TROPICAL CYCLONE KATHLEEN

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ABSTRACT

Tropical Cyclone Kathleen moved through the western United States on 10-12 September 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 kt.

There have been three other signigicant 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 1200 GMT on the 9th; however, the intensity at landfall and the speed of movement were unusual. Kathleen moved in excess of 30 kt 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 its intensity unusually far north. Its 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 the intensity.

1. INTRODUCTION

Tropical Cyclone Kathleen moved through the western United States on 10-12 September 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 kt. 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 and the objective forecast guidance are presented. Fourth, the speed of movement of the storm is discussed in relationship to the upper level steering flow and the Fujiwhara (1923) effect. Finally, the intensity as related to Kathleen's speed of movement; sea-surface temperature patterns; advection of warm, moist air from the Gulf of California, and upper-level wind fields is discussed.

2. TROPICAL CYCLONE KATHLEEN

Kathleen began as a tropical disturbance 260 nm southwest of Acapulco, Mexico, 0000 GMT 6 September 1976 (Figure 1). Since the positions in Figure 1 are estimates of the location of the eye of the storm 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

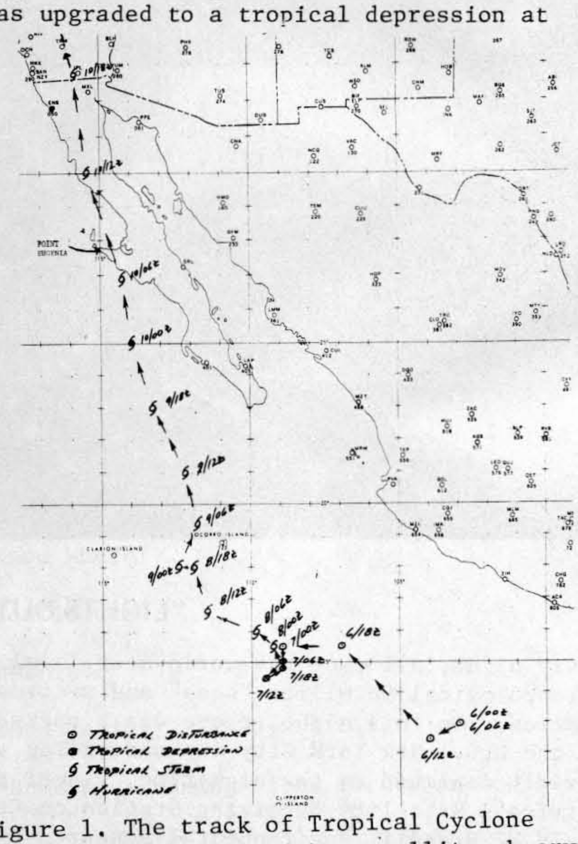


Figure 1. The track of Tropical Cyclone Kathleen as determined by satellite observations of the eye of the storm.

0600 GMT on the 7th when it was near 15°N, 109°W. Showing little movement, the winds were estimated at 35 kt by 0000 GMT on the 8th and the depression was upgraded to Tropical Storm Kathleen. Kathleen began its north-northwest track by 1200 GMT on the 8th. Winds on Socorro Island increased to 50 kt as Kathleen passed 50 nm west of the island at 0300 GMT on the 9th.

The storm was upgraded to hurricane intensity with winds estimated at 70 kt at 0000 GMT on the 10th. At 0046 GMT an Air Force reconnaissance aircraft located the center near 25.3°N, 114.8°W. 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 nm east of the center and were estimated to be 80 kt. This may be due to a funnelling effect caused by the terrain of Baja. A 98.6 kPa central pressure was reported. A second penetration (from the southwest) one hour later estimated maximum surface winds of 55 kt about 50nm west of the center. Heavy rain and turbulence were reported. This type of wind configuration is not unusual. Kathleen was downgraded to a tropical storm at 0600 GMT on the 10th.

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

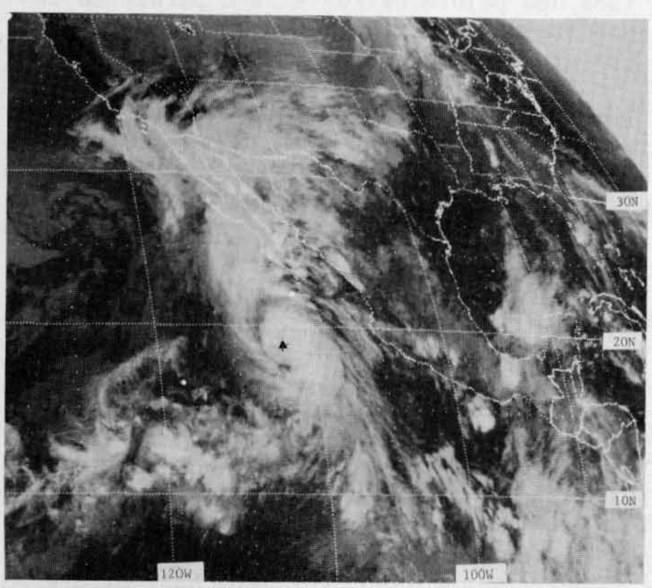


Figure 2. Two-mile, Infrared satellite data, 0415 GMT, 9 September 1976. Kathleen's approximate position indicated by ▲ .

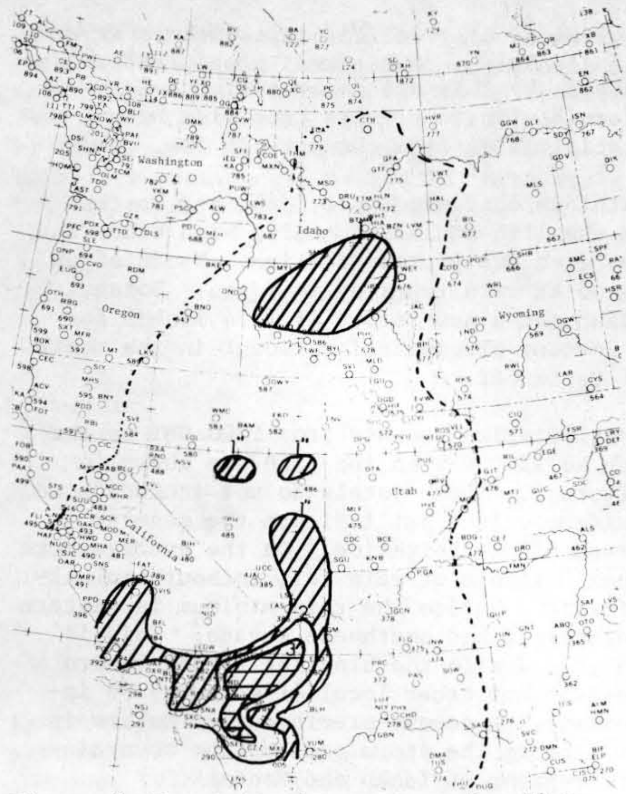


Figure 3. Precipitation pattern for 72-hr. period from 1200 GMT 9 Sept. to 1200 GMT 12 Sept. Contour interval is 1 inch.

Moving rapidly northward at 30 - 33 kt, Kathleen crossed the western tip of the Point Eugenia Peninsula and moved onshore 190 nm south of San Diego at 1130 GMT on the 10th. Kathleen crossed into southern California and was centered near Imperial, California, at 1800 GMT on the 10th. The storm continued its northward track and was located 120 nm southeast of Reno, Nevada, by 0600 GMT 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 9 September. 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 1800 GMT on the 10th, Imperial reported a surface pressure of 99.73 kPa. Yuma, Arizona, reported a wind gust of 66 kt. 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 45 kt 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 1200 GMT on the 9th to 1200 GMT 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 is largely due to the blocking by 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.

3. 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 Weather (1962)). Kathleen's track differs from all three previous storms. It should be noted that all four occurred in the month of September.

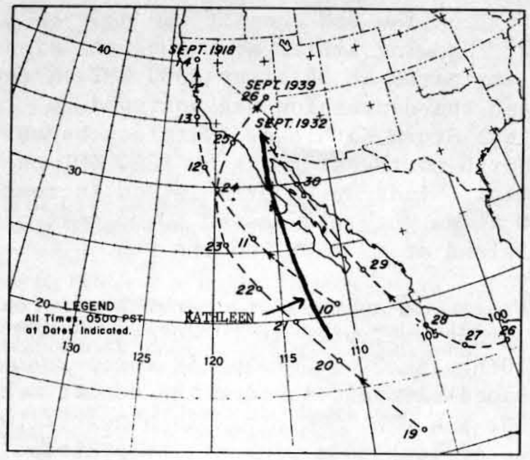


Figure 4. Tracks of three previous tropical cyclones that significantly affected the West Coast this century (Weaver, 1962) and Kathleen's.

a. Northern California Storm of 12 - 14 September 1918

This storm crossed the West Coast of the United States farther north than any tropical 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 18° - 19°C 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. On the morning of the 14th Red Bluff received 4.70 inches of rain in a three-hour period.

b. The Tehachapi Storm of 30 September 1932

This storm moved up the Gulf of California and weakened rapidly upon landfall. Rainfall from the upper circulation amounted to less than 0.5 inches 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 25 September 1939

The storm was reported to have a 97.1 kPa central pressure and 60 kt 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 kt winds and a central pressure of 99.8 kPa 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 19°C at Los Angeles and San Diego. Los Angeles received 5.42 inches of rain. Higher amounts were associated with terrain features with Mount Wilson receiving over 11 inches. In contrast to the 1918 storm, little convective activity was reported.

4. 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 accelerated north-northwest quite rapidly after 1800 GMT on the 9th reaching speeds of greater than 30 kt. 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 kt (Hansen, 1972). For the period since satellite data became available, Kathleen's rate of movement was record setting.

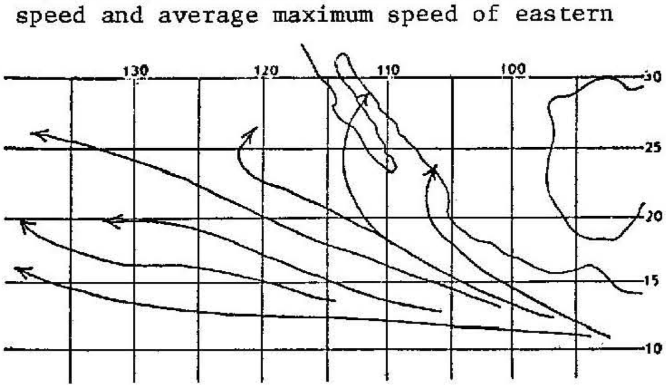


Figure 5. Mean Eastern Pacific tropical cyclone trajectories (Hansen, 1972).

TABLE I

SPEED	
Median	10.3 kt
Standard Deviation	3.0 kt
MAXIMUM SPEED	
Mean	13.4 kt
Standard Deviation	2.3 kt

b. Track

Eastern Pacific tropical storms either move westward or recurve into Mexico (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 1200 GMT on the 9th. From Kathleen's position at 1200 GMT on the 9th, there was a 71% chance (climatologically) that it would move to the north-northwest at 9 kt. The direction was correct but the speed was too slow. Farther north, climatology indicates a track that is more northerly and also higher speeds. This is verified well. Based on this climatology, sharp recurvature into Mexico 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 1200 GMT on the 9th.

5. 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 50 kPa forecasts valid at 1200 GMT on the 10th show flow from the south throughout the critical time when Kathleen was moving toward landfall (see Figure 8a - c). The verification for 1200 GMT 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 50 kPa forecast valid at 1200 GMT on the 11th do not show the cut-off low moving on to the California coast until the 11th (Figure 10a - c). The 50 kPa 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. There-

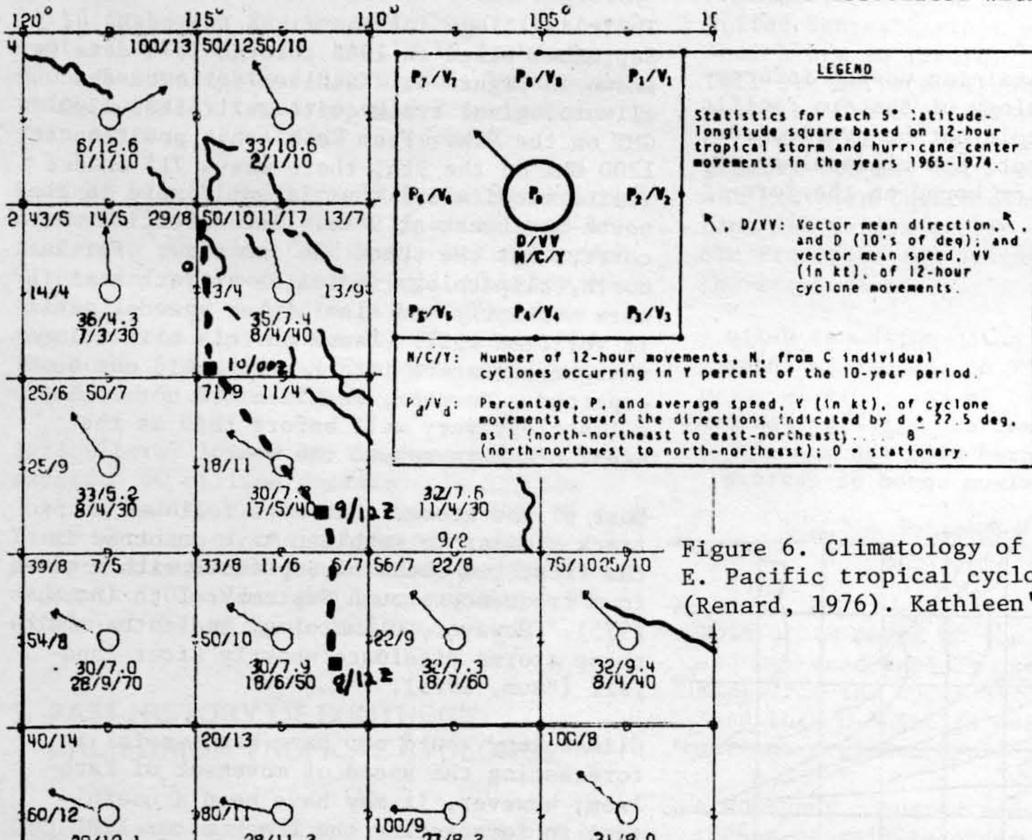


Figure 6. Climatology of 12-hr. movement of E. Pacific tropical cyclones, 1-15 September, (Renard, 1976). Kathleen's track, dashed.

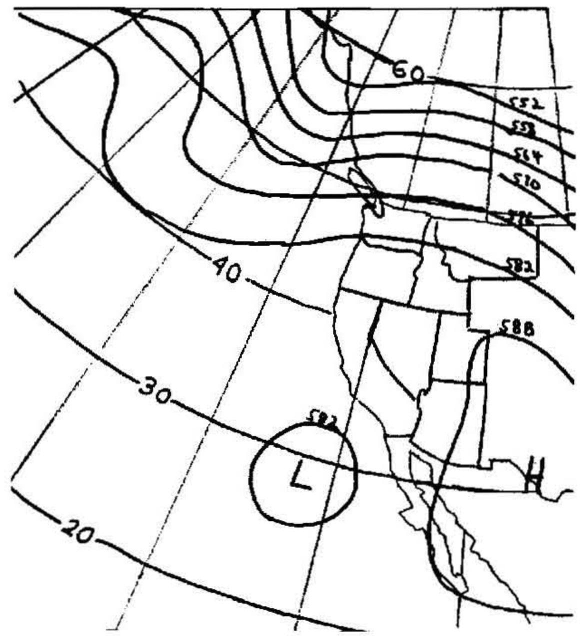


Figure 7. 50 kPa initial analysis for 0000 GMT 9 September 1976.

fore, they should not have significantly contributed to the error in the track forecast of Kathleen.

6. OBJECTIVE FORECAST GUIDANCE

a. 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 1200 GMT on the 9th is shown in Figure 11.

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 tract almost per-

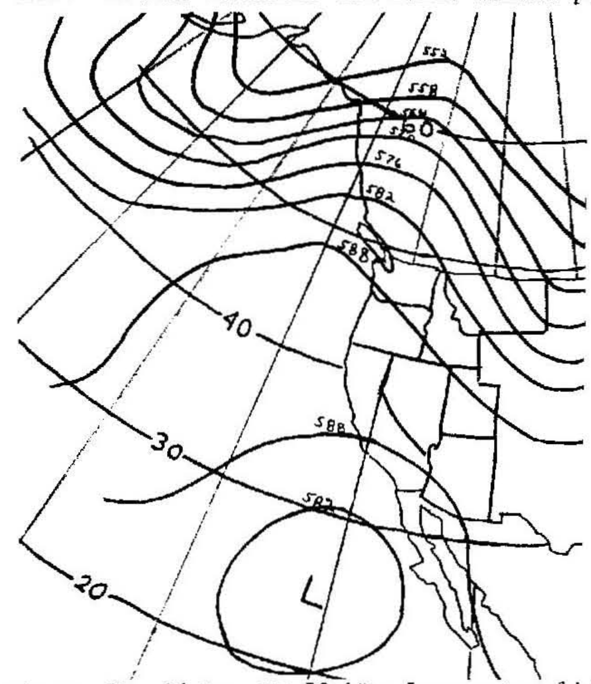


Figure 8b. 36-hr. PE 50 kPa forecast valid 1200 GMT, 10 September 1976.

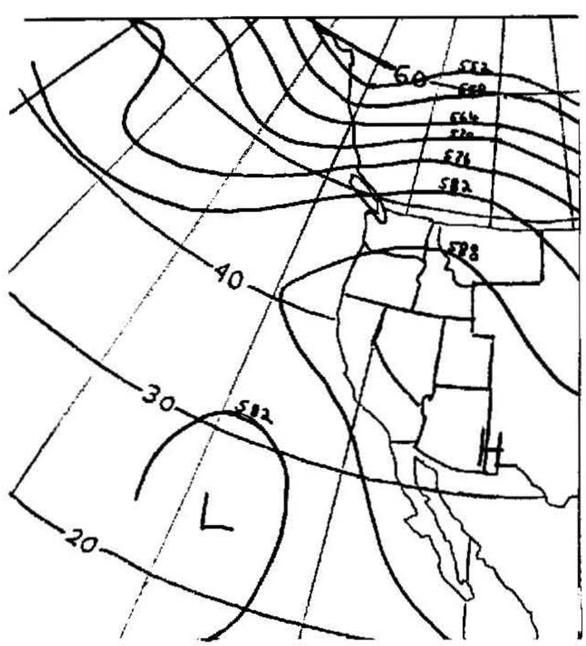


Figure 8a. 36-hr. Barotropic 50 kPa forecast valid 1200 GMT, 10 September 1976.

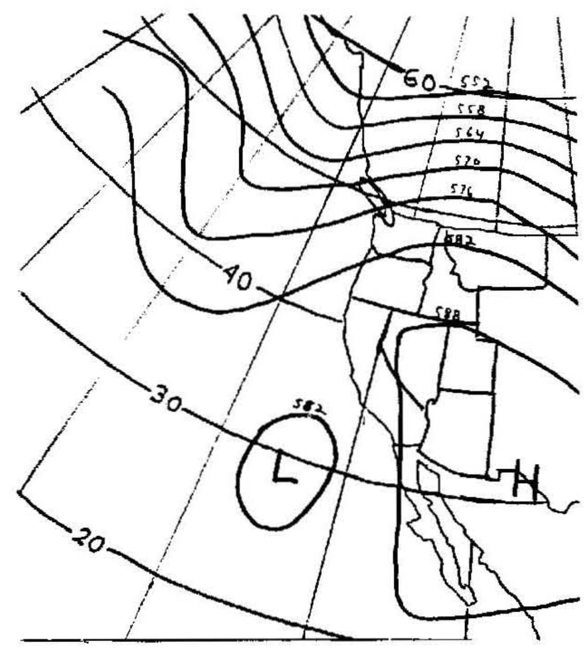


Figure 8c. 36-hr LFM 50 kPa forecast valid 1200GMT 10 September 1976.

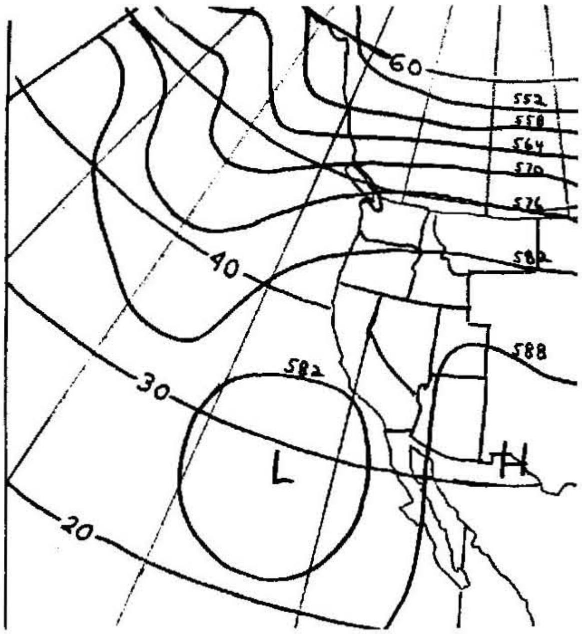


Figure 9. 50 kPa Analysis valid 1200 GMT 10 September 1976.

fectly 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 1200 GMT 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 speed; however, the MFM was still 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).

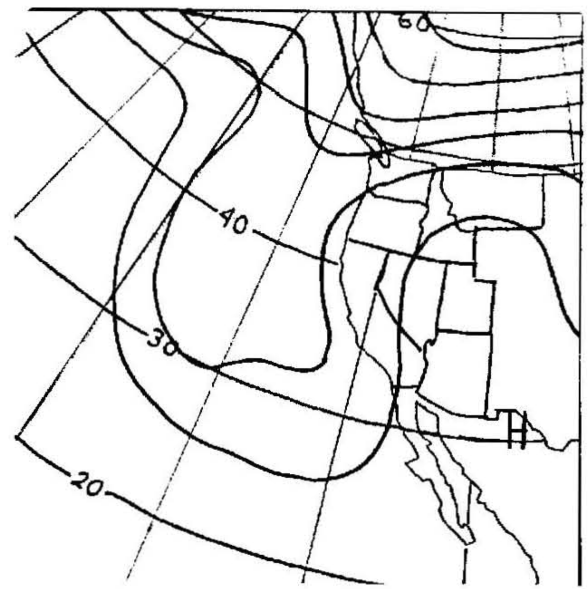


Figure 10b. 48-hr LFM 50 kPa forecast valid 1200 GMT on 11 September 1976.

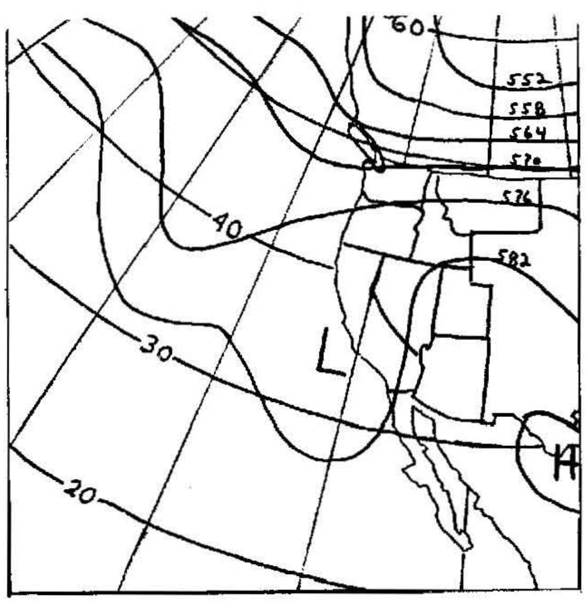


Figure 10a. 36-hr PE 50kPa forecast valid 1200 GMT on 11 September 1976.

Figure 10c. 50 kPa Analysis valid 1200 GMT on 11 September 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 1200 GMT on the 9th is also shown in Figure 11. Because of the peculiarities of eastern Pacific tropical storms and the relatively low number of recurving 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.

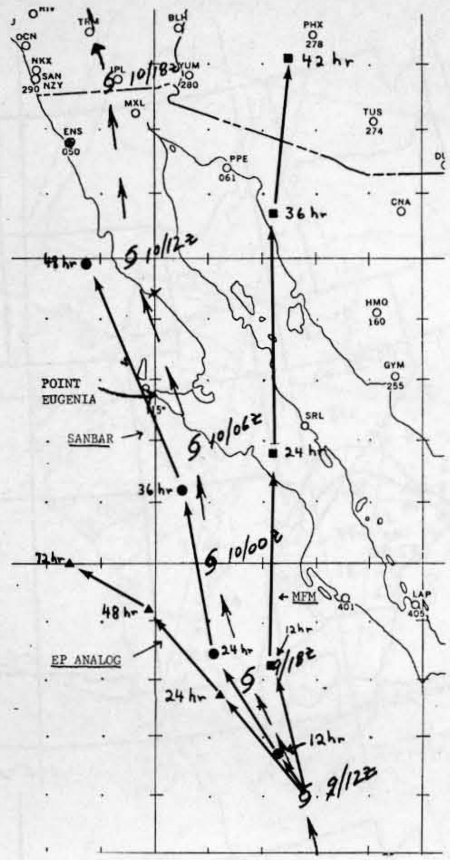


Figure 11. Objective track guidance provided by SANBAR (●), MFM (■), and EPANALOG (▲) based on data from 1200 GMT on the 9th.

b. Objective Precipitation Guidance

The MFM model was run in a precipitation mode based on data from 1200 GMT 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 is shown in Figures 12a - d.

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 are very misleading.

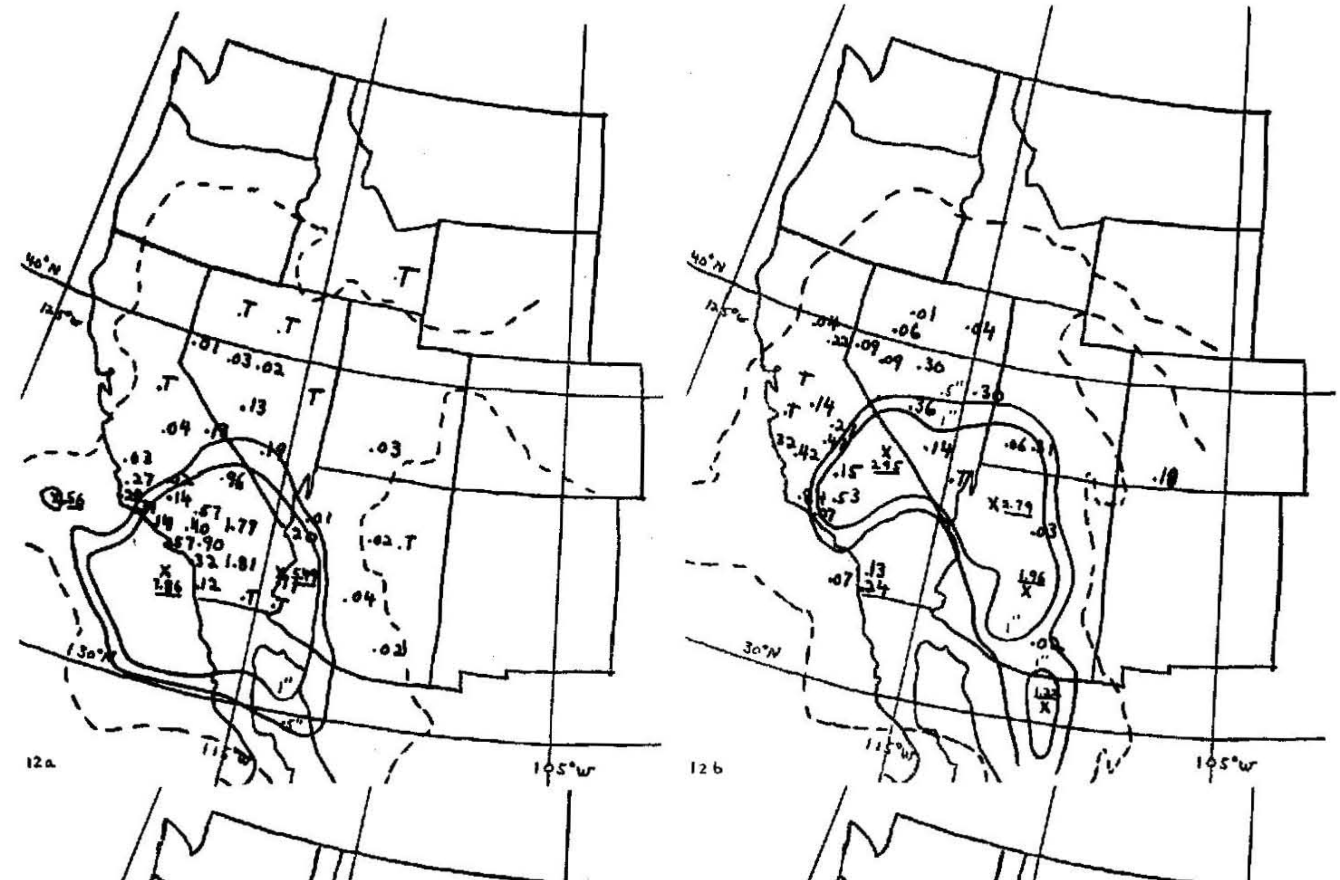
A more serious problem lies in the misleading forecast of where the precipitation would occur. The precipitation forecast for Arizona by 18 hours was completely erroneous. By 24 hours the MFM failed to forecast the precipitation associated with the cut-off low moving into California and the precipitation 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, since 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 Figures 13a - d. The observed 12-hour precipitation amounts are also shown.

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



Figures 12 a-d. (a) MFM forecast of precipitation amounts for 18 GMT the 10th to 00 GMT on the 11th. The .5 in. and 1" contours are shown. The dashed line indicates the general area of forecast precipitation; maximums marked by "x" and amounts underlined. Observed amounts are shown. (b) Same as 12a for period 00GMT to 06 GMT on the 11th. (c) Same as 12a for period 06 GMT to 12 GMT on the 11th. (d) Same as 12a for period 18 GMT on the 11th to 00 GMT on 12th.

Idaho that did verify 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.

Figures 13a-d. (a) Same as 12a for LFM forecast for period 12 GMT on the 10th to 00 GMT on the 11th. (b) Same as 13a for period 00 GMT to 12 GMT on the 11th. (c) Same as 13a for period 12 GMT on the 11th to 00 GMT on the 12th. (d) Same as 13a for period 00 GMT to 12 GMT on 12th.

7. 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, 100 kPa through 10 kPa, for the period of Kathleen is shown in Figures 14a - d. The deep layer mean wind is defined as:

$$V_d = (75V_{100} + 150V_{85} + 175V_{70} + 150V_{50} + 100V_{40} + 75V_{30} + 50V_{25} + 50V_{20} + 50V_{15} + 25V_{10}) /900.$$

The darkened symbol in Figure 14 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 it 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.

b. Fujiwhara Effect

Analyses and data like that shown in Figure 14 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 direction of movement.

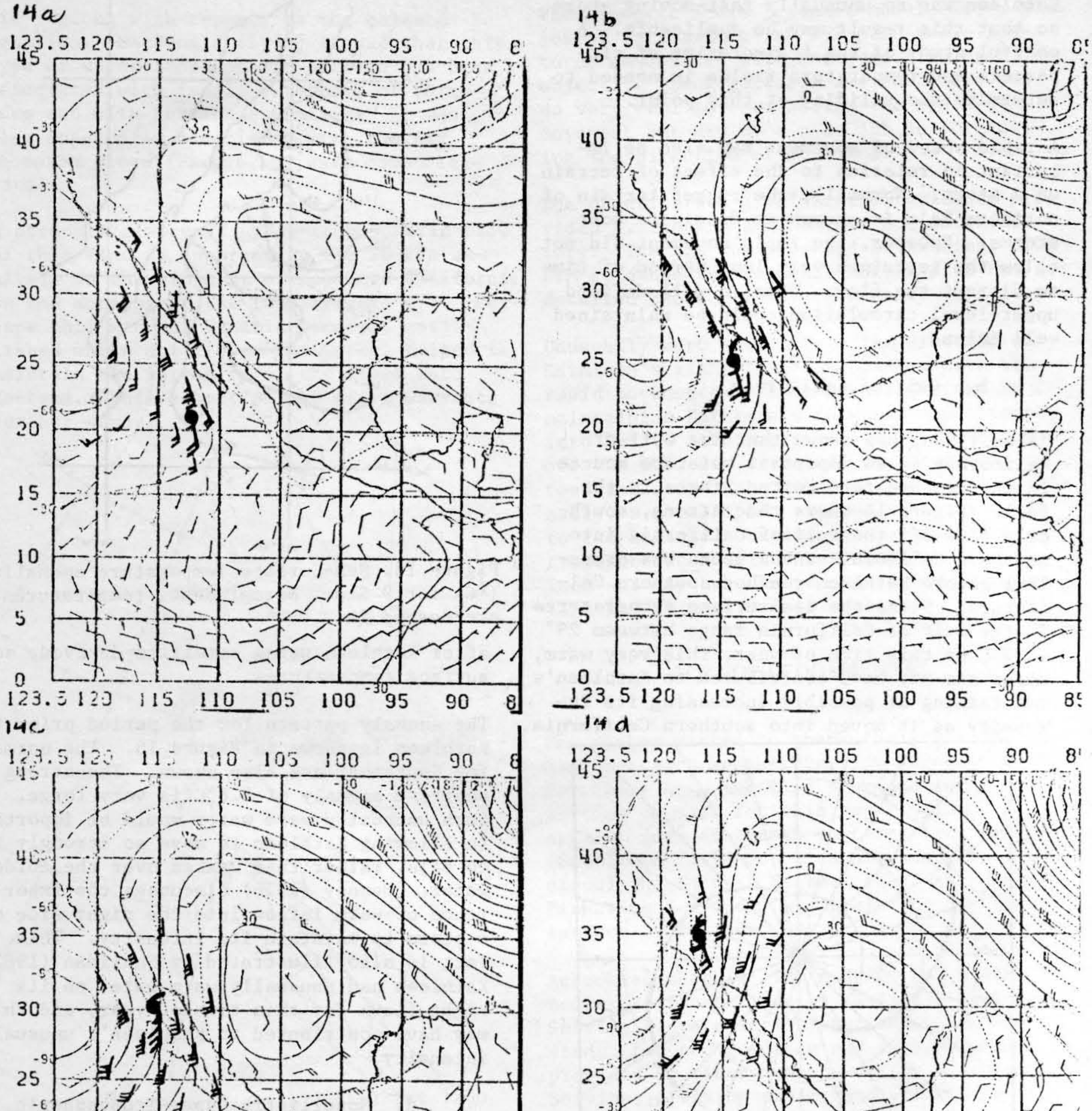
When two low-pressure centers come in close proximity (700 nm), they tend to interact and dumbbell about each other in what is called the Fujiwhara effect (Brand, 1970). In the case of Kathleen, there would appear to be an interaction between the cut-off low off the California coast and Kathleen resulting 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 15. 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. There is some scatter about the line but this can be explained by small errors in determining the position of the lows. 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.

8. 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 non-elliptic upper tropospheric flow.

a. Speed

Snellman (1961) has shown that tropical storms which move rapidly tend to decrease slowly in intensity while those that move 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 85 kPa 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 readily be entrained into the center of a slow-moving storm and weaken it.



Figures 14a-d. (a) Deep layer mean wind analysis valid 12 GMT on the 9th. Wind barbs at regular NMC Grid Points. Kathleen's position (§), and heavy wind barb attached is best track instantaneous storm motion. (b) Same as a for 00 GMT on the 10th. (c) Same as (a) for 12 GMT on the 10th. (d) Same as (a) for 00 GMT.

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 14 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 29° - 32°C at this time of year, this very warm, moist air may have contributed to Kathleen's maintaining or possibly increasing its intensity as it moved into southern California.

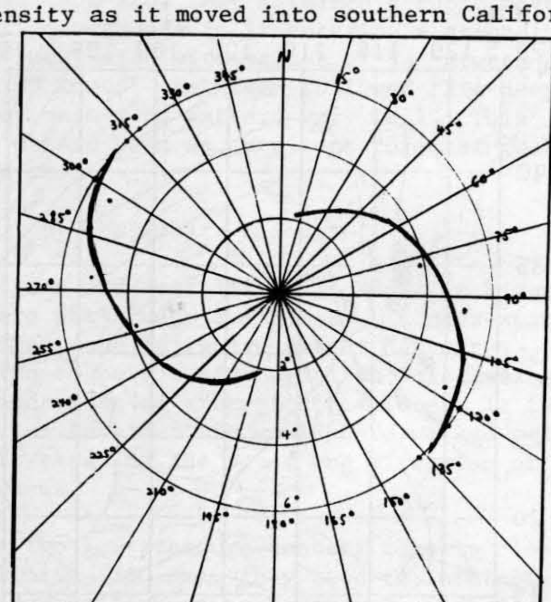


Figure 15. Plot of the relative positions of the cut-off low and Kathleen as described in the text. The radial distance is in degrees of latitude and angles in degrees based on true north.

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.

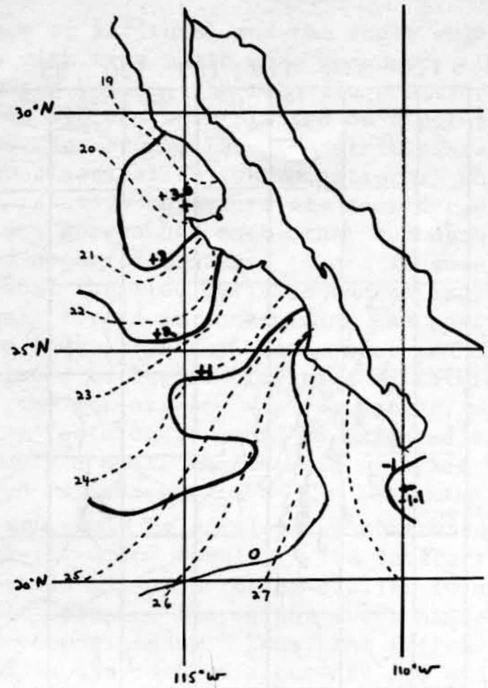


Figure 16. Sea-Surface Temperature anomalies (°C) for 9 Sept. Normal Sept. temperatures are dashed in.

The anomaly pattern for the period prior to Kathleen is shown in Figure 16. The normals for September are also shown. 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 its right flank for this time of year, and this may have contributed to Kathleen's unusual intensity.

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 20 kPa analysis in the vicinity of southern California on the morning of the 12th (Figure 17). 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.

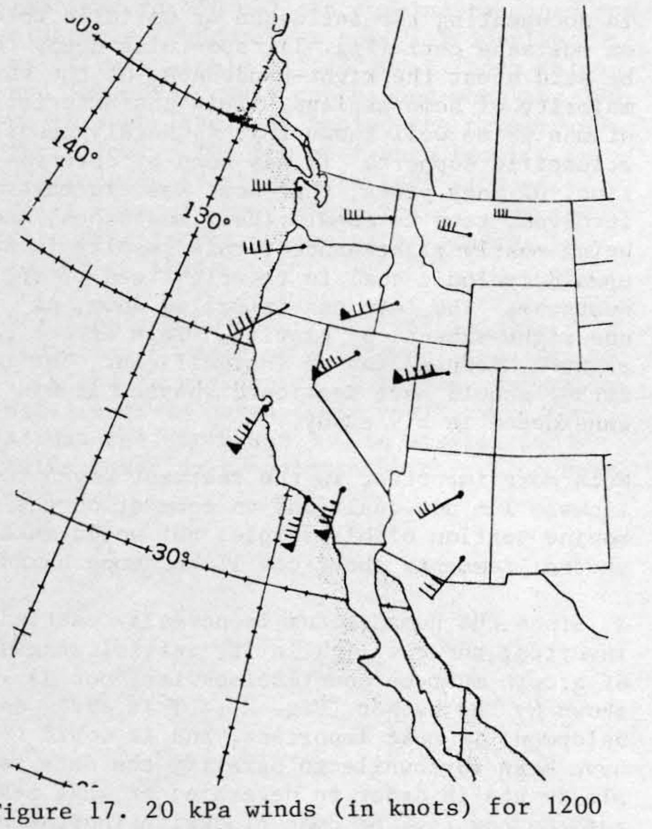


Figure 17. 20 kPa winds (in knots) for 1200 GMT on 10 September.

9. CONCLUSIONS

Kathleen was the most destructive tropical cyclone to strike the western United States this century. Kathleen's speed of movement was the most significant feature. This rapid acceleration and resulting high speed were 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 the 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.

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