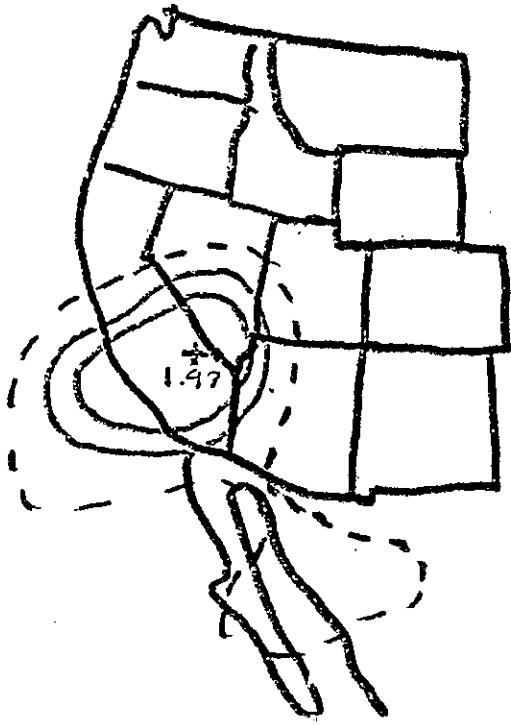
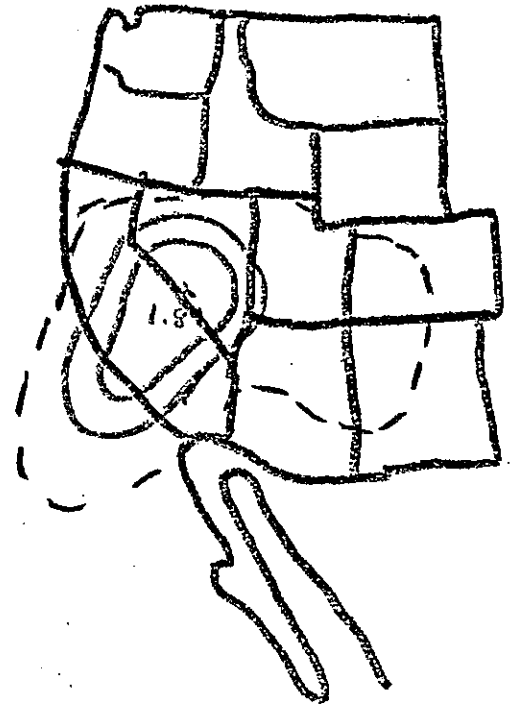


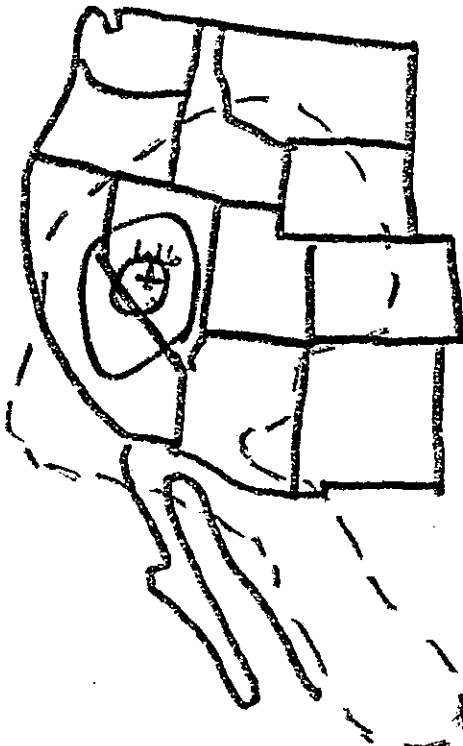
Figure 15d. Same as 15a, except for the period from 1800Z on the 11th to 0000Z on the 12th.



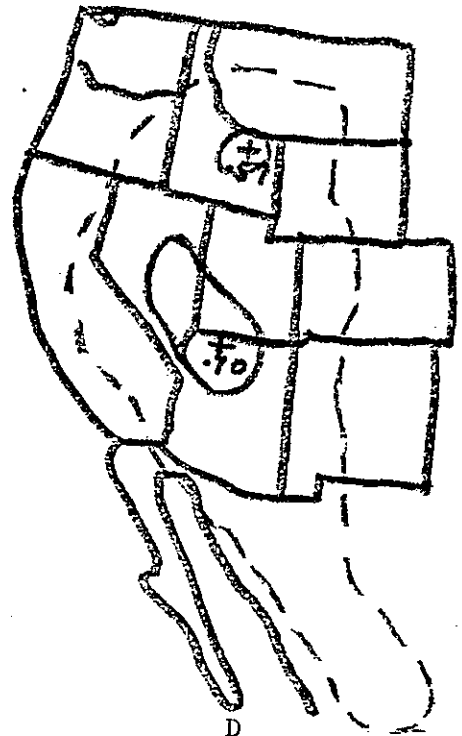
A



B



C



D

Figure 16. LFM 12-, 24-, 36-, and 48-hour precipitation forecasts of 12-hour precipitation amounts are shown in A, B, C, and D, respectively. The .5-inch and 1-inch contours are shown. The dashed line indicates the general area where precipitation was forecast. The forecast location of maximum precipitation is indicated by "+" and the amount is shown. The initial data are from 1200Z on the 10th.

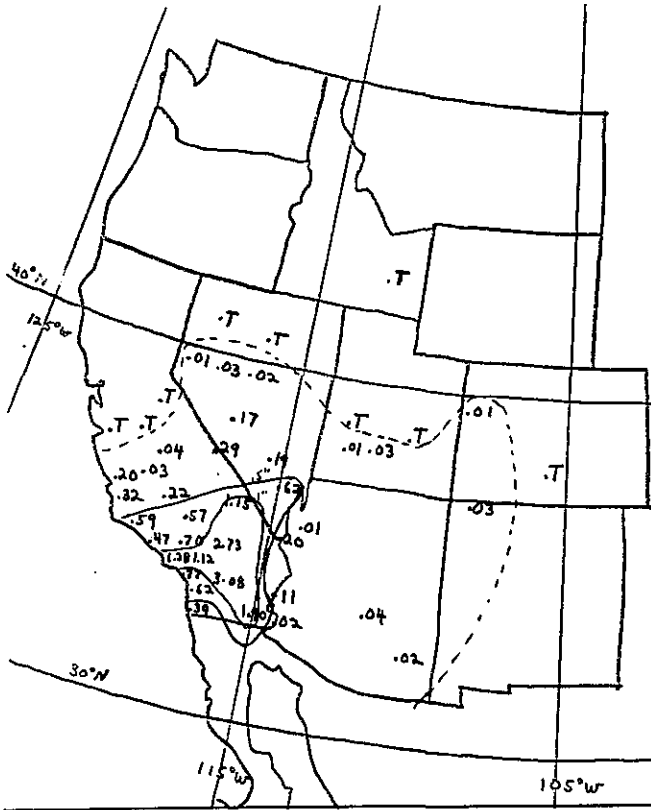


Figure 17a. 12-hour observed precipitation amounts ending at 0000Z on the 11th. The .5 inch and 1 inch contours are drawn.

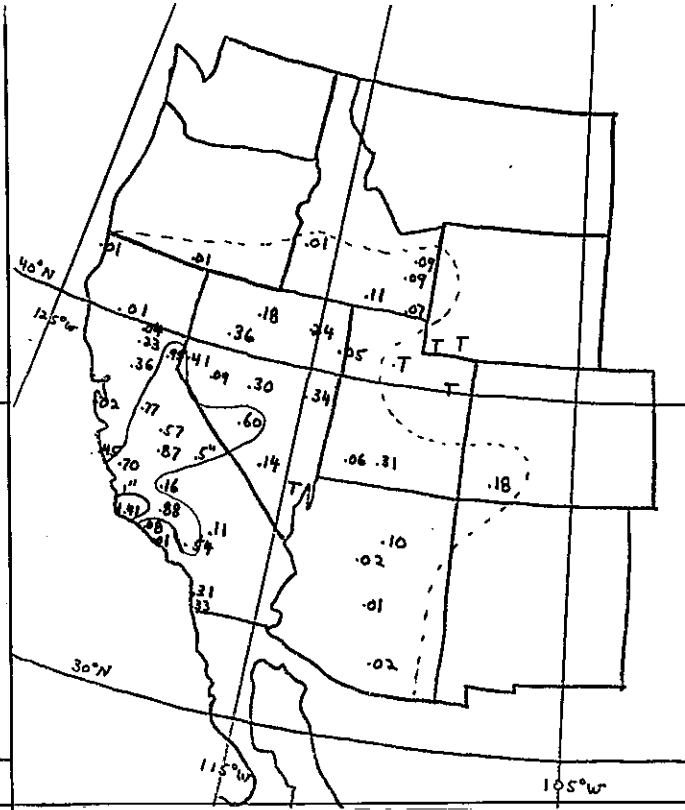


Figure 17b. Same as 17a, except ending at 1200Z on the 11th.

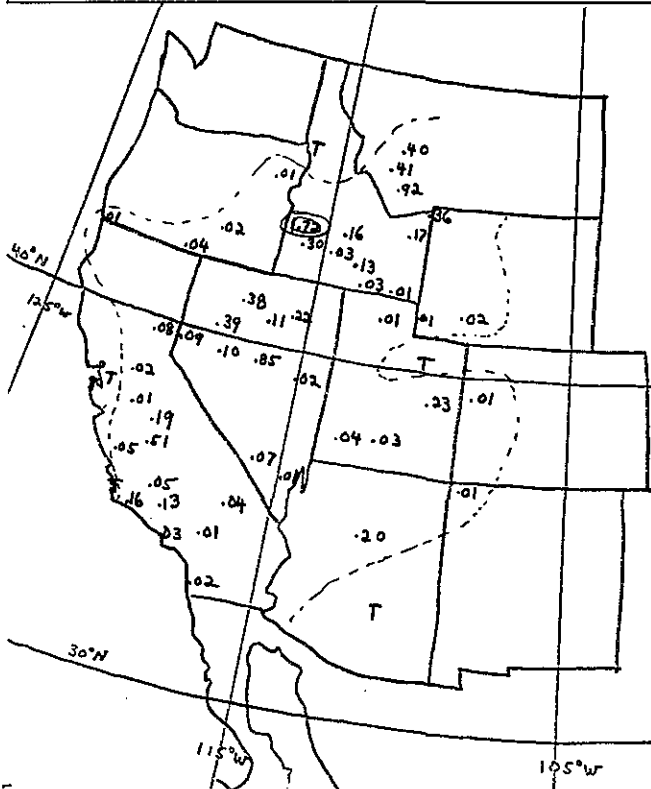


Figure 17c. Same as 17a, except ending at 0000Z on the 12th.

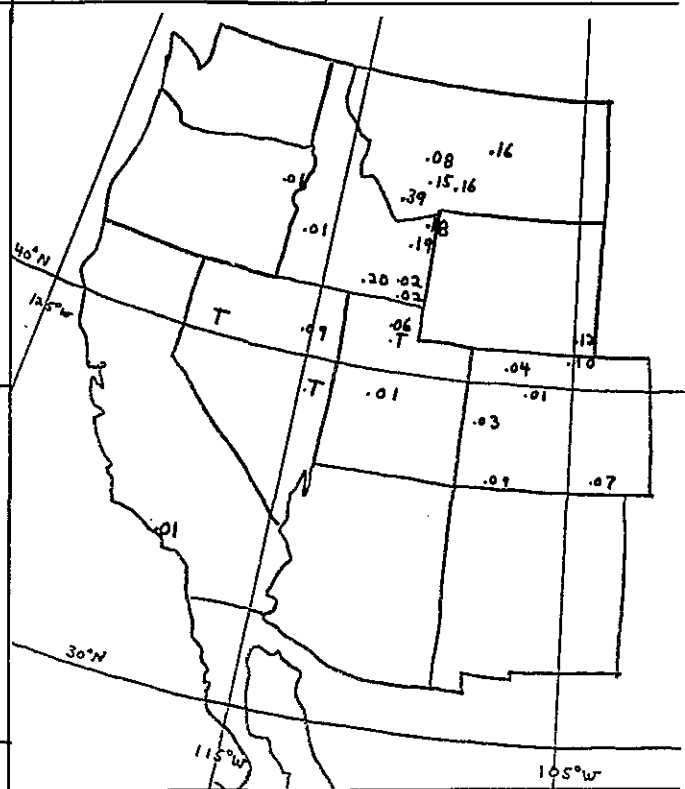


Figure 17d. Same as 17a, except ending at 1200Z on the 12th.

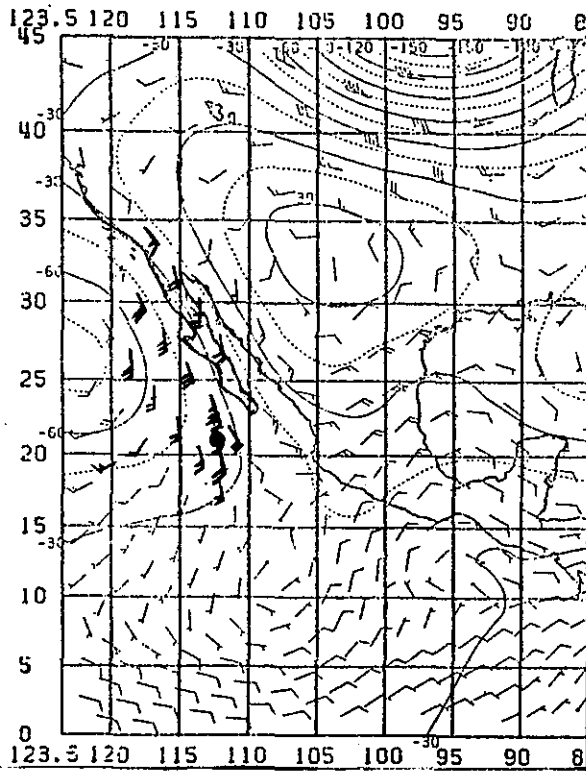


Figure 18a. Deep Layer Mean Wind Analysis for the 9th, 1200Z. Wind Barbs are at the Regular NMC Grid Points. Kathleen is indicated by "●".

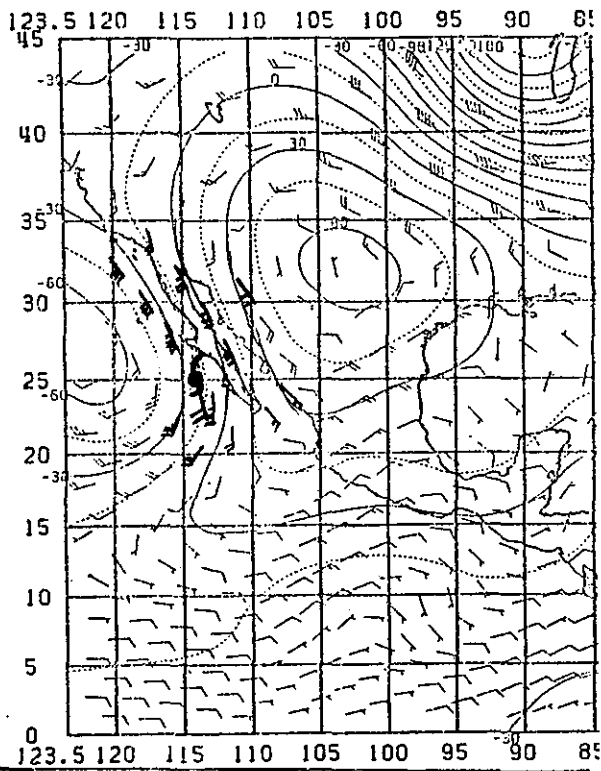


Figure 18b. Same as 18a except for 10th, 00Z.

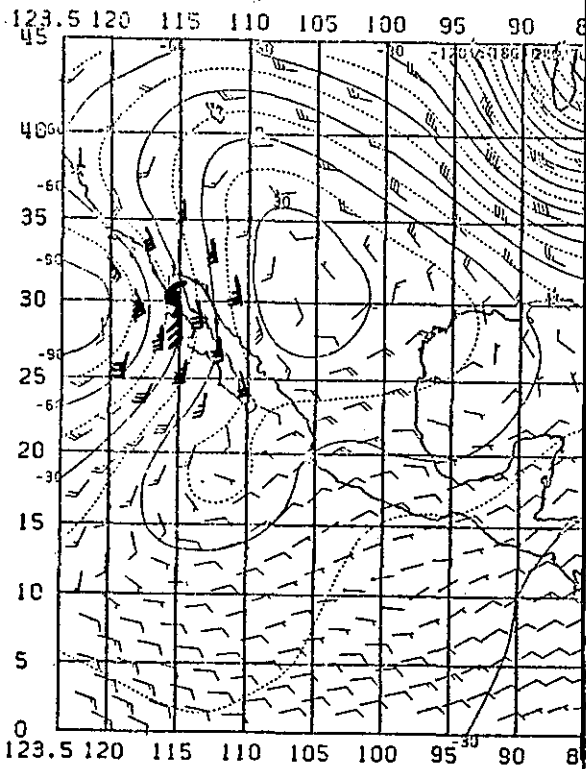


Figure 18c. Same as 18a except for 10th, 12Z.

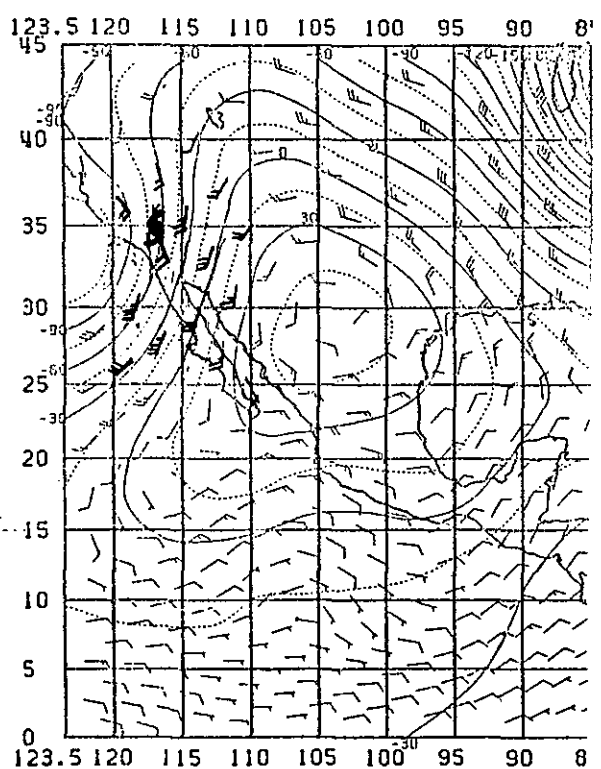


Figure 18d. Same as 18a except for 11th, 00Z.

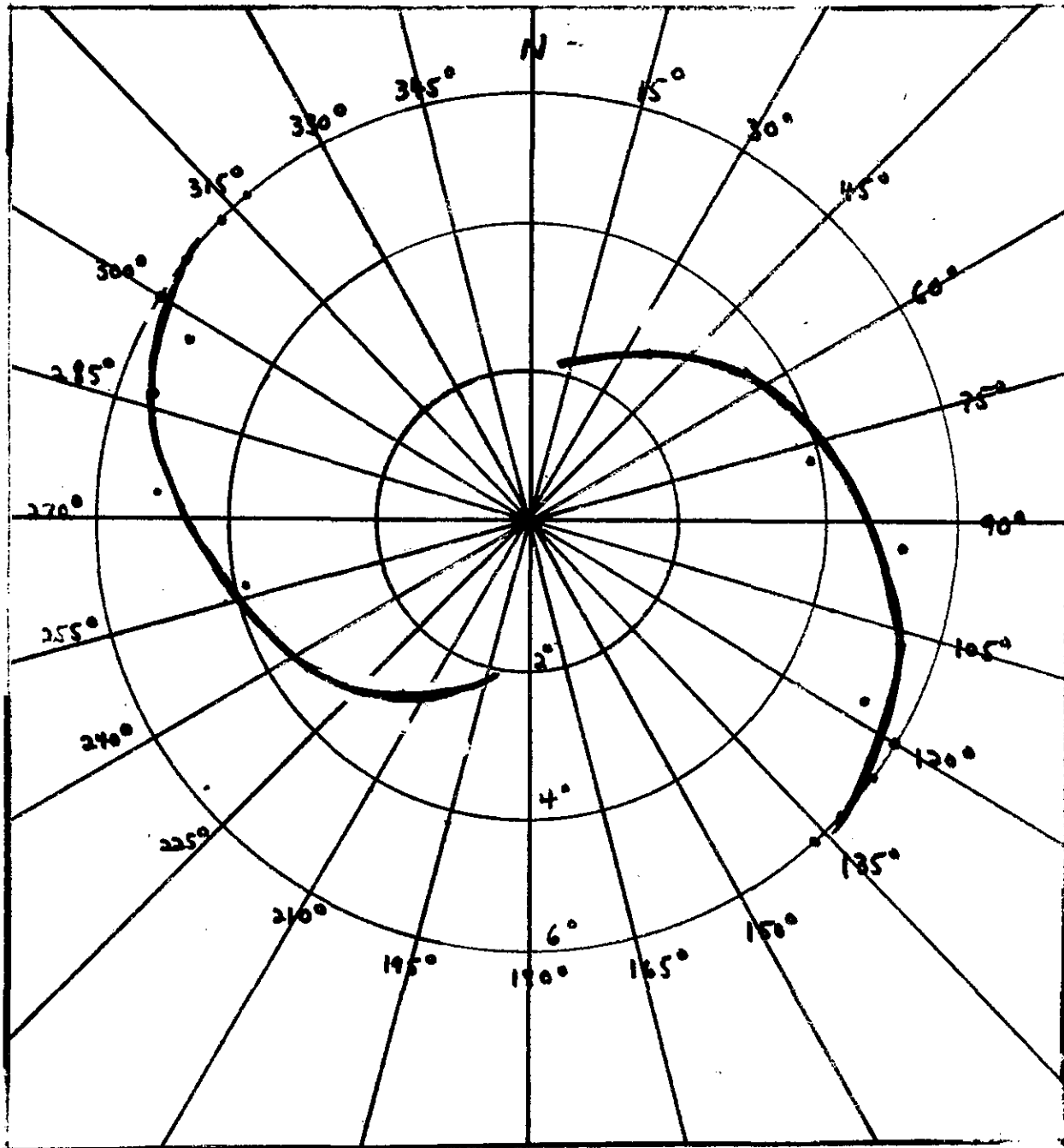


Figure 19. Plot of the relative positions of the cut-off low and Kathleen as described in the text. The radial distance is in degrees of latitude and the angles are in degrees based upon true north.

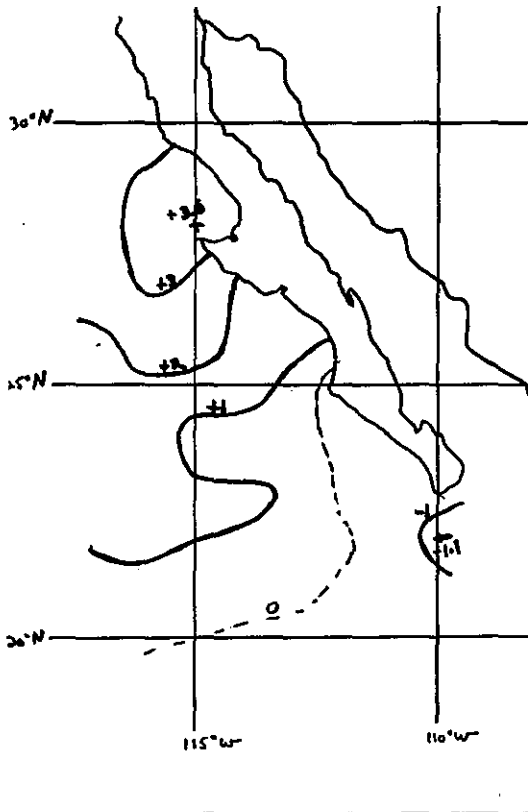


Figure 20. Sea-surface temperature anomalies in degrees Celsius for September 9th.

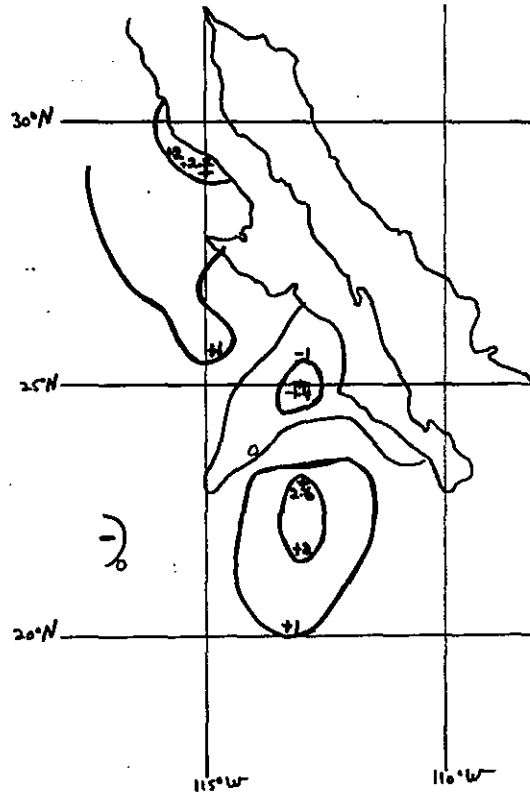


Figure 21. Sea-surface temperature anomalies in degrees Celsius for September 14th.

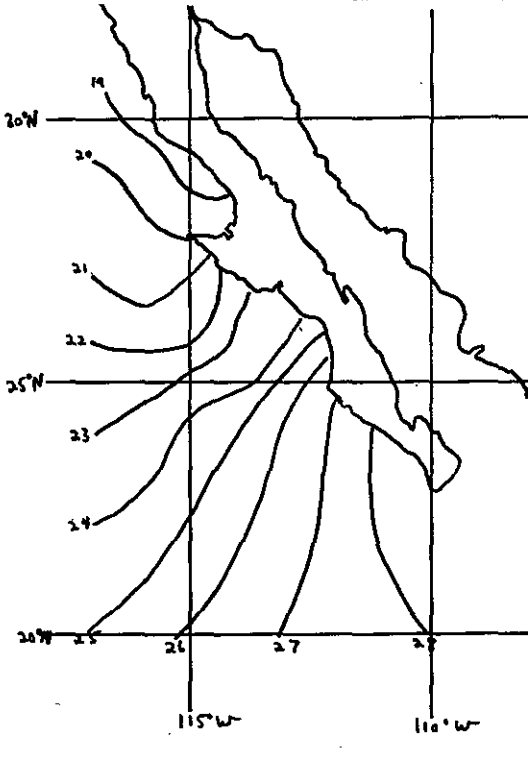


Figure 22. Sea-surface temperature normals in degrees Celsius for September (Robinson, 1973).

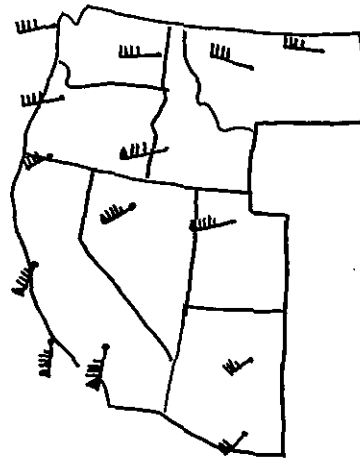
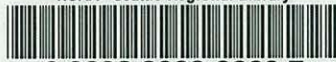


Figure 23. 200-mb winds in knots at 1200Z, September 10th.

Western Region Technical Memoranda: (Continued)

- No. 45/2 Precipitation Probabilities in the Western Region Associated with Spring 500-mb Map Types. Richard P. Augulis, January 1970. (Out of print.) (PB-189434)
- No. 45/3 Precipitation Probabilities in the Western Region Associated with Summer 500-mb Map Types. Richard P. Augulis, January 1970. (Out of print.) (PB-189414)
- No. 45/4 Precipitation Probabilities in the Western Region Associated with Fall 500-mb Map Types. Richard P. Augulis, January 1970. (Out of print.) (PB-189435)
- No. 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)
- No. 47 Statistical Analysis as a Flood Routing Tool. Robert J. C. Burnash, December 1969. (PB-188744)
- No. 48 Tsunami. Richard P. Augulis, February 1970. (PB-190157)
- No. 49 Predicting Precipitation Type. Robert J. C. Burnash and Floyd E. Hug, March 1970. (PB-190962)
- No. 50 Statistical Report on Aeroallergens (Pollens and Molds) Fort Huachuca, Arizona, 1969. Wayne S. Johnson, April 1970. (PB-191743)
- No. 51 Western Region Sea State and Surf Forecaster's Manual. Gordon C. Shields and Gerald B. Burdwell, July 1970. (PB-193102)
- No. 52 Sacramento Weather Radar Climatology. R. G. Pappas and C. M. Veliquette, July 1970. (PB-193347)
- No. 53 Experimental Air Quality Forecasts in the Sacramento Valley. Norman S. Benes, August 1970. (Out of print.) (PB-194128)
- No. 54 A Refinement of the Vorticity Field to Delineate Areas of Significant Precipitation. Barry B. Aronovitch, August 1970.
- No. 55 Application of the SSARR Model to a Basin Without Discharge Record. Vail Schermerhorn and Donald W. Kuehl, August 1970. (PB-194394)
- No. 56 Areal Coverage of Precipitation in Northwestern Utah. Philip Williams, Jr., and Werner J. Heck, September 1970. (PB-194389)
- No. 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)
- No. 58 Air Pollution by Jet Aircraft at Seattle-Tacoma Airport. Wallace R. Donaldson, October 1970. (COM-71-00017)
- No. 59 Application of P.E. Model Forecast Parameters to Local-Area Forecasting. Leonard W. Snellman, October 1970. (COM-71-00016)
- NOAA Technical Memoranda NWS
- No. 60 An Aid for Forecasting the Minimum Temperature at Medford, Oregon. Arthur W. Fritz, October 1970. (COM-71-00120)
- No. 61 Relationship of Wind Velocity and Stability to SO₂ Concentrations at Salt Lake City, Utah. Werner J. Heck, January 1971. (COM-71-00232)
- No. 62 Forecasting the Catalina Eddy. Arthur L. Eichelberger, February 1971. (COM-71-00223)
- No. 63 700-mb Warm Air Advection as a Forecasting Tool for Montana and Northern Idaho. Norris E. Woerner, February 1971. (COM-71-00349)
- No. 64 Wind and Weather Regimes at Great Falls, Montana. Warren B. Price, March 1971.
- No. 65 Climate of Sacramento, California. Wilbur E. Figgins, June 1971. (COM-71-00764)
- No. 66 A Preliminary Report on Correlation of ARTCC Radar Echoes and Precipitation. Wilbur K. Hall, June 1971. (COM-71-00829)
- No. 67 Precipitation Detection Probabilities by Los Angeles ARTC Radars. Dennis E. Ronne, July 1971. (Out of print.) (COM-71-00925)
- No. 68 A Survey of Marine Weather Requirements. Herbert P. Benner, July 1971. (Out of print.) (COM-71-00889)
- No. 69 National Weather Service Support to Soaring Activities. Ellis Burton, August 1971. (Out of print.) (COM-71-00956)
- No. 70 Predicting Inversion Depths and Temperature Influences in the Helena Valley. David E. Olsen, October 1971. (Out of print.) (COM-71-01037)
- No. 71 Western Region Synoptic Analysis-Problems and Methods. Philip Williams, Jr., February 1972. (COM-72-10433)
- No. 72 A Paradox Principle in the Prediction of Precipitation Type. Thomas J. Weitz, February 1972. (Out of print.) (COM-72-10432)
- No. 73 A Synoptic Climatology for Snowstorms in Northwestern Nevada. Bert L. Nelson, Paul M. Fransioli, and Clarence M. Sakamoto, February 1972. (Out of print.) (COM-72-10338)
- No. 74 Thunderstorms and Hail Days Probabilities in Nevada. Clarence M. Sakamoto, April 1972. (COM-72-10554)
- No. 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)
- No. 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)
- No. 77 A Study of Radar Echo Distribution in Arizona During July and August. John E. Hales, Jr., July 1972. (COM-72-11136)
- No. 78 Forecasting Precipitation at Bakersfield, California, Using Pressure Gradient Vectors. Earl T. Riddiough, July 1972. (COM-72-11146)
- No. 79 Climate of Stockton, California. Robert C. Nelson, July 1972. (COM-72-10920)
- No. 80 Estimation of Number of Days Above or Below Selected Temperatures. Clarence M. Sakamoto, October 1972. (COM-72-10021)
- No. 81 An Aid for Forecasting Summer Maximum Temperatures at Seattle, Washington. Edgar G. Johnson, November 1972. (COM-73-10150)
- No. 82 Flash Flood Forecasting and Warning Program in the Western Region. Philip Williams, Jr., Chester L. Glenn, and Roland L. Raetz, December 1972. (COM-73-10251)
- No. 83 A Comparison of Manual and Semiautomatic Methods of Digitizing Analog Wind Records. Glenn E. Rasch, March 1973. (COM-73-10669)
- No. 84 Southwestern United States Summer Monsoon Source--Gulf of Mexico or Pacific Ocean? John E. Hales, Jr., March 1973. (COM-73-10769)
- No. 85 Range of Radar Detection Associated with Precipitation Echoes of Given Heights by the WSR-57 at Missoula, Montana. Raymond Granger, April 1973. (COM-73-11030)
- No. 86 Conditional Probabilities for Sequences of Wet Days at Phoenix, Arizona. Paul C. Kangieser, June 1973. (COM-73-11264)
- No. 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)
- No. 88 A Surge of Maritime Tropical Air--Gulf of California to the Southwestern United States. Ira S. Brenner, July 1973.
- No. 89 Objective Forecast of Precipitation Over the Western Region of the United States. Julia N. Paegle and Larry P. Kierulff, September 1973. (COM-73-11946/3AS)
- No. 90 A Thunderstorm "Warm Wake" at Midland, Texas. Richard A. Wood, September 1973. (COM-73-11845/AS)
- No. 91 Arizona "Eddy" Tornadoes. Robert S. Ingram, October 1973. (COM-74-10465)



NOAA Technical Memoranda NWSWR: (Continued)

- No. 92 Smoke Management in the Willamette Valley. Earl M. Bates, May 1974. (COM-74-11277/AS)
- No. 93 An Operational Evaluation of 500-mb Type Stratified Regression Equations. Alexander E. MacDonald, June 1974. (COM-74-11407/AS)
- No. 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)
- No. 95 Climate of Flagstaff, Arizona. Paul W. Sorenson, August 1974. (COM-74-11678/AS)
- No. 96 Map Type Precipitation Probabilities for the Western Region. Glenn E. Rasch and Alexander E. MacDonald, February 1975. (COM-75-10428/AS)
- No. 97 Eastern Pacific Cut-off Low of April 21-28, 1974. William J. Alder and George R. Miller, January 1976. (PB-250-711/AS)
- No. 98 Study on a Significant Precipitation Episode in the Western United States. Ira S. Brenner, April 1975. (COM-75-10719/AS)
- No. 99 A Study of Flash Flood Susceptibility--A Basin in Southern Arizona. Gerald Williams, August 1975. (COM-75-11360/AS)
- No. 100 A Study of Flash-flood Occurrences at a Site versus Over a Forecast Zone. Gerald Williams, August 1975. (COM-75-11404/AS)
- No. 101 Digitized Eastern Pacific Tropical Cyclone Tracks. Robert A. Baum and Glenn E. Rasch, September 1975. (COM-75-11479/AS)
- No. 102 A Set of Rules for Forecasting Temperatures in Napa and Sonoma Counties. Wesley L. Tuft, October 1975. (PB-246-902/AS)
- No. 103 Application of the National Weather Service Flash-flood Program in the Western Region. Gerald Williams, January 1976. (PB-253-053/AS)
- No. 104 Objective Aids for Forecasting Minimum Temperatures at Reno, Nevada, During the Summer Months. Christopher D. Hill, January 1976. (PB252866/AS)
- No. 105 Forecasting the Mono Wind. Charles P. Ruscha, Jr., February 1976. (PB254650)
- No. 106 Use of MOS Forecast Parameters in Temperature Forecasting. John C. Plankinton, Jr., March 1976. (PB254649)
- No. 107 Map Types as Aid in Using MOS PoPs in Western U. S. Ira S. Brenner, August 1976. (PB259594)
- No. 108 Other Kinds of Wind Shear. Christopher D. Hill, August 1976. (PB260437/AS)
- No. 109 Forecasting North Winds in the Upper Sacramento Valley and Adjoining Forests. Christopher E. Fontana, September 1976.
- No. 110 Cool Inflow as a Weakening Influence on Eastern Pacific Tropical Cyclones. William J. Denney, November 1976.
- No. 111 Operational Forecasting Using Automated Guidance. Leonard W. Snellman, February 1977.
- No. 112 The MAN/MOS Program. Alexander E. MacDonald, February 1977.
- No. 113 Winter Season Minimum Temperature Formula for Bakersfield, California, Using Multiple Regression. Michael J. Oard, February 1977.

PROPERTY OF
 NOAA Library E/OC43
 7800 Sand Point Way NE
 Seattle WA 98115-5070