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LARGE SCALE PATTERNS ASSOCIATED WITH MAJOR FREEZE EPISODES IN THE AGRICULTURAL SOUTHWEST

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Ronald S. Hamilton
National Weather Service Office (Ag)
Riverside, California

and

Glenn R. Lussky
Scientific Services Division
National Weather Service Western Region
Salt Lake City, Utah

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UNITED STATES DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary
/
National Oceanic and Atmospheric Administration
John V. Byrne, Administrator
/
National Weather Service
Richard E. Hallgren, Director

This publication has been reviewed
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Scientific Services Division,
Western Region.

Glenn E. Rasch

Glenn E. Rasch, Chief
Scientific Services Division
Western Region Headquarters
Salt Lake City, Utah

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I. INTRODUCTION

This Technical Memorandum is geared toward those who are responsible for forecasting minimum temperatures for growers of frost-sensitive agriculture. It is slanted toward forecasting in California, though the principles applied in this document may also apply to other Western Region locales as well. The primary goal of this paper is to get forecasters thinking about frost and to prepare them to forecast frost and freeze conditions before the winter months arrive.

Many offices are responsible for a variety of agricultural forecasts. Unfortunately, one often doesn't think about a possible frost or freeze until the event has nearly arrived. This is the situation that we must strive to prevent. The conditions which lead to frosts and freezes over the West (i.e., with a Gulf of Alaska ridge and a trough over the Rockies) may occur throughout the year. We, therefore, have the opportunity to recognize the developing large scale pattern associated with wintertime freezes throughout the year. In the summertime, this may mean cooler than normal temperatures. It is apparent that recognizing the signals which lead to colder than normal temperatures is not a seasonal venture. Studying the large scale patterns throughout the year is an important process, as it will better prepare us to recognize the potential for the first frost of the season. This, in turn will help the growers with greater advance warning.

Increasing the lead time with which we warn the growers of an impending frost or freeze is the greatest challenge that we now have in the field of agricultural forecasting. Aside from special cases, we are able to do an adequate job of forecasting the minimum freezing temperatures with a 12-24 hour lead time. However, the growers need this information well before this time frame. We must learn to identify synoptic and large scale patterns that may produce damaging freezes earlier. To do this, we will investigate the various large scale regimes which trigger cold air outbreaks in the western agricultural regions. We will also examine a number of the most severe West Coast freeze cases during the past 60 years, paying close attention to the evolution of the cold air over the West. Finally, we will review a checklist of possible indicators for freeze conditions or critical minimum temperatures. Hopefully, this paper will help prepare the forecasters to recognize, in advance, the situations which often lead to freezing conditions in the agricultural regions of the western United States.

II. DISCUSSION

A. Overview

The most important service we can provide growers of winter frost sensitive agriculture is advance warning of possible critical minimum temperatures. This means being able to understand which synoptic patterns have the potential for bringing significantly colder air southward into (mainly) California while these patterns are still in the developmental stage.

There are a number of features which are critical for the development of freezing temperatures in California, or for that matter, anywhere. These are:

1) low 1000-500 mb thicknesses,

2) low moisture content,

3) light surface wind speeds,

4) lack of nighttime cloud cover, and

5) location and depth of snow cover.

Low thickness values are the result of a deep layer of cold, dense air. They are generally a reflection of low 500 mb heights, high surface pressures, or both. The lowest thicknesses and coldest air are often associated with a combination of these two observations. This is not to say that low temperatures will only occur under these conditions. In fact, readings just below freezing will often occur in the interior California valleys under a strong upper level ridge. However, critical minimum readings will not occur under such a regime. On the contrary, a strong upper level ridge is considered to be one of the most favorable patterns by the growers.

Since 500 mb height fields and surface pressure fields are readily available on all of the extended range forecasts (out to 120 hrs), we have guidance which may suggest the potential development of very cold air masses. We can also attempt to determine, well ahead of time, the development of a significant upper level trough over the West by using conditional climatology (teleconnections). This can give us more than five days lead time on the potential movement of a cold air mass over the western United States.

Low moisture content is important, both in the air and on the ground, to create critical freezing temperatures. The temperature of a surface underlying moist low-level air will not cool very much, partly due to the excellent absorption of outgoing longwave radiation by atmospheric water vapor and partly due to the fact that the temperature can never be lower than the dew point temperature. There are two important considerations for forecasting low moisture levels well in advance. The most obvious relates to the upstream trajectory of the cold air mass. An upstream trajectory over water will add or maintain moisture in the air mass. For the Western Region, an upstream trajectory from the north or northeast will bring in much drier air. The second consideration is the amount of moisture on the ground or in the top layer of the soil. Available ground moisture may evaporate into a dry air mass, thus reducing the amount of radiational cooling.

Light surface and low-level wind speeds will help develop the nocturnal inversion. If winds are not light, turbulence will mix the low levels, creating a more isotropic vertical thermal structure. This does not appear to be a significant factor during extended periods of critical nighttime temperatures, since the air through the entire atmospheric column is very cold. However, during the more marginal freeze episodes, this feature becomes more important.

The extent of cloud cover, especially in the lower to mid levels of the troposphere, is also an important consideration. Water droplets, like water vapor, are very effective absorbers of terrestrial radiation and keep the earth's surface warmer when present.

The location and depth of snow cover is also critical for the development of significantly cold temperatures. The existence of snow cover upstream from your forecast area will enhance the cold air potential over your area (Namias, 1985). The temperatures at the low levels of the air mass - as it translates southward - will not moderate very much due to the radiative properties of the snow surface.

Most of these key features are basic to meteorological understanding. The difficult part is recognizing these features before they occur in order to provide an adequate lead time to the growers Many questions must be addressed, including:

1) What large scale developments, if any, are expected to occur during the forecast period?

2) Is the forecast pattern expected to have an overland or overwater trajectory?

3) What are the potential surface patterns with such an upper air flow? Is a cold, dry southward moving air mass possible?

The most difficult elements to forecast in the medium range (3 to 5 day) time scale are the low level winds and the cloud cover. It is, therefore, not reasonable to expect an accurate forecast of these parameters days in advance. As a result, it is probably best to initially assume that there will be clear skies and light winds during this period, effectively enhancing nighttime cooling. Any weather statement issued for this range should highlight the chance for freezing conditions within a certain number of days.

Assuming that the smaller scale conditions are ideal for maximum nighttime cooling, the three questions asked above can be answered by using the 500-mb forecast from the extended progs. Of course, it is not as simple as just looking at the progs and interpreting them. We should all realize how misleading they can be at times, especially in the extended range. Statistical and climatological studies may be useful in determining any possible errors in the extended progs. The use of teleconnections, known model biases, type maps, correlation studies and the prognostic map discussion (PMD) issued over AFOS by Western Region Headquarters/Scientific Services Division may be of great help to the forecaster and should be used as guidance on a daily basis.

B. Large Scale Patterns

There are basically three large scale upper level development patterns which should alert the forecaster that critical temperatures may occur in the near future. These are:

1) Development or intensification of a long wave ridge in the Gulf of Alaska,

2) retrogression (westward movement) of a central U.S. long wave trough toward the western U.S., and

3) the potential for split flow and formation of a closed or cut-off upper level low over the western United States.

Probably one of the best tipoffs toward the formation of an upper level trough over the West is the development or intensification of an upper level ridge in the Gulf of Alaska. Teleconnection charts (NOAA Technical Memorandum NWS WR-182, 1983) can be helpful in diagnosing this pattern change. Significant 500 mb positive anomalies at 140W/50N and 60N not only point to a high probability for negative height anomalies over the Rockies, but also depict a positive tilt to the positive and negative anomaly patterns. The positive tilt indicates the potential for more of an overland trajectory of the cold air push which is necessary for a hard freeze in the West. The long range progs will often give the forecaster an indication of such a ridge development in the Gulf of Alaska.

The retrogression of a central U.S. trough into the western U.S. is often accompanied by the building of a ridge in the Gulf of Alaska. Once again, a critical feature of this pattern development is the nature of the upstream flow - whether the upstream ridge builds strongly enough into northwestern Canada to cause an overland trajectory into the western U.S. out of the north. This retrogressive pattern is favorable for significantly cold minimum temperatures because the trough will generally be replacing a relatively dry ridge over the West. As a result, the soil moisture will generally be low over the region as the trough shifts westward. This, in turn, may act to enhance the cold temperatures as the trough develops over the West. This is especially true if the short waves which first "carve out" the long wave trough position over the West have an overland trajectory. It is important to note that in this pattern, the extended progs have often not been deep enough or far enough west with the retrograding trough. An example of this tendency occurred around the 20th of November 1983. The 96-hour spectral forecast suggested a change in the large scale pattern over the West from the ridge conditions which had been prevalent to an upper level low over North Dakota, with a trough extending southwestward through Arizona. Forecast heights over southern California were 5580 meters. The verifying pattern had the upper level low centered over Salt Lake City with a trough extending southwestward through southern California. Heights verified at 5440 meters over southern California.

The potential for a split to develop over the western U.S. can often 8be anticipated in the extended progs when the westerlies over the Pacific Ocean become strong and zonal with a long wave length between long wave troughs. The large scale is generally characterized by strong wave numbers two (2) and three (3), with the main trough locations in the winter climatological positions near Hudson Bay and over Siberia. This pattern will generally not bring a hard, widespread freeze over the West since the flow will not bring a cold, dry arctic air mass into the region. Additionally, this pattern will often contain enough moisture to prevent excessively cold temperatures from occurring. However, the cold air within the closed low of the southern branch of westerlies may be cold and dry enough to bring freezing conditions over localized areas.

These are the three main large scale patterns which result in the most damaging cold weather to the western agricultural regions. Since 1900, there have been four major (extended) freeze events in southern California (1913, 1922, 1937 and 1949). The general flow pattern of these events were all remarkably similar - with a deep upper level trough over the West and strong north to northeasterly (overland) flow of cold air into California. This pattern is most likely to develop when a strong ridge intensifies in the Gulf of Alaska. The development of this pattern appears to be critical for the occurrence of a major freeze. During the four events mentioned above, minimum temperatures in the upper teens to low twenties were common over California as far south as San Diego county, with isolated temperatures in the mid-teens. These temperatures even extended out to the coast, as low-level off-shore flow prevented an inland surge of the marine air mass. Critical nighttime temperatures persisted for over a week. These extended freeze events are often preceeded by snowfall down to unusually low elevations, followed by clearing and light winds. As a result, maximum temperatures over the freeze areas remain mostly in the 40s.

Since the retrograding trough pattern follows a relatively warm, dry regime over the West, there is generally not a great deal of snow cover over the lower elevations of California during the initial stages of the cold pattern. This may be one reason why the critical minimum temperatures associated with this pattern usually do not last as long as the extended freeze events mentioned above. More air mass modification takes place when more of the upstream ground lacks snow cover. This is not to say that the freezes are any less severe. One or two nights of temperatures in the lower 20s can do just as much agricultural damage as ten consecutive nights will do. Since this is generally a fairly dry pattern, clouds are not normally a major forecast problem.

A split flow in the eastern Pacific, with closed lows in the southwest U.S., can produce temperatures that are quite low in a few areas. Critical temperatures, however, are generally not as widespread throughout all districts as they are for the other freeze patterns. This pattern will generally contain enough moisture to prevent a widespread freeze. Compared to the retrogressive pattern, clouds can be more of a forecast problem in a split flow regime. The west side of the closed or cut-off low will often be the driest and the coldest. Critical temperatures will only last one or two nights. Mesoanalyses are very important in this regime as the area of cold, dry air is relatively narrow and can be difficult to analyze properly.

The medium range 500 mb progs, while often providing important information regarding the potential evolution of cold temperatures over the West, normally have trouble with the details of the short wave features and at times, will show remarkably different short wave patterns from one prog series to the next. The orientation of the large scale trough may also change from one prog series to the next. Generally speaking, these changes in the progs are improvements. As an example, suppose yesterday's 120-hour MRF forecast showed a weak trough dropping into the Western Region. Today's 96-hour prog shows a significantly stronger trough entering the region. This trough will more than likely verify as deep or deeper than the latest model run suggests. These trends are important and should always be checked on a daily basis.

It is equally important to know how the extended progs are verifying. Knowledge of a systematic bias in the model can be a great advantage when assessing the extended progs. Since the MRF became the main operational model beyond 72 hours early in 1985, the Western Region PMD noted, quite extensively, the biases of the model. This has been an important step in the evaluation of the trends suggested by the model.

Most importantly, to simply look at the extended (3 to 10 day) progs and issue a forecast based on a perfect prog is not an acceptable forecast service to the agricultural users. Forecasters should think first about the needs of the users in an effort to give them the best possible long range guidance upon which they can make their own important decisions.

There is one other set of long range forecast products which can be utilized in the forecast process. These are the surface and thickness charts. The extended range surface charts can reinforce one's viewpoint on the potential for cold air over the West.

An important key toward the development of cold air over the western U.S. is the existence of very cold air and a strong surface high pressure system over the interior portions of Alaska and northwestern Canada. If such an air mass exists, with a mechanism to transport the cold air southward to the west of the Rockies, then the potential for a freeze is greater. Movement of such an air mass basically requires the existence (or development) of a long wave trough over the western states with north to northwesterly flow over Canada into the southwestern states. This is the large scale upper level pattern which has already been discussed. Therefore, given this large scale pattern, along with a large mass of cold air in northern Canada (as evidenced by the high surface pressures), the forecaster must be aware of potentially damaging freezes.

This is essentially the large scale set-up that is necessary for critical freezes over the southwest. Following is a checklist which may be used as indicators for a potentially major freeze:

1) low 500 mb heights (less than 5500 meters) with the trough between 110W and 120W. Potential for this may be indicated by either:

a) the building of 500 mb heights near 55N/140-145W, or

b) a retrograding central U.S. trough.

2) an overland trajectory of the upper level flow, from the north or northeast out of Canada.

3) development of a cold air mass with high surface pressures over northwestern Canada.

If the extended range progs (or other guidance) suggest the potential for these features, freezing temperatures are a definite possibility in the near future. This potential should be highlighted in the agricultural forecast products.

As the event nears the 3-5 day range, the forecaster will hopefully have a handle on the potential for a freeze. His attention then should begin to shift toward the forecast details. Of these details, the track and location of the surface high center is very important. Figure 1 shows the surface high tracks for five significant California freezes in the early 1900s. The tracks are very similar, originating over northwestern Canada and moving south-southeastward over southern Idaho. Central pressures over southern Idaho ranged from 1030 to 1048 mbs for these freezes, with an average of 1037 mbs. Surface lows always precede the arctic air push, as indicated for eight cases in Figure 2. These are not quite as clustered as the surface high locations, indicating that the cold air push is less dependent on the exact location and movement of this feature. The mean track of the surface lows follows a path from near Washington state, through central Utah and near the Colorado/New Mexico border. The low pressure center generally intensifies as it moves through central or southern Utah (near the base of the long wave trough). The location of these lows, when coupled with the Great Basin highs, creates a synoptic pattern which maintains the off-shore flow necessary to keep the cold, dry air over the agricultural areas. These surface systems are obviously associated with upper level short waves which move through the long wave trough over the West. Their directional movement is probably quite representative of the mean upper level flow for these dates.

If the flow pattern is highly meridional (a necessity in order to have strong northerly flow out of Canada into the West), the large scale pattern may dominate the weather, especially in terms of temperature. The propagating short waves will act only to modify the temperatures in the cold pattern. This is evident when examining the surface maps from January 1-11, 1949, a major period of freezing temperatures in southern California with a long wave trough over the West. Table 1 shows the range of temperatures over three California counties during this period, along with the surface pressures at eight Western Region locations. (The locations of the counties listed in Tables 1 and 2 are shown in Figure 3). The two coldest mornings were the 4th and 5th. These were the dates during which the strong high was building in over the Great Basin, as shown by the station pressures. In particular, the surface pressures were highest over Boise and Salt Lake City on these dates. Even though a weak short wave trough passed through the Western Region long wave trough (evidenced in the surface pressure drop during the 7th through 9th), the temperatures remained critical, probably due to the orientation and strength of the long wave trough. In addition to increased persistence of cold air with highly meridional flow, modification of the southward moving cold air mass will decrease the more rapidly the air mass moves southward. Strong meridional flow will enhance this effect.

Rapid movement of the surface high will generally be evident from the surface pressure tendencies. It is important to monitor these tendencies for two reasons. First, the more rapidly the pressure rises, the more rapidly the system (and cold air) is moving in. Secondly, if strong positive tendencies are located west of the Rockies, you can be more sure that the high is settling in over the Great Basin. If the strongest pressure rises are east of the Rockies, the highest pressures (and coldest air) will likely stay east of the mountains, preventing a major freeze in southern California.

The discussion above presents some of the basics on using the extended progs to help forecast the intrusion of cold air into the agricultural southwest. There are also many new research papers which link large scale developments to other hemispheric or global features. One of these influences appears to be the sea surface temperature (SST) and outgoing longwave radiation (OLR) patterns over the tropics and the oceans. Weickmann, Lussky and Kutzbach (1985) have used cross-spectral analysis to relate large fluctuations in the winter equatorial Pacific OLR and global circulation features. One thing that stands out in the paper is that there are some very strong relationships between propagating equatorial cloudiness (implied from the OLR) and mid-latitude circulation features over the Northern Hemisphere. Their figures 9c and 10a (reprinted as Figures A1 and A2 at the end of this paper) both make strong suggestions that there is a direct relationship between enhanced cloudiness near 10S/160W and an upper level ridge/trough anomaly couplet in the Gulf of Alaska and southwestern U.S., respectively, with anomalous upper level northeasterly flow into the southwest. They also note that while the OLR anomalies are not entirely predictable, they do follow a general progression which occurs with a degree of regularity. Thus, a forecaster may eventually be able to imply the Gulf of Alaska ridge development up to 10 or more days in advance by tracking the tropical OLR anomalies. (This assumes that the study is indeed applicable and that the data are made available to the forecasters).

There are also indications that 500 mb surface heights in the vicinity of Hawaii may be related climatologically to critical freezing conditions and major freeze episodes over southern California. An unpublished report by Lawn and Pareens (1957) indicates that when a 500 mb low develops near Hawaii, a relatively strong meridional flow pattern - with upper level ridge development in the Gulf of Alaska and trough development over the West - will occur within about 48 hours. They also suggest that the stronger the Hawaiian trough, the stronger the downstream development will be; in other words, more highly amplified flow across the eastern Pacific and western U.S. occurs, resulting in colder temperatures for the southwestern states. It must be emphasized here that the results and implications of this study have not been tested for statistical significance. Nevertheless, they may still be of some use to the forecaster as guidance for potential freeze patterns.

Correlation studies such as this may yield important clues on the potential to forecast significant weather changes with increased advance warning. The forecasters should make every effort to move foreward in the utilization of these studies. Considering the difficulty in obtaining skillful model forecasts beyond 5 days, utilization of climatological research may be the best (and quickest) way to improve our forecasting abilities beyond the 5 day time scale.

III. CASE STUDIES

Table 2 documents the temperatures found in a number of California counties during five freeze cases. It is apparent that the first four of the cases were associated with a large scale trough pattern over the West due to the length of time between the first and final significant widespread freeze (from 9 to 19 days). The cases of 1937 and 1924 each have a five day break in them, probably indicating a temporary break in the large scale pattern before the trough became reestablished over the Rockies. The 1949 and 1922 cases show freezing temperatures for nearly 10 consecutive days. The 1978 case is an example where large scale trough development was not a key factor in the occurrence of critical temperatures. We will examine the surface maps for the 1937 and 1924 cases as examples of the progression of surface pressure patterns over the West. We will also look at the surface and 500 mb maps for the 1978 case.

A. January 18-25, 1937

The surface analyses for each date of this case are found in Figures 4a-h. All analyses are valid during the evening hours (probably around 00Z) of the stated date. You may have noticed in Table 2 that freezing temperatures had also occurred over southern California during the previous week. This set of maps shows the surface analyses following what was probably the reestablishment of the long wave trough over the west.

At the beginning of the map series, a precedent surface low is seen over eastern Nevada. Northerly winds around the west side of the low are pulling cold air southward out of Canada. The center of the low was near 1000 mb (pressure on the surface maps for the 1937 and 1924 cases are given in inches of mercury - use Table 3 to convert to millibars). The cold dome of high pressure is seen well north in Canada with a central pressure near 1043 mb. Note from Table 2 that freezing temperatures had already returned under the low level northerly flow the previous morning. This indicates that under a strong large scale trough over the west, freezing temperatures may occur even before the surface high has begun to build over the Great Basin. Figures 4b and 4c show the trough exiting the region through southern Utah and New Mexico, with the high building in over the northwestern states. Minimum temperatures over southern California remained in the freezing range, with slight cooling overall during the two days. Over the next few days (from the 21st through the 24th), the high center settled over southwestern Idaho and northeastern Nevada. It was during the mornings of each of these four days that the most critical temperatures occurred, with most readings from the upper teens to the lower 20s. The surface map for the evening of the 24th (Figure 4g) shows that a strong low has finally developed over the west coast of British Columbia. As the feature moved southward, warmer and more moist air gradually replaced the cold, dry air over the West. The freezing temperatures remained over southern California through the morning after Figure 4h (the 26th), as the surface high was still the dominant feature over that area. However, the low pressure pushed southward on the 26th, becoming the dominant weather feature and helping to keep the temperatures up on the morning of the 27th (therefore not included on the list in Table 2).

B. December 18-27, 1924

The surface pressure fields for this case are shown in Figures 5a-h (excluding the 20th and 21st). Table 2 shows that temperatures were mainly in the mid to upper 20s on the 18th and 19th. They then were above freezing for a few days, dropping back down into the upper 20s by the 24th. The hard freeze hit from the 25th through the 27th. The surface maps show us why this sequence occurred.

On the mornings of the 18th and 19th (Figures 5a,b), a strong, cold high pressure system built in over the western states. The precedent low is seen exiting the region to the southeast on the 18th. Temperatures, however, did not get too extreme over southern California. This is probably because the surface high did not build in as far southwest as has been shown to appear to be necessary (i.e.- over southwest Idaho). Instead, the high shifted southeastward out of northern Idaho into northwestern Wyoming. Southern California thus escaped the strong cold push.

A short wave trough undoubtedly moved through the West during the next couple of days. Surface low pressure associated with this trough moderated the temperatures. On the 22nd, the surface pressure pattern (Figure 5c) showed low pressure dominating the West with a center over the Great Basin. This low moved to the southeast over the next 36 hours as a strong high again built in behind it. Temperatures on the morning of the 23rd were not yet critical, just edging the freezing mark. Dew point observations indicated that there was still quite a bit of moisture in southern California. Even on the morning of the 24th, temperatures were still generally in the upper 20s. The surface ridge built in strongly over the Great Basin during the day on the 24th (Figure 5e), with its center now in southwestern Idaho. Temperatures were generally in the low 20s for the next three mornings as the ridge maintained its location and intensity (Figures 5f,g). On the 27th, a short wave trough approached the northwest states, weakening the ridge. That night, temperatures were no longer critical.

These two examples have illustrated the surface patterns often associated with freezing temperatures over southern California. They also show how critical the location of the surface high is with respect to the intensity of the cold push into the southwest. These were two cases where the push of cold, dry air was mainly directed by the set-up of the large scale ridge/trough couplet over the Gulf of Alaska and the Rockies, respectively.

C. December 7-8, 1978

In contrast to the previous two cases, the following is one where the large scale was not stable, but rather was apparently evolutionary. In light of this fact, it is not surprising that this is also a case where the significant freezing temperatures lasted only two days even though readings dropped into the upper teens in a few locales.

The sequence of surface pressure analyses is shown in Figures 6a-f, beginning on the morning of the 4th and ending on the morning of the 9th. This sequence shows a strikingly different progression of the cold dome of high pressure into the western states. The movement/development of the precedent trough, however, would be representative of those shown in Figure 1.

Figures 7a-f are the 500 mb analyses valid at the same time as the corresponding surface charts in Figure 6. The upper air pattern on the 6th (Figure 7c) shows a very similar pattern to those seen in the previous cases. However, the patterns on the 4th and the 9th suggest that this was not a long term large scale feature as the other cases were. Let's look a little closer at this case.

On the 4th (Figures 6a and 7a), surface high pressure dominated in the eastern Pacific and into the southwestern states. No significant high pressure center was evident in northwestern Canada. A weak trough was evident over the northwestern states, associated with a 500 mb trough in the northeast Pacific. 500 mb temperatures associated with this system were quite cold at less than -35 C. The large scale pattern shows an apparent long wave trough in the central U.S., with a short wave ejecting to the east. By the morning of the 5th, the 500 mb short wave in the Gulf of Alaska (Figure 7b) had dropped sharply over the western states, while the heights behind it rose dramatically. These developments were also reflected at the surface (Figure 6b), as a low pressure center had developed over Colorado with a trough extending westward to a secondary low near southwestern Utah. Pressures over northwestern Canada had also begun to rise, though the pattern still did not resemble that expected for a major freeze. Highest pressures were located over the northeast Pacific at over 1040 mb. By the next morning, the upper level flow (Figure 7c) had become much more meridional, with a very intense ridge over the Gulf of Alaska and nearly northerly flow from northwestern Canada into the base of the short wave trough located over the southwestern states. At the surface, the low center was located along the Arizona/New Mexico border with the surface ridge building into northwest Canada.

During the 7th and 8th (Figures 6d, 6e, 7d and 7e), the upper level trough moved slowly eastward as the cold air moved southward. The surface high dropped south-southeastward and strengthened, from a 1033 center on the 7th to a 1037 center on the 8th. On the 8th, the center was located over northern Nevada, approximately the ideal location for a cold push into southern California. Not surprisingly, these were the coldest mornings of this case. By the 9th (Figures 6f and 7f), a weak upper level short wave ridge had moved over the western states as the trough progressed over the southcentral Plains. Though not shown on Table 2, temperatures slightly below freezing did occur over portions of California as surface pressures remained quite high. At this time, however, there was one strong indication that the cold temperatures would not last much longer - this being the strong upper level trough development over the Gulf of Alaska. Indeed, during the next two weeks, this Gulf of Alaska trough tendency would keep the southwestern U.S. under, at worst, northwesterly flow. A Gulf of Alaska trough virtually assures that no polar outbreak will occur over the winter agricultural southwest.

There are a number of points to make regarding this case.

1) While this wasn't a long-lasting freeze, it was just as dangerous to the crops as the others discussed previously. Simply put, a one-day freeze can do just as much damage as an extended freeze.

2) Though the long wave trough may seem to be too far east to affect the southwest with cold air, a strong short wave may drop in farther west than the previous ones had done.

3) The surface high need not be over northwestern Canada very long before dropping southward over the western states. In this case, there was no strong evidence of a cold dome of high pressure building in northwestern Canada. Even so, critical temperatures developed over the southwest quite rapidly as high pressure built in from the Pacific behind the strong short wave trough.

Developments such as this are just as important to forecast as are the major, extended freeze cases like those discussed earlier. These cases in fact are more difficult to forecast, particularly with any amount of lead time. Their potential is not always well advertized. They, therefore, require greater attention by the forecaster. It is apparent that we must look at as much detail as possible when determining the potential for critical temperatures. A large scale analysis will not always be sufficient. Every situation requires careful scrutiny and important indicators must be checked daily. If the forecaster becomes apathetic and misses some significant information, this may result in a 24 hour loss of lead time to the growers. It is our job to see that this does not happen.

IV. SUMMARY

The authors hope that the discussion and cases presented will give the reader a better idea regarding some of the important large and small scale features to look for when forecasting critical temperatures. The following is a brief checklist of atmospheric conditions which are pertinent to a major freeze over southern California.

1) Disappearance of the Gulf of Alaska trough and subsequent upper level ridging extending into northwestern Canada.

2) Surface high pressure building over northwestern Canada.

3) Increasing flow out of the north along the Pacific coast states.

4) Potential for an overland trajectory of pressure systems into the southwestern states.

5) A surface high pressure center moving through eastern Washington toward southern Idaho.

6) Central pressures in the high greater than 1030 mbs over southwestern Idaho.

7) Surface pressures over southwestern California greater than 1016 mbs and rising.

These are by no means to be considered the final or the only conditions to examine routinely. As illustated by the December 1978 case, temporary, yet significant, freezes may occur with strong, cold short wave troughs.

Additionally, there is much more that could be done to improve the mesoscale analysis necessary to more accurately forecast the minimum temperatures on a short-term basis. Local rules of thumb could and should be developed regarding surface pressures, thicknesses, 500 mb heights, 700 mb heights and temperatures, winds, cloud cover and so on as they each relate to the local minimum temperatures. In the end, there is plenty of room for improvement in the forecasting of all time and space scales. Research studies at each scale will be necessary in an effort to improve our services to those concerned with critical minimum temperatures.

V. REFERENCES

[1] Lawn, G.W. and F.J. Pareens, Jr., 1957: "A Study of Circulation Patterns Associated with Cold Weather in California", Pacific Gas and Electric Company, 10 pp.

[2] Namias, J., 1985: "Some Empirical Evidence for the Influence of Snow Cover on Temperature and Precipitation", Monthly Weather Review, 113, 1542-1553.

[3] NOAA Technical Memorandum NWS WR-182, 1983: "500 Millibar Sign Frequency Teleconnection Charts - Winter", Salt Lake City, Utah.

[4] Weickmann, K.M., G.R. Lussky and J.E. Kutzbach, 1985: "Intraseasonal (30-60 Day) Fluctuations of Outgoing Longwave Radiation and 250 mb Stream-function during Northern Winter", Monthly Weather Review, 113, 941-961.

TABLE 1

A comparison between regional surface pressures and California minimum temperatures for January 1949.

	Range of minimum temperatures			Station pressures (tenths of mbs with leading 10 omitted)							
	County			Station							
1949	Butte	Riverside	San Diego	SEA	BOI	GTF	SLC	PDX	RNO	SFO	LAX
1- 3	26/30	19/25	23/27	356	308	376	264	252	241	234	183
1- 4	22/28	26/36	19/27	315	359	280	339	322	324	281	230
1- 5	21/22	20/25	19/26	322	447	240	437	356	340	281	230
1- 6	27/28	27/32	24/28	240	413	159	426	288	356	230	176
1- 7	27/27	26/30	25/29	163	146	026	212	207	186	123	159
1- 8	26/28	24/27	26/30	288	210	261	176	261	140	142	120
1- 9	22/26	18/26	32/38	362	264	420	180	345	193	152	098
1-10	23/27	23/30	32/35	345	321	406	230	335	227	173	146
1-11	27/32	20/27	28/30	321	376	420	291	298	268	173	115

Station Locations:

SEA - Seattle, Washington
BOI - Boise, Idaho
GTF - Great Falls, Montana
SLC - Salt Lake City, Utah
PDX - Portland, Oregon
RNO - Reno, Nevada
SFO - San Francisco, California
LAX - Los Angeles, California

TABLE 2

Reported minimum temperature ranges over the agricultural areas of the counties

Date	Los Angeles	Orange	Ventura	River- side	San Bern.	San Diego	Fresno	Tulare	Butte
				County					
1- 8-37	24/27	26/32	25/32	25/30	26/30				
1- 9-37	22/25	24/32	21/32	20/25	21/25				
1-10-37	24/27	24/28	20/30	19/27	20/27				
1-11-37	25/27	26/28	22/29	21/26	22/26				
1-18-37	26/30	27/29	27/32	24/30	25/29				
1-19-37	26/29	27/30	26/32	23/27	24/27				
1-20-37	25/26	25/27	22/27	21/26	22/25				
1-21-37	22/24	26/30	21/28	21/26	22/26				
1-22-37	22/24	22/24	18/25	18/24	17/23				
1-23-37	22/24	22/25	22/30	20/24	19/23				
1-24-37	24/27	25/27	22/26	18/24	16/24				
1-25-37	26/28	27/28	25/28	23/26	24/26				
1-26-37	25/28	25/27	22/27	21/26	20/25				
1- 3-49	22/25	24/32	24/32	19/25	28/32	23/27		24/27	26/30
1- 4-49	21/24	22/32	22/32	16/26	17/26	19/27		19/25	22/28
1- 5-49	22/27	21/25	24/32	20/25	21/24	19/26		18/23	21/22
1- 6-49	24/32	26/30	26/32	27/32	28/32	24/28		20/23	27/28
1- 7-49	26/30	26/32	29/32	26/30	27/30	25/29		22/28	27/27
1- 8-49	25/28	27/32	25/30	24/27	25/27	26/30		24/28	26/28
1-10-49	26/28	24/28	22/28	18/26	19/26	32/38		18/22	22/26
1-11-49	30/32	30/32	24/32	23/30	24/29	32/35		18/20	23/27
1-12-49	25/28	26/30	15/30	20/27	21/27	28/30		18/21	27/32
1-20-22	18/24				19/22				
1-21-22	18/23				20/23				
1-22-22	22/25				20/24				
1-23-22	22/26				24/26				
1-24-22	23/26				23/27				
1-25-22	23/26				23/27				
1-26-22	24/26				27/30				
1-27-22	24/27				26/29				
1-28-22	25/28				26/29				
12-18-24	26/28	27/29	25/27	26/28	27/28				
12-19-24	26/28	28/30	25/28	24/26	25/26				
12-23-24			29	32					
12-24-24				27					
12-25-24	23/25	23/29	21/25	20/24	20/23				
12-26-24	23/26	22/25	21/28	23/26	23/26				
12-27-24	23/26	23/28	23/29	23/27	22/26				
12- 7-78			22/28		20/27	21/28	22/26	22/25	24/26
12- 8-78			23/30		19/27	19/27	22/27	21/24	23/27

TABLE 3

Pressure conversion table between inches of mercury and millibars where 1" Hg = 33.86389 mb

" Hg	mb
29.4	995.6
29.6	1002.4
29.8	1009.1
30.0	1015.9
30.2	1022.7
30.4	1029.5
30.6	1036.2
30.8	1043.0
31.0	1049.8
31.2	1056.6

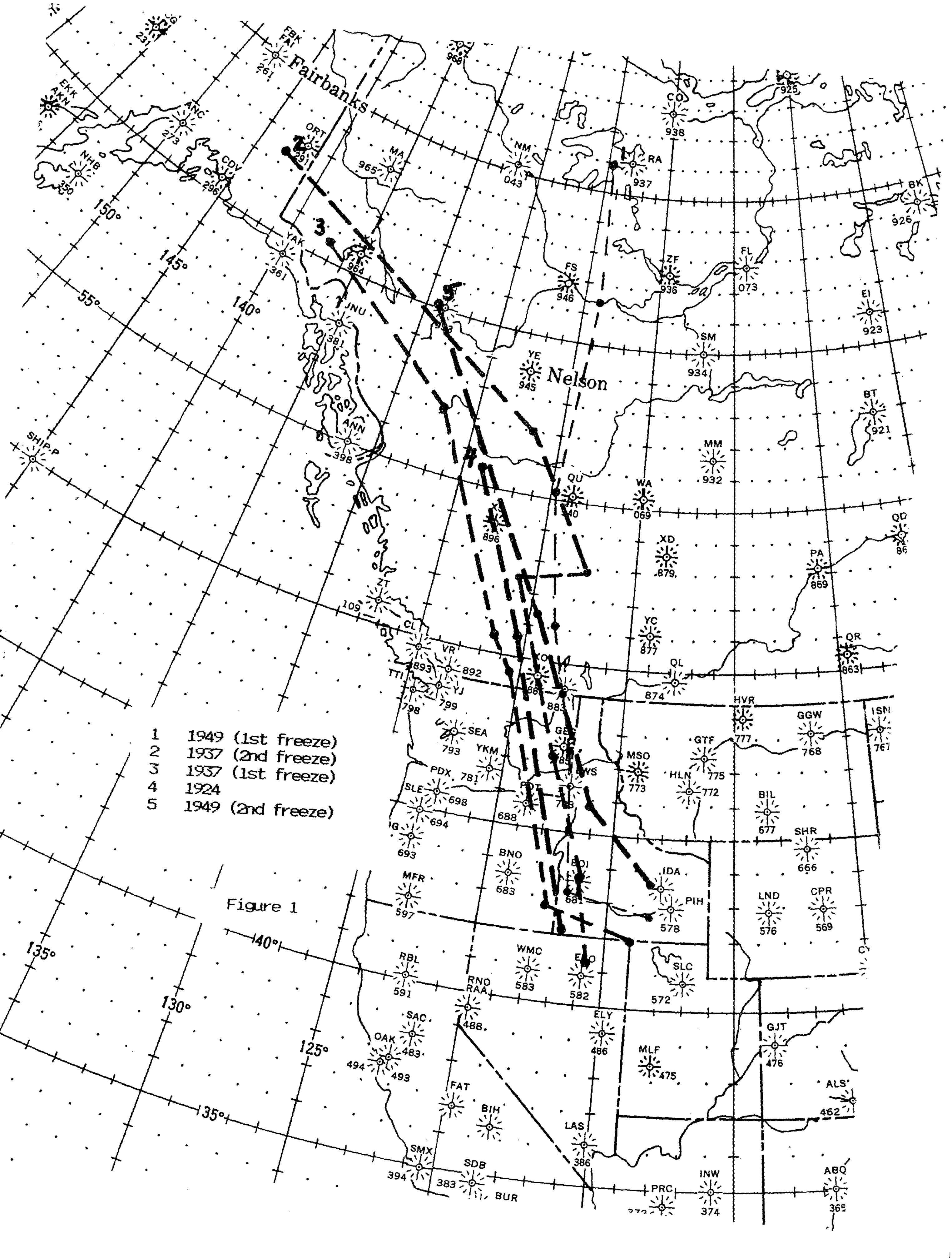

Fairbanks
Nelson
1 1949 (1st freeze)
2 1937 (2nd freeze)
3 1937 (1st freeze)
4 1924
5 1949 (2nd freeze)
150°
145°
140°
135°
130°
125°
55°
40°
35°
FBK
FAI
ANC
ORT
CDV
YAK
JNU
ANN
SHIP-P
NM
RA
CO
MA
FS
ZF
FL
SM
YE
MM
WA
QU
XD
PA
YC
QL
QR
ZT
CL
VR
YJ
SEA
YKM
PDX
SLE
PDT
GEG
LWS
BOI
MSO
HLN
GTF
HVR
GGW
ISN
BIL
SHR
IDA
PIH
LND
CPR
BNO
MFR
RBL
WMC
ELO
SLC
RNO
RAA
SAC
OAK
ELY
MLF
GJT
FAT
BIH
LAS
SMX
SDB
BUR
PRC
INW
ABQ
ALS

Figure 1

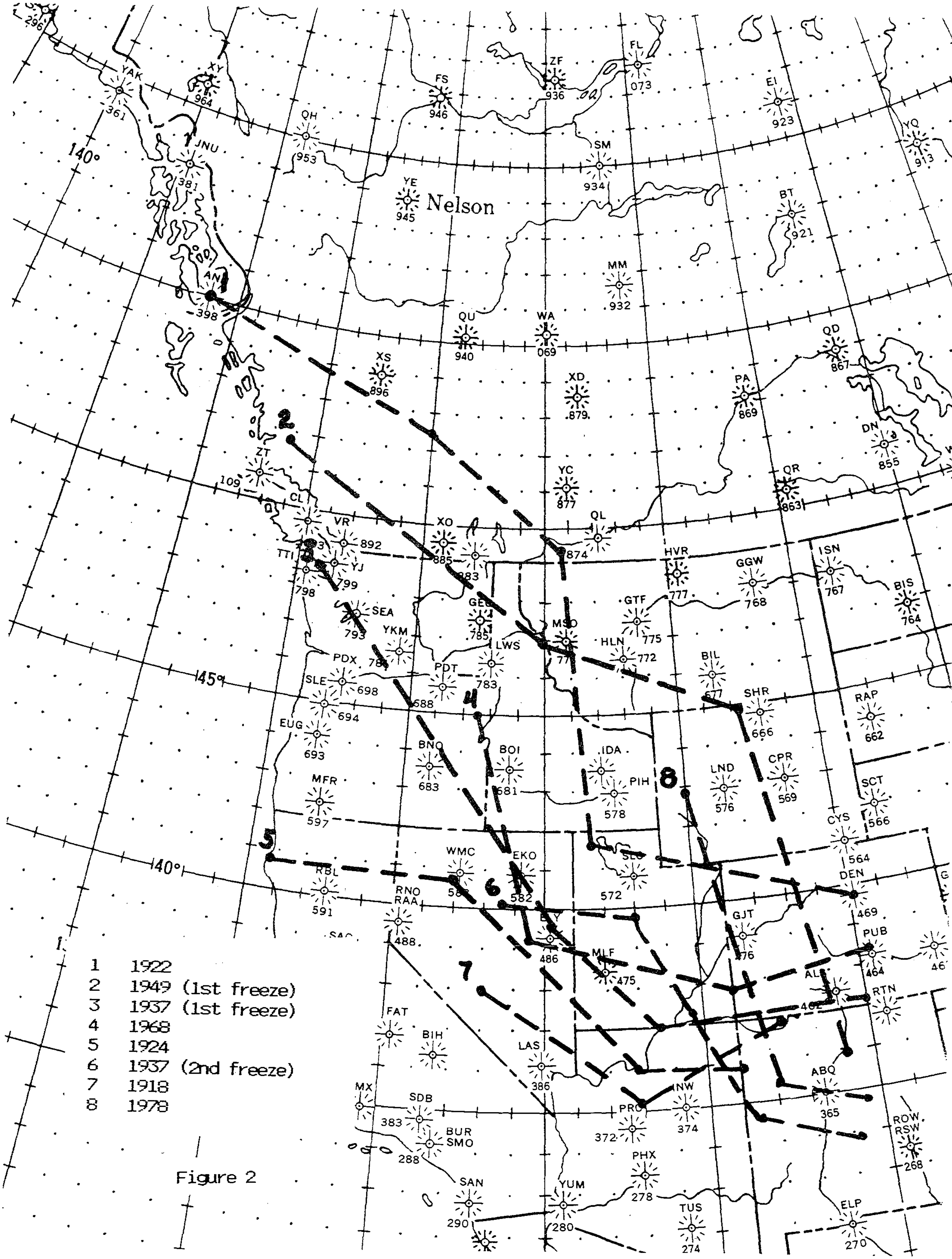
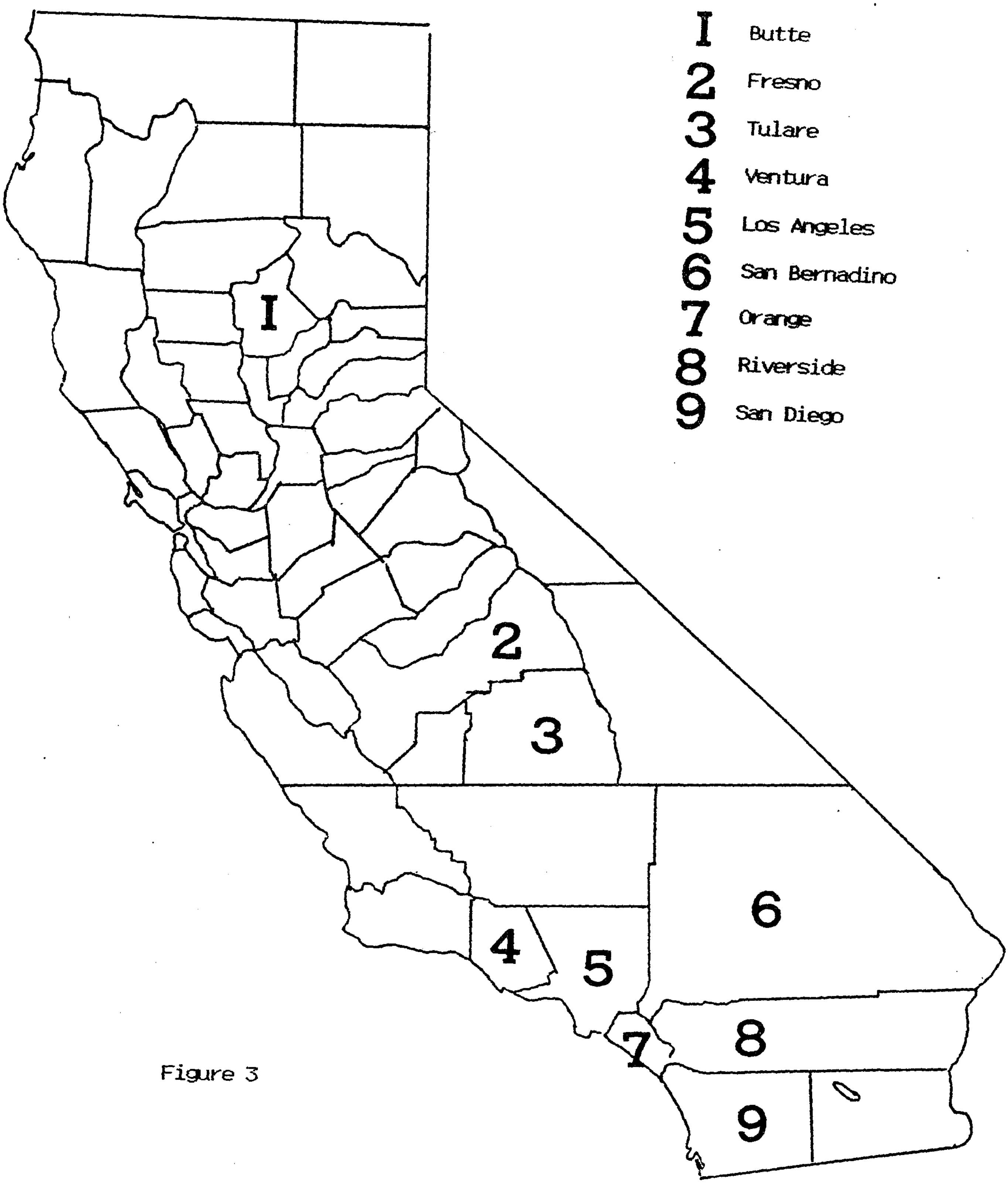

1 1922
2 1949 (1st freeze)
3 1937 (1st freeze)
4 1968
5 1924
6 1937 (2nd freeze)
7 1918
8 1978
Nelson
140°
45°
40°

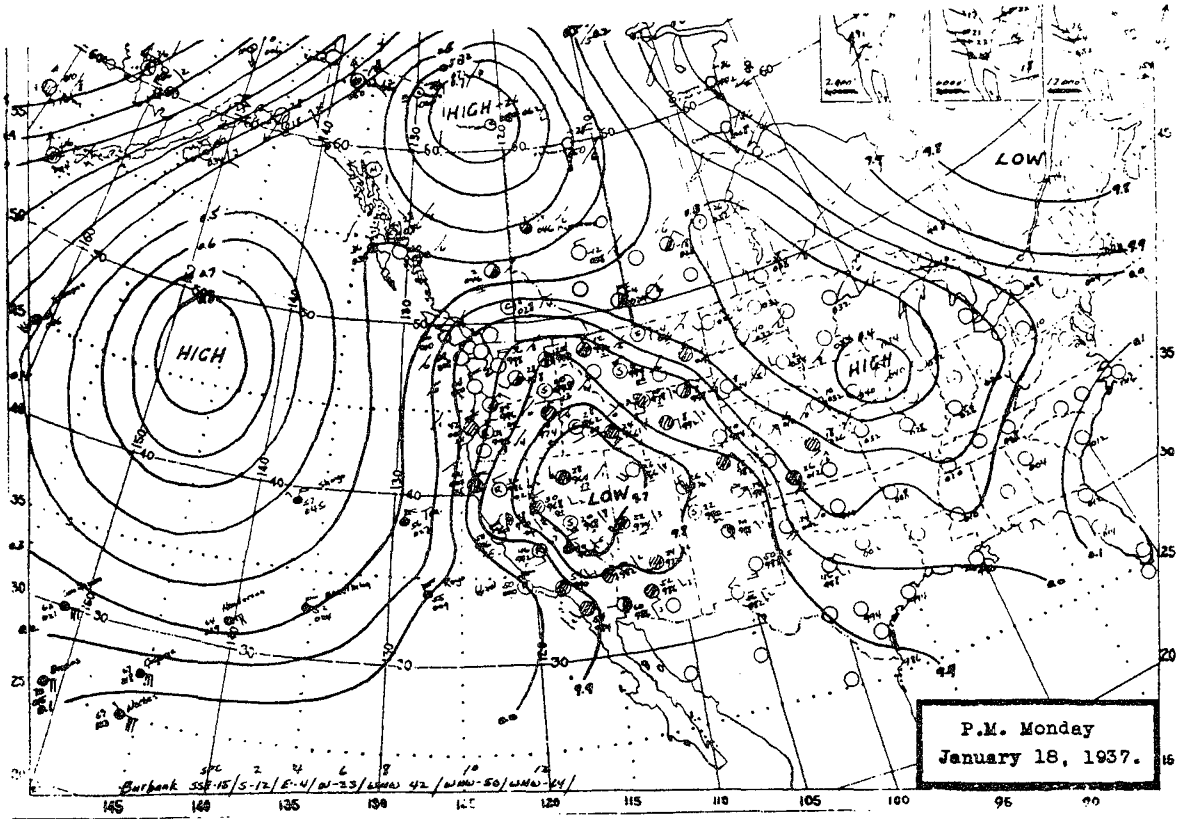
Figure 2



I Butte
2 Fresno
3 Tulare
4 Ventura
5 Los Angeles
6 San Bernadino
7 Orange
8 Riverside
9 San Diego
I
2
3
4
5
6
7
8
9

Figure 3

a


HIGH
HIGH
LOW
HIGH
LOW
P.M. Monday
January 18, 1937.

b

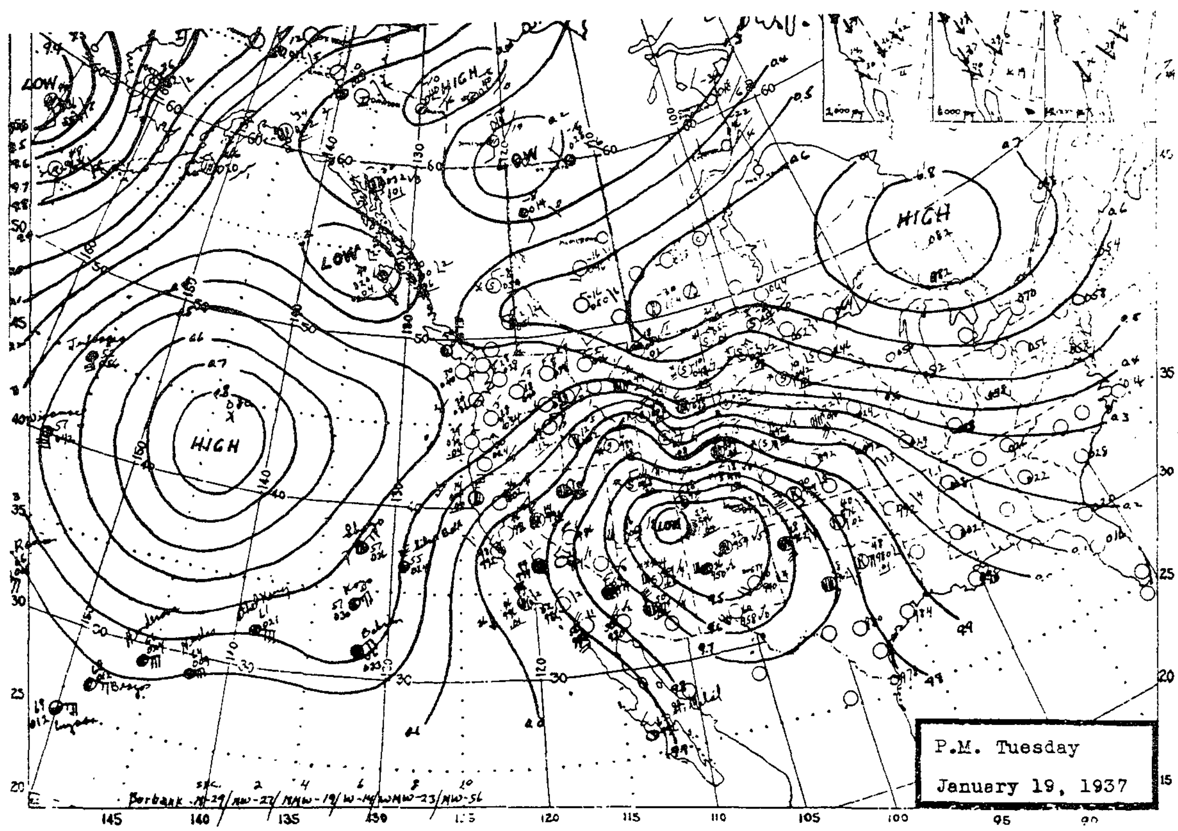
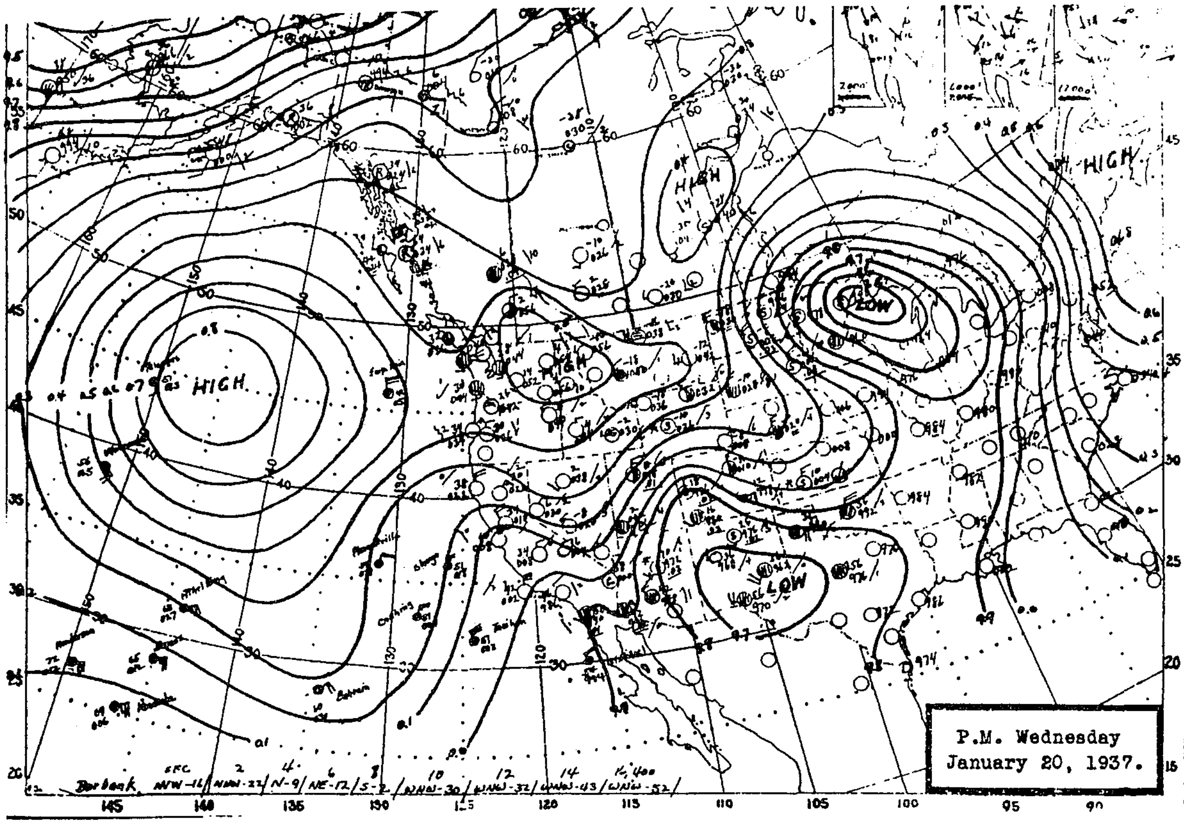

LOW
HIGH
LOW
LOW
HIGH
HIGH
LOW
P.M. Tuesday
January 19, 1937

Figure 4

c



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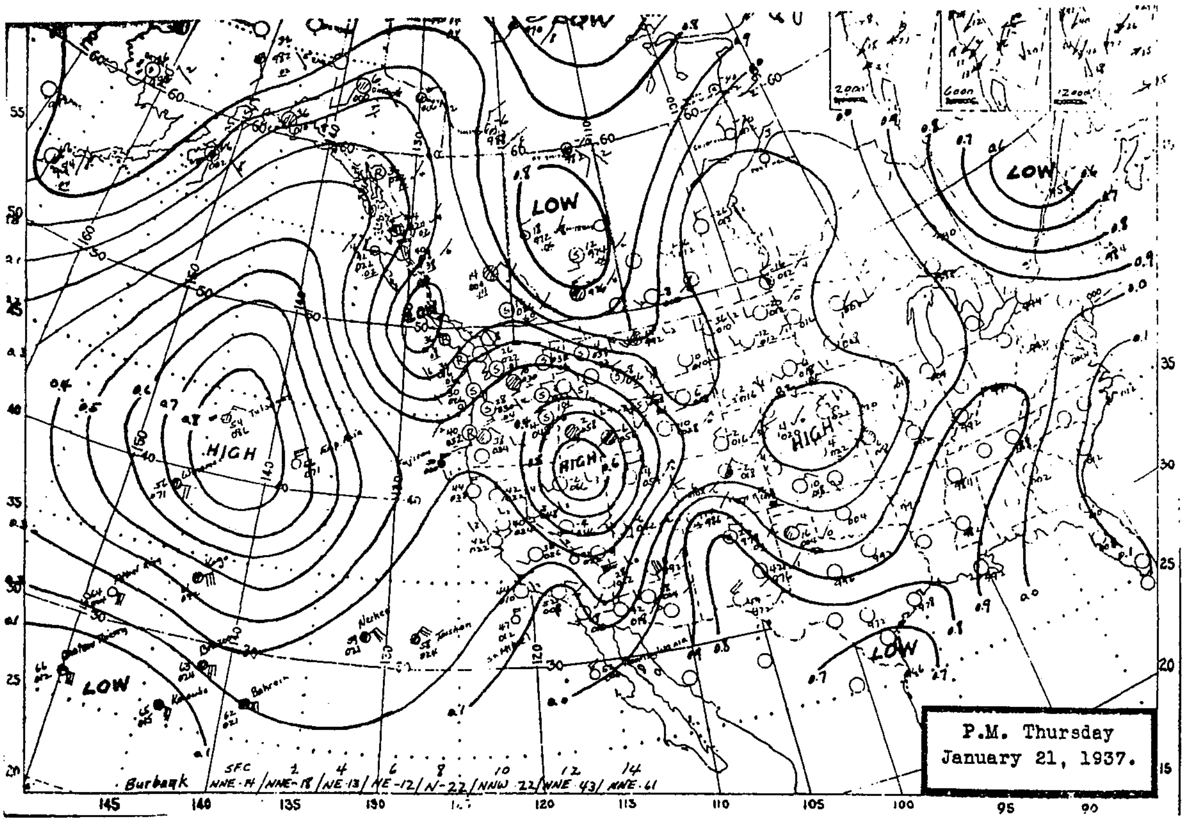

Figure 4 (cont.)

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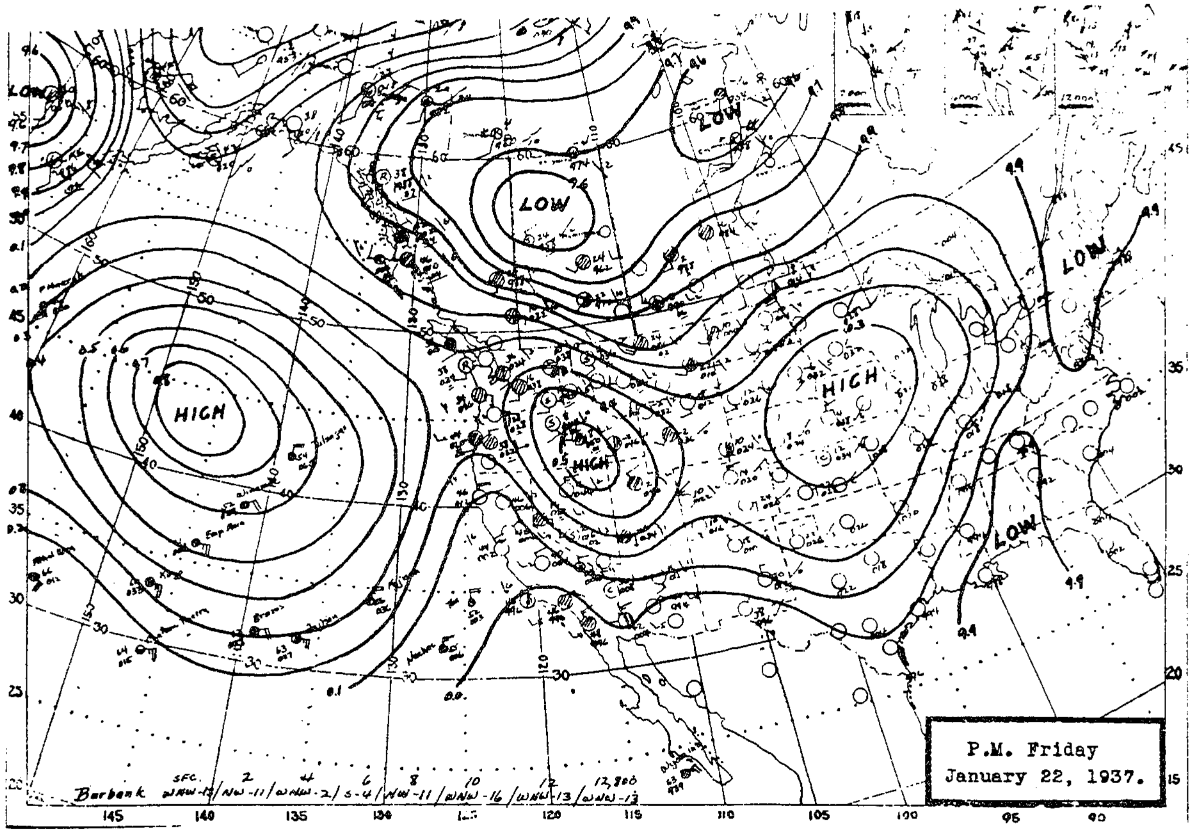

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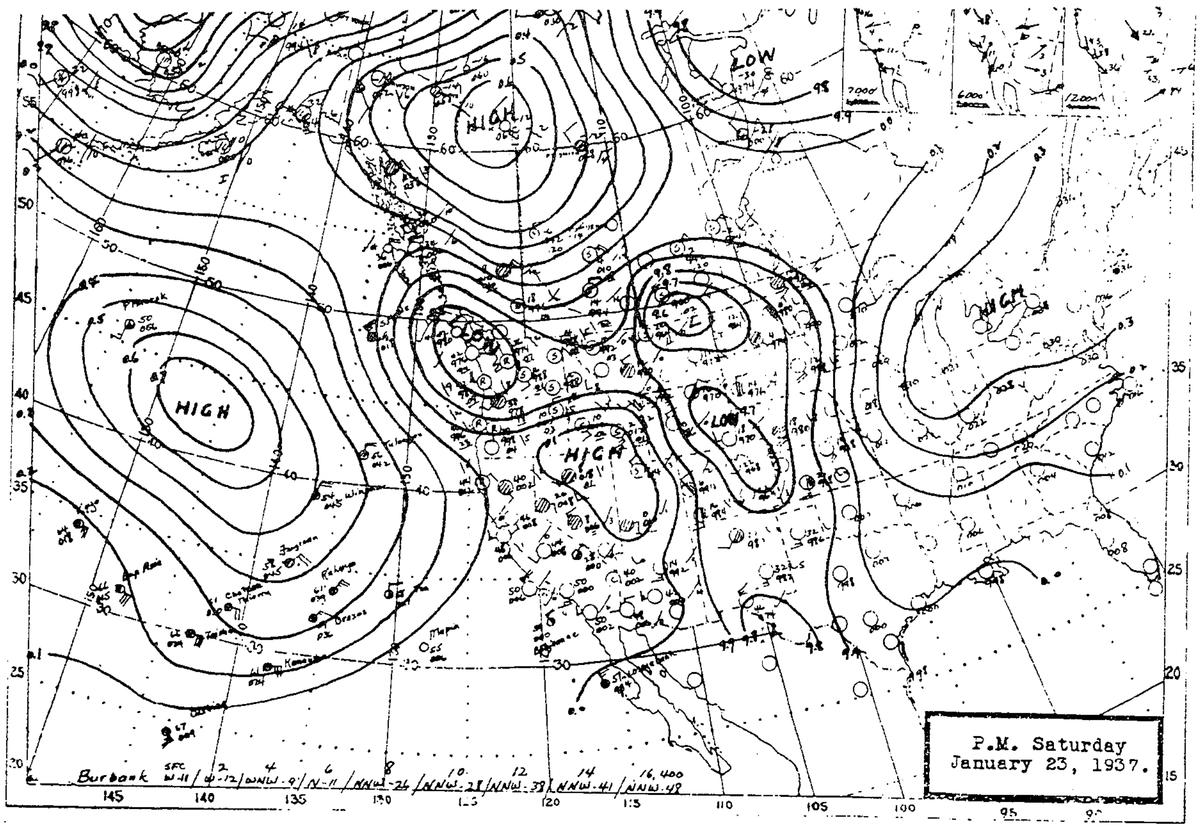
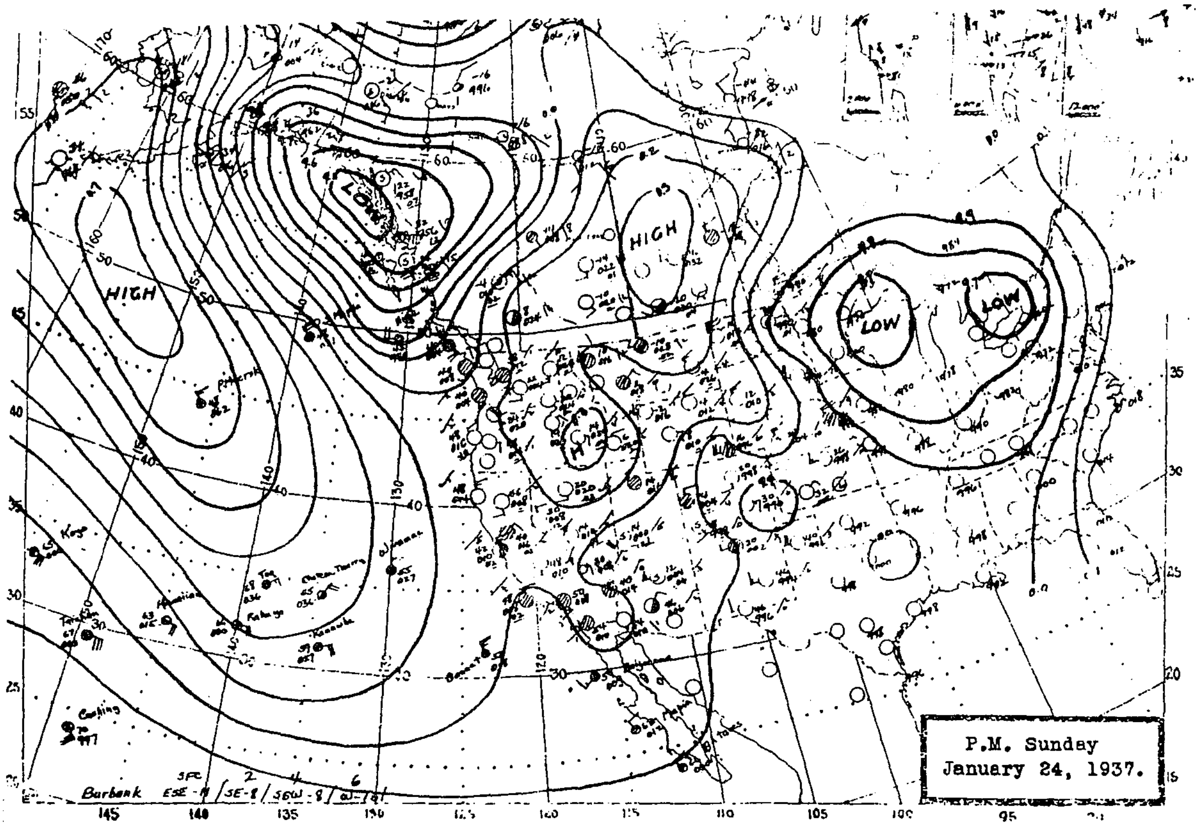


Figure 4 (cont.)

g



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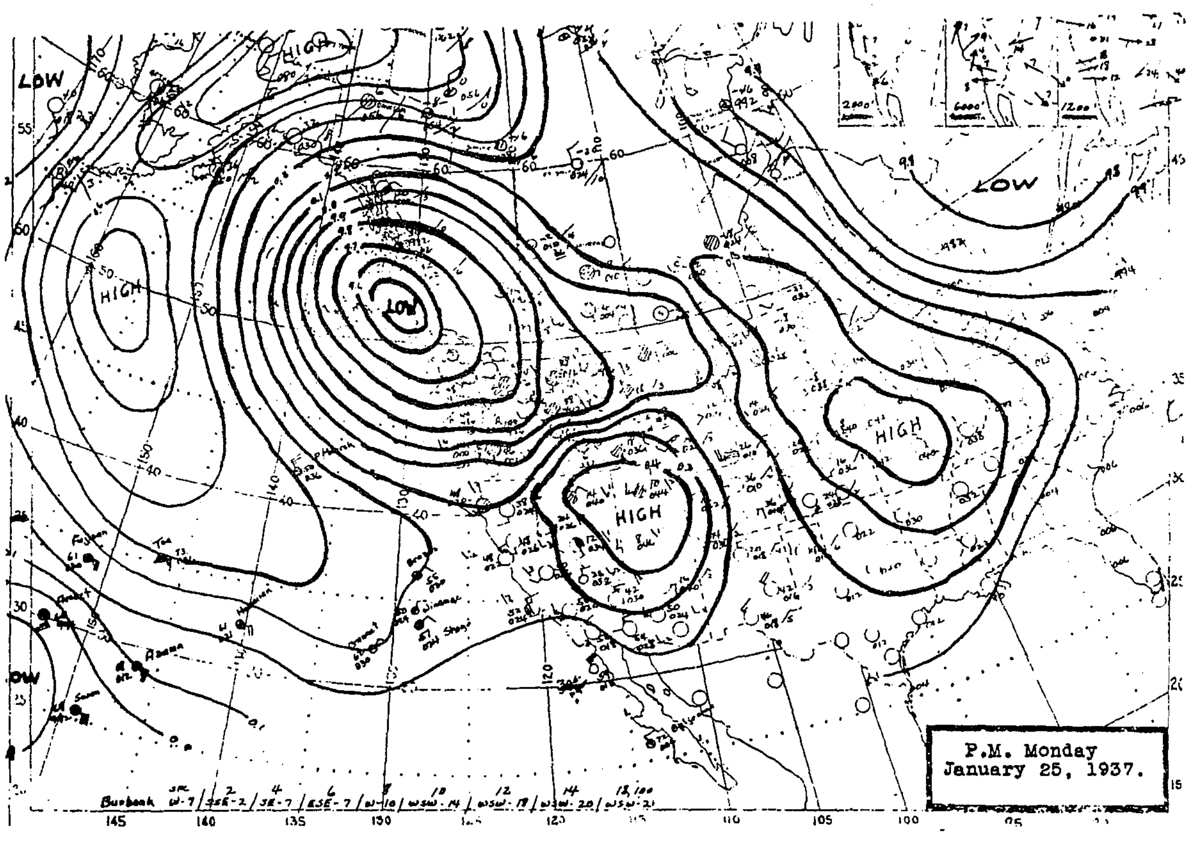

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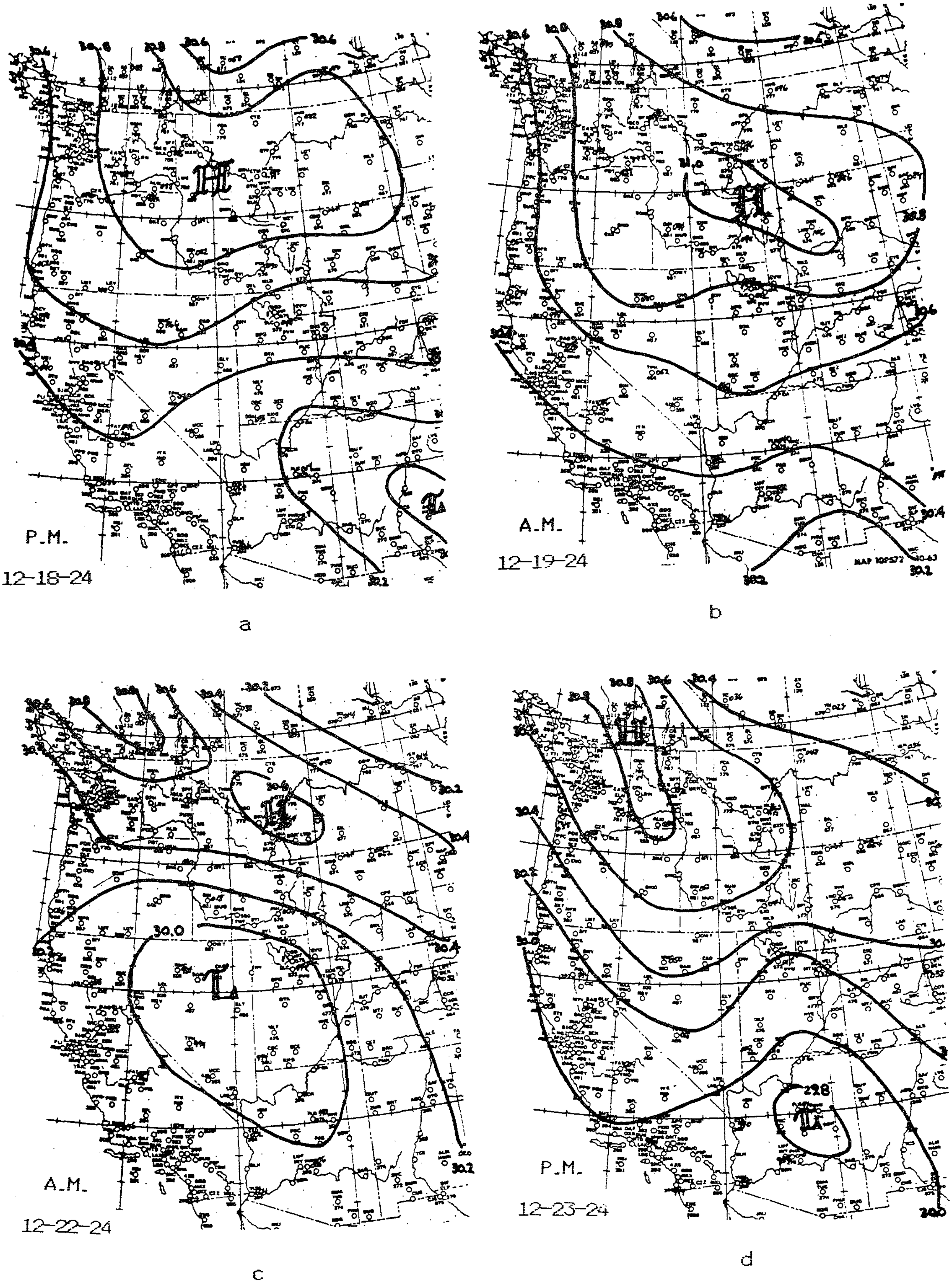
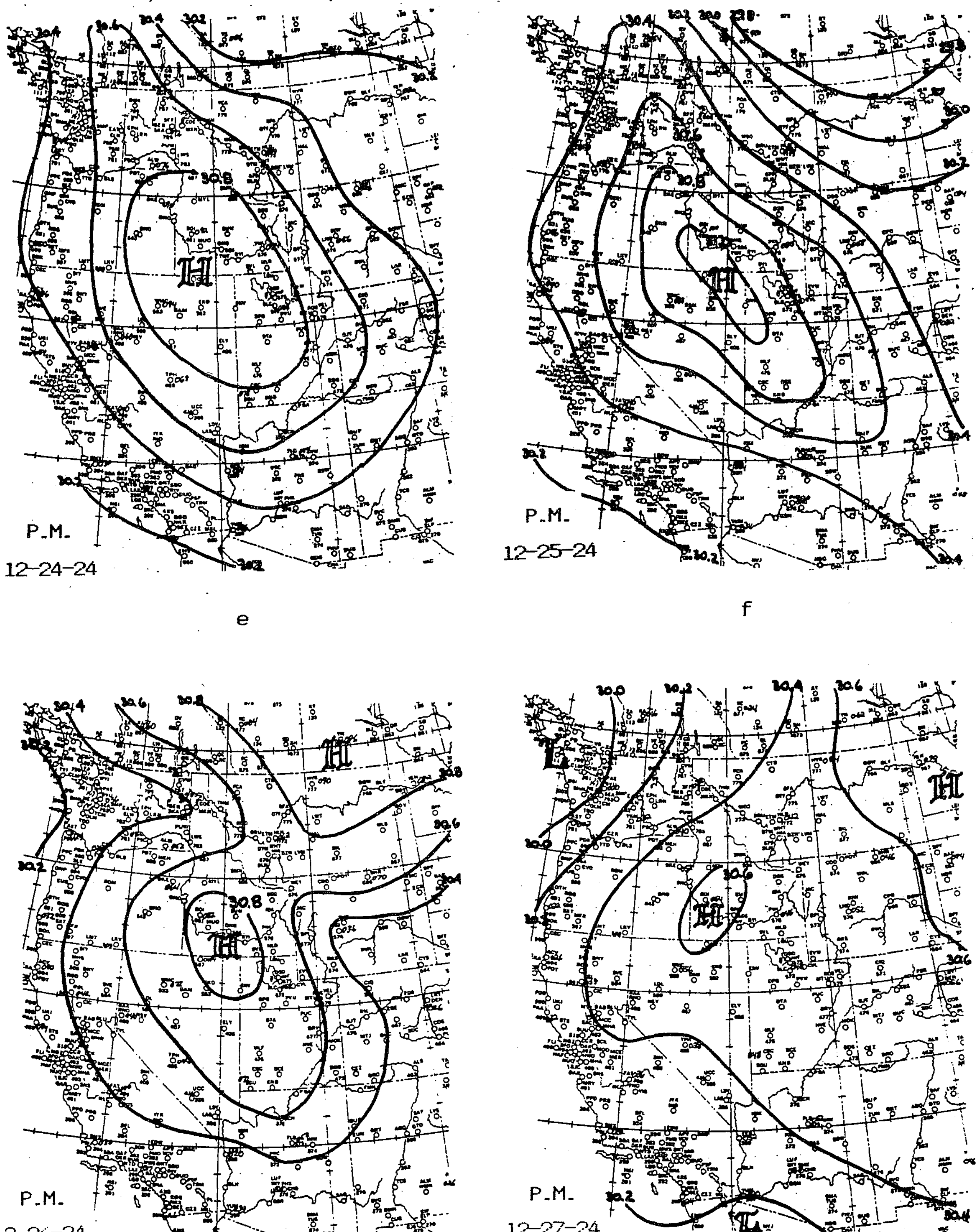


Figure 5



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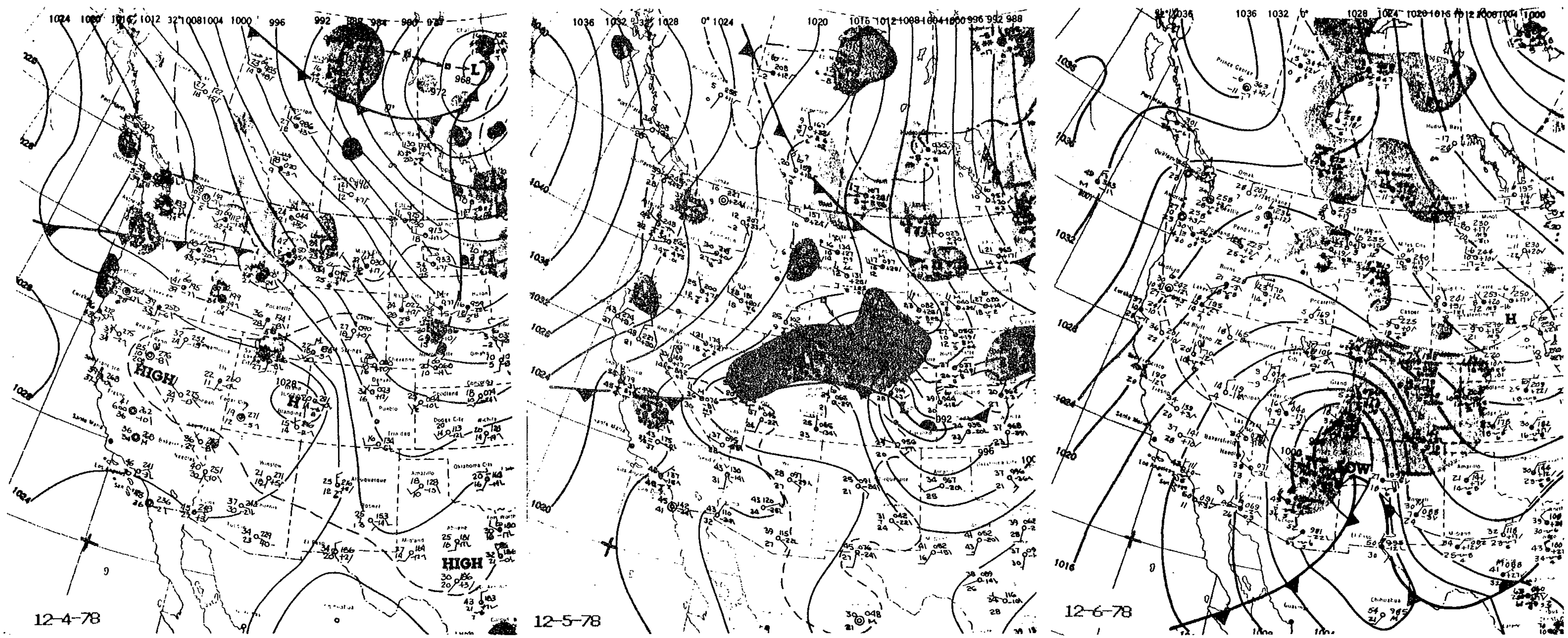
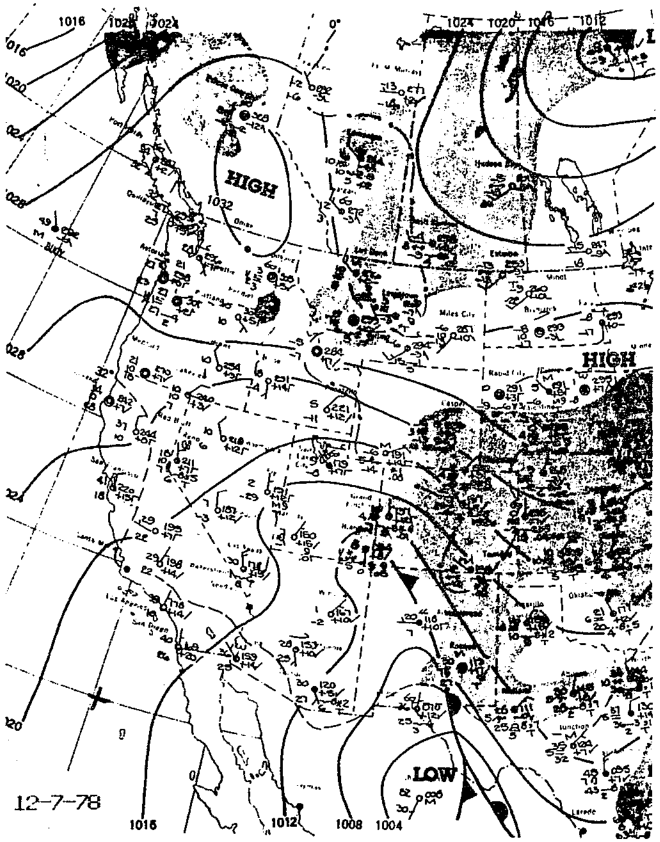


a b c

Figure 6



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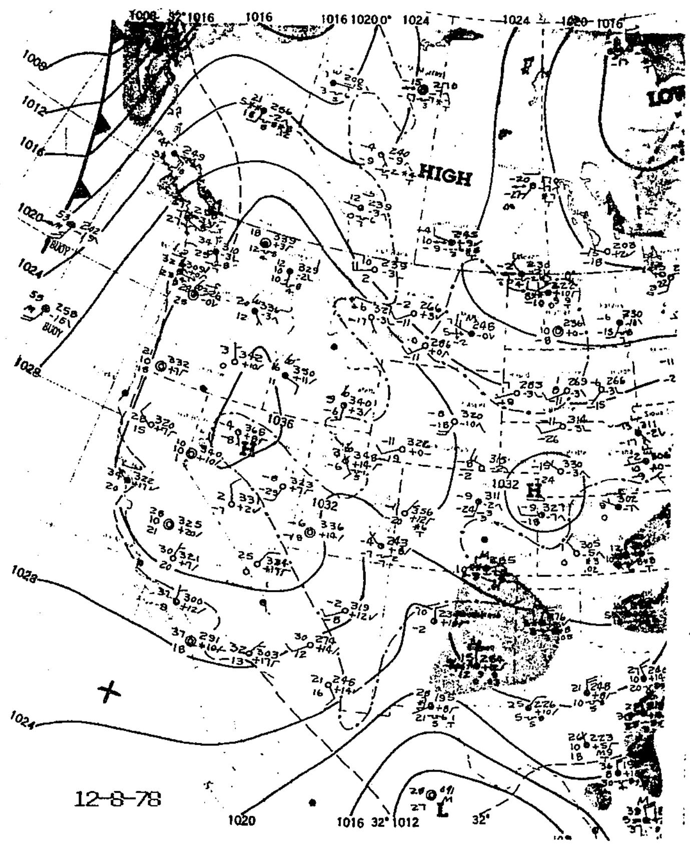

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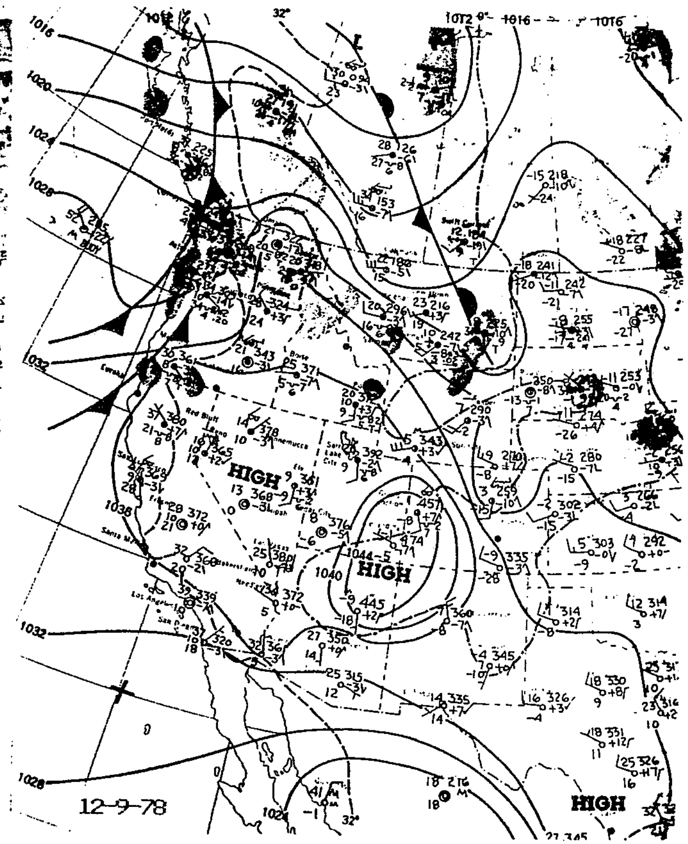

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Figure 6 (cont.)

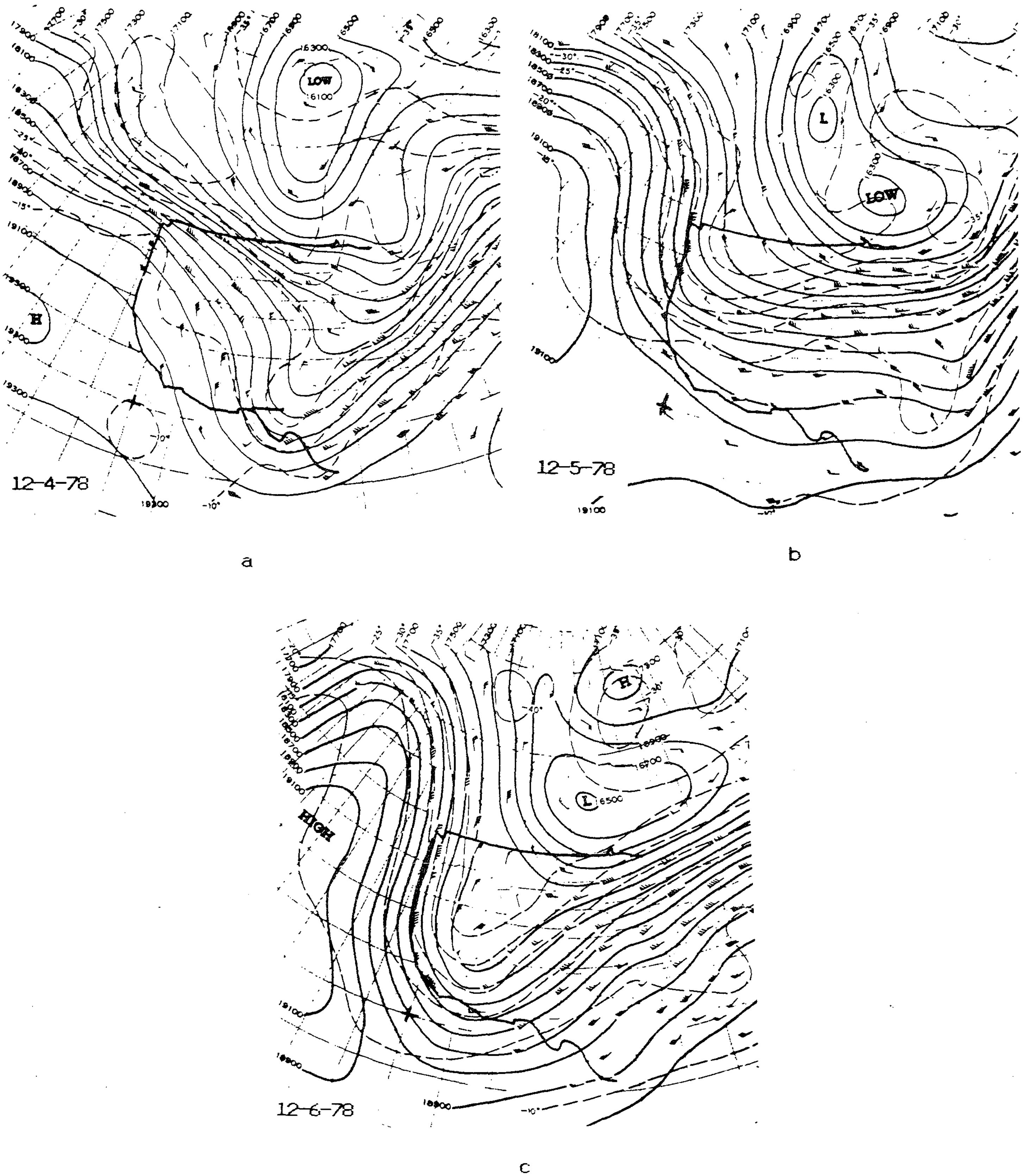
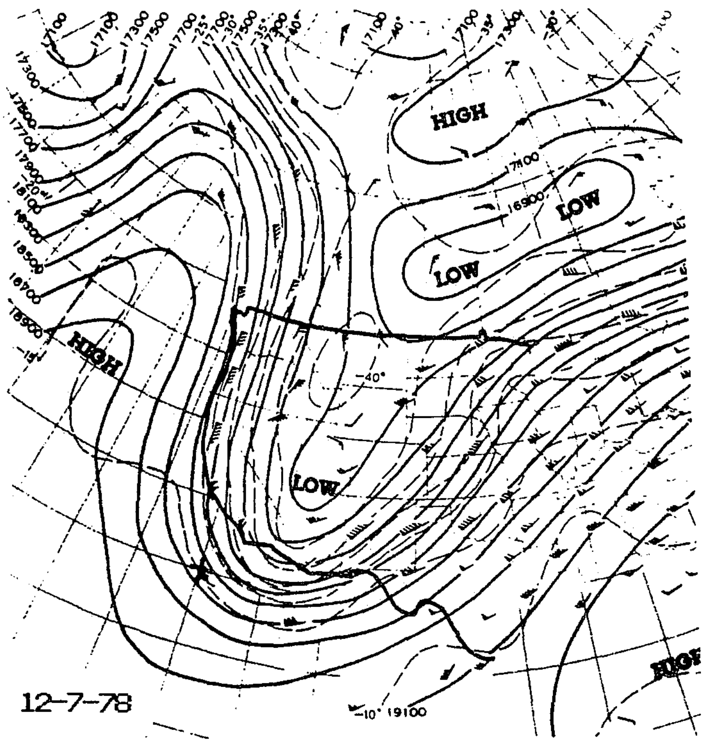


Figure 7



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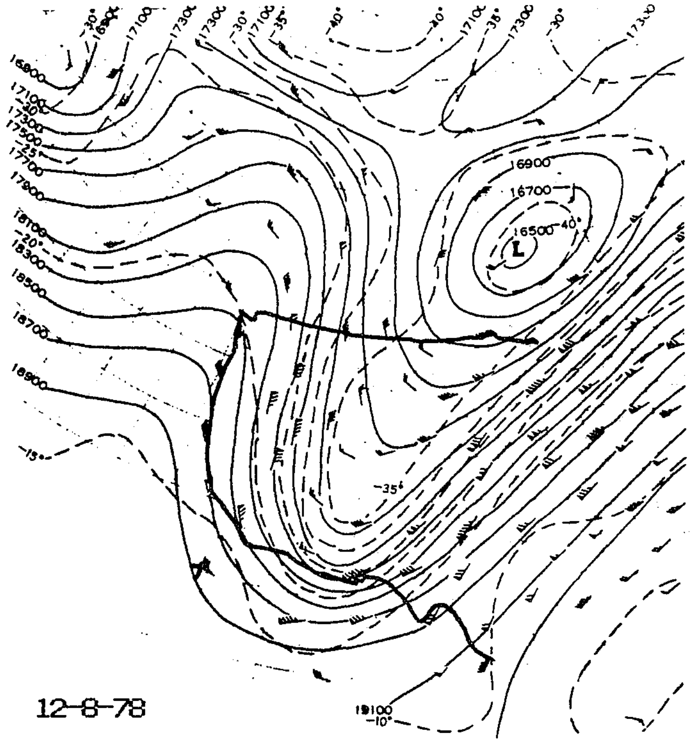
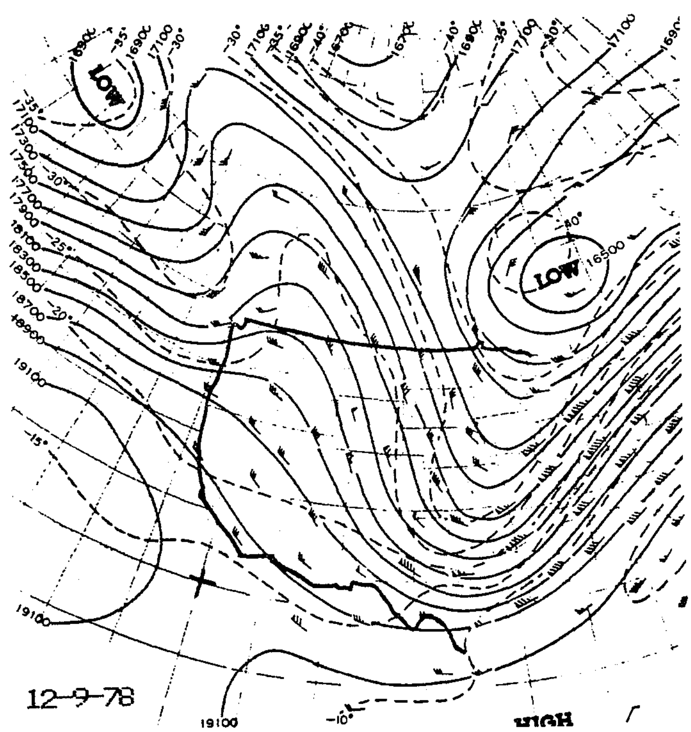


e



f

Figure 7 (cont.)

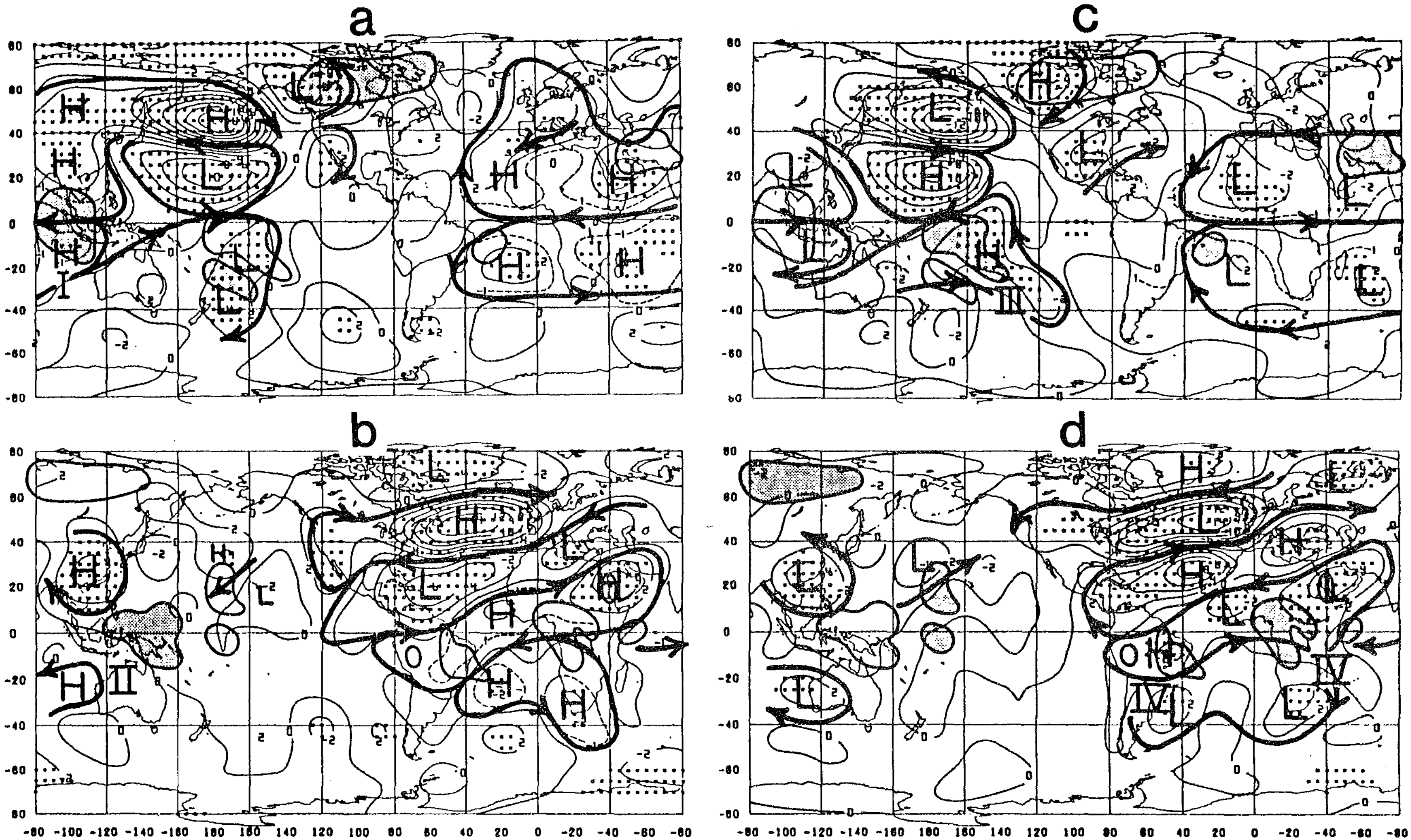


FIG. 9. Aspects of the life cycle of 28–72 day atmospheric oscillations during northern winter are depicted by streamfunction composites. Time runs from a to b to c to d to a. The individual panels represent composites of anomalous streamfunction for: (a) negative PAC index, (b) negative ATL index, (c) positive PAC index and (d) positive ATL index. The contour interval is 2.0×10^7 m^2 s^{-1}; intermediate contours in the vicinity of Africa are dashed. Heavy solid lines on a–d enclose regions of anomalous enhanced (stippled) or suppressed (clear) cloudiness; the regions were taken from Figs. 4e and 4g. The heavy solid lines with arrows are schematic streamlines while the Hs and Ls represent anticyclonic and cyclonic circulation centers, respectively. The dots represent points which passed a two-sided t-test at the 95% level (Chervin and Schneider, 1976).

Figure A1 (see 9c above)

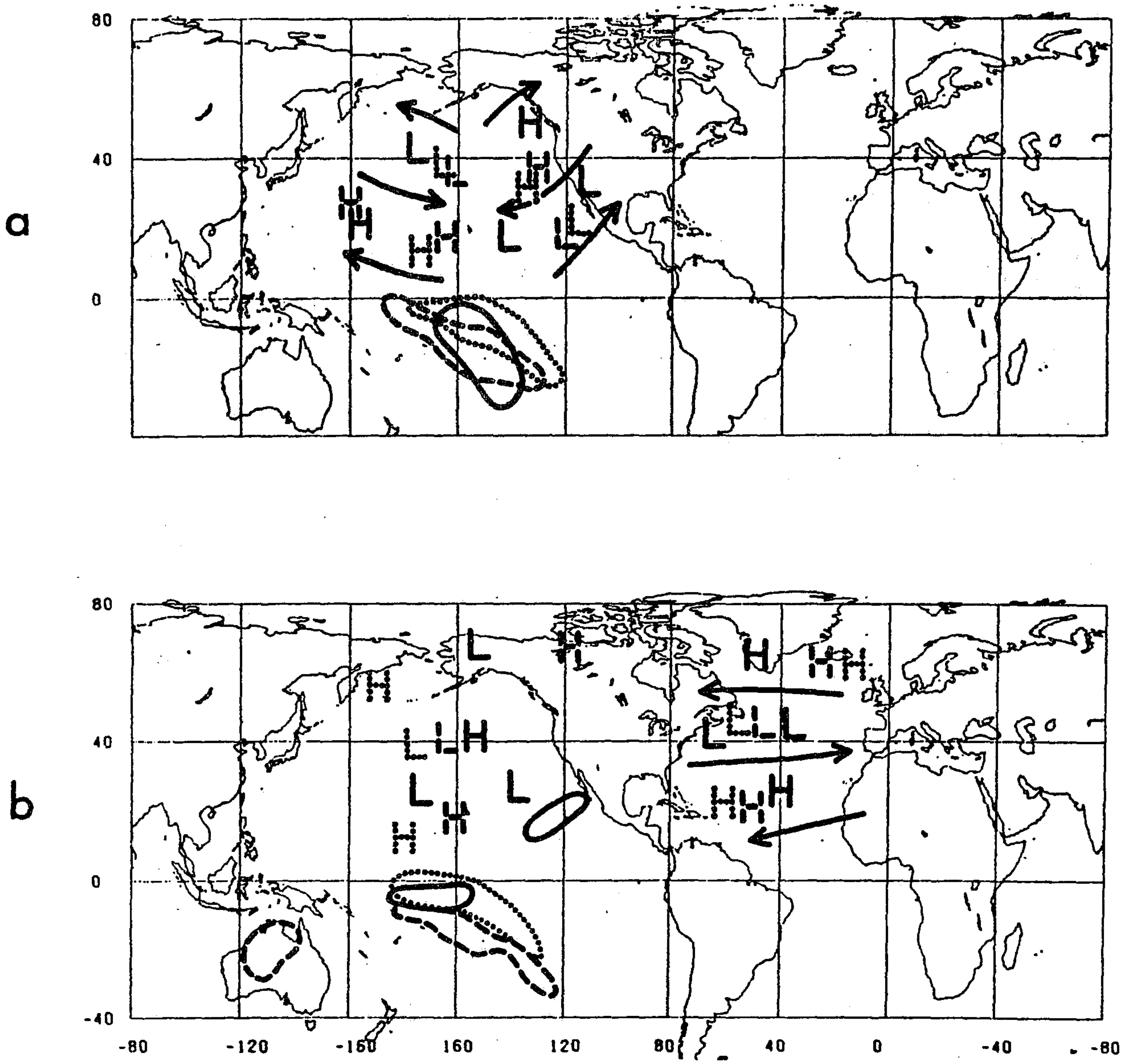


FIG. 10. (a) Schematic circulation anomalies over the Pacific during period of maximum negative OLR anomalies (greater than 10 W m^{-2}) near 10°S, 150°W for three northern winter, intraseasonal oscillations; dotted lines: 1977/78, dashed lines: 1979/80, solid lines: 1978/79. (b) Schematic circulation and OLR anomalies 8–12 days after (a).

Figure A2 (see 10a above)

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127 Development of a Probability Equation for Winter-Type Precipitation Patterns in Great Falls, Montana. Kenneth B. Mielke, February 1978. (PB-281-387/AS)
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