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Synoptic and Mesoscale Factors Influencing Stratus and Fog in the Central California Coastal Region

by

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Based on the analysis, the formation of the stratus and fog was found to be initiated by the movement of an upper-level cut-off low and a shortwave ridge. Their movements provided increased subsidence and upper-level negative vorticity advection (NVA) over Southern California, which, in turn, produced higher pressure over the Vandenburg region. This coupled with relatively lower pressure over Oakland, set up flow conditions that lead to the formation of the stratus and fog. The Vandenburg/Oakland pressure gradient produced southerly flow, which carried warm moist air over relatively cooler water. The moist air condensed and stratus and fog developed.

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by

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of the requirements for the degree of

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ABSTRACT

This study was done to describe the synoptic and mesoscale events associated with the development of fog and stratus along the Central California Coast during the 30 April to 5 May 1990 period. These events were compared and contrasted to the synoptic and mesoscale evolution found for stratus surge and Catalina Eddy events.

Based on the analysis, the formation of the stratus and fog was found to be initiated by the movement of an upper-level cut-off low and a short-wave ridge. Their movements provided increased subsidence and upper-level negative vorticity advection (NVA) over Southern California, which, in turn, produced higher pressure over the Vandenburg region. This coupled with relatively lower pressure over Oakland, set up flow conditions that lead to the formation of the stratus and fog. The Vandenburg/ Oakland pressure gradient produced southerly flow, which carried warm moist air over relatively cooler water. The moist air condensed and stratus and fog developed.

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I. INTRODUCTION

During the warmer spring through fall seasons, the coastal areas of Central and Southern California experience periods of low stratus and fog lasting from a few hours to several days in length. A period of less than one hour can bring a shift from sunny skies to stratus and fog.

Several studies have looked at the frequent development of fog and stratus layers along the Central California Coast, especially during the summertime. Felsch (1990) studied the development of a stratus surge along the California Coast which he defined as the "apparent movement of a narrow band of stratus from south to north along the west coast of the United States". It is considered to be an anomalous mesoscale event during the summer season because macroscale winds are predominately from the northwest. Mass and Albright (1989) suggest that an eddy in the atmospheric flow, referred to as the Catalina Eddy, results when the normal regime of westerly and northwesterly surface flow within the Southern California regime is interrupted by periods of southerly flow, elevated marine layers, and increased low level cloudiness within approximately 100 km of the coast. The first step in the formation of the Catalina Eddy is the passage of a shortwave trough into the Pacific Northwest, accompanied by a surge of cooler air from upstream of the trough. These synoptic-scale changes intensify the lower-level pressure gradient, strengthening the northerly flow along the Central California Coast. The increased winds produce lee troughing south of the San Rafael mountains, lower pressures to the north and higher pressures to the south along the area south of Point Conception, which produces southerly flow. In another paper, Mass and Albright (1987) describe the stratus alongshore surge as a northward propagating, topographically trapped gravity current. Dorman (1985) suggests that internal solitary (coastally trapped) Kelvin waves, in Southern California's marine layer, account for the existence of the stratus overcast or stratus surge.

These previous studies have emphasized the northward movement of stratus along the California Coast and the formation of the Catalina Eddy. There are, however, periods when stratus and fog form in situ along the California Coast, that are not clearly associated with the northward surge of marine air examined in these previous studies. Between 30 April 1991 through 5 May 1991, the central coast of California and the Monterey Peninsula in particular, transitioned from clear sky conditions to low stratus and coastal fog conditions in a relatively short time period. Between 30 April through 5 May 1991 satellite images indicate that fog formed initially along the Central California Coast and then expanded both north and south. This paper examines this single event in detail to show the factors responsible for the formation of stratus along the Central California Coast and then compares these factors to those identified in other coastal stratus surge events mentioned above.

Specifically the objectives of this study are to:

1) Describe the synoptic and mesoscale events associated with the development of fog and stratus along the Central California Coast during the 30 April to 5 May 1990 period.

2) Compare the events in this case to the synoptic and mesoscale evolution found for stratus surge and Catalina Eddy events.

3) Identify the physical processes and their interaction that produced coastal stratus.

4) Find a better analysis technique for use in evaluating coastal fog and stratus along the Central California Coast.

5) Examine whether routine data and analysis are sufficient to analyze the onset of stratus and fog events.

II. BACKGROUND

The formation of coastal fog and low stratus clouds along the California Coast requires physical conditions conducive to fog formation in general. In general, fog forms when: 1) air is cooled to its dew point; or 2) water is evaporated into air until the air reaches saturation (Petterssen 1969). In either case, condensation nuclei must be present in sufficient quantities. The principle mechanism for coastal fog and stratus formation is through cooling of relatively moist near surface air. Although nighttime radiational cooling may contribute to the formation and inland penetration of California Coastal stratus and fog, this type of coastal stratus or fog is generally considered to be an advective type fog. Advective stratus or fog develops when warm moist air flows over a cold body, usually water. The moisture-laden air, over cold water, is quickly cooled to its dew point and stratus or fog forms (Williams 1973).

Favored regions for advection fogs are those where cold and warm ocean currents, or water masses, are adjacent to one another (Petterssen 1969). The California Coast during the summertime is one such place. According to Petteressen (1969), the prevailing winds along the California Coast during the summertime are from a northerly direction. This prevailing flow sets up a southward ocean current along the California Coast and a net ocean transport westward, or offshore. This offshore transport produces upwelling along the California Coast, bringing colder water to the surface along the coastline. During periods of southerly flow, the air cools as it flows from warmer to colder water, resulting in an increase in relative humidity and favorable conditions for fog formation.

According to (Petterssen 1969), low stratus clouds and fog banks are physically the same, although they occur at different levels in the atmosphere. The visible moisture will be in the form of ground fog when favorable fog conditions exist and an inversion is present at the surface. Stratus cloud layers, on the other hand, form when there is an elevated inversion present and, again, conditions are favorable for fog formation. The visible moisture under these circumstances will be in the form of an above-ground stratus layer. Inversions may become elevated when the sun rises and heats the earth, and the adjacent layer of air. The result is that the ground fog "lifts", forming low-level stratus clouds.

Since ocean temperature conditions that produce advective fog and low stratus clouds exist year round, the primary question for the formation of coastal stratus and fog is what synoptic conditions in the atmosphere produce a transition from clear to cloudy conditions. A previous study by Mass and Albright (1989) have addressed the large-scale changes that produce northward propagation of stratus along the coast. Felsch (1990) has generalized these results and identified typical factors that lead to stratus surges along the California Coast. Felsch's results are as follows:

1) A common surface feature present during a stratus surge was a thermal trough aligned from the northwest corner of California through the Central Valley, coastward of its normal summer season position.

2) A common upper-level feature present during a stratus surge was either an upper-level low over, or to the south of, the Central California Coast or a shortwave ridge aligned northeast to southwest across Northern California.

3) The pressure gradient relaxation at night due to radiation cooling initiates the surge, which opposes the large-scale flow.

4) The surge potential is based on the existence of stratus in Southern California.

However, this and other studies have not addressed the conditions that lead to the initial formation of coastal stratus and why certain regions are favored for formation. The coastal mountains potentially influence the locations of the formation of the stratus layer, particularly with respect to upslope fog formation and lee troughing in certain regions. This study examines the initial formation of coastal stratus in one case.

III. DATA DESCRIPTION

Surface and upper-level atmospheric analyses based on the National Meteorological Center (NMC) final Global Data Assimilation System (GDAS) analysis (Kanamitsu 1989) gridded fields were obtained from NCAR. The NMC final GDAS gridded fields include data that arrived too late for the NMC real-time analyses.

Routine surface hourly observations and upper atmospheric rawinsonde data provided detailed information about small-scale structure and evolution. The upper atmospheric soundings were plotted and examined to determine the presence, levels, and evolution of inversion layers. The surface hourly observations were used to examine surface weather and other variables for coastal stations in order to provide a more complete description than available from satellite imagery. In addition, these observations plus observations from the Naval Postgraduate School May 1990 student cruise were used to do mesoscale analyses to define the detailed structure that lead to the formation of the coastal stratus.

To provide a more complete quantitative mesoscale analysis, objective analyses using the surface land, ship and buoy data were done. These objective analysis were made using multi-quadric (MQ) interpolations as described by Hardy (1990). Multi-quadric interpolation utilizes hyperboloid basis functions to fit scattered data points and produce continuous fields that can be defined on a uniform grid. Since this objective analysis method fits observations closely, care was taken to check each data point against nearby stations, as well as previous and following times.

Analyses of pressure, temperature, dew point and wind were examined every three hours on a 20 km grid covering the area from approximately 116° W to 128° W and 33° N to 40° N. This area was chosen to encompass the Central California Coast, where the fog and stratus developed in this study.

To produce as much consistency from one analysis to the next, the same set of observation stations were used in each analysis. This was done to avoid pressure changes due to missing data at a particular time. Because some station reports were missing from the data set, these times were filled using multi-quadric interpolation in time for a particular station. A consistent set of pressure observations were generated for the 54 stations used in this study. Other variables were not interpolated in time because these variables were of secondary importance in this study.

Since little offshore data was available four points on the western boundary of the region were generated from the NMC large-scale analyses. This procedure prevented boundary problems along the western boundary.

The MQ method was evaluated against the NMC analysis for its usefulness in determining what causes the summertime periods of low stratus along the Central California Coast. One of the goals of this paper is to find a better analysis technique for use in evaluating coastal fog and stratus along the Central California Coast. As will be discussed in Chapter V, the MQ analyses are more representative of the mesoscale pressure and wind as they are based on actual station observations with no smoothing of the data. The MQ analysis produced higher resolution gridded fields, with the resolution determined by the observation spacing. The observation spacing is less than the 2.5° grid spacing used by NMC, and the observations are plotted on 20km gridded fields, while, as mentioned, NMC uses a 2.5° grid, which significantly smooths the mesoscale structure present in the observations.

IV. SYNOPTIC ANALYSIS

This case study focuses on a coastal stratus and fog event along the Central California Coast that occurred between 01 May and 04 May 1990. On 01 May, Central California experienced clear skies and warm temperatures, which were associated with offshore flow through most of the lower atmosphere. On 02 May, a transition from clear skies to stratus/fog in the late afternoon occurred in the Monterey Bay area. The low stratus and fog along the California coast remained for several days, as shown by the Salinas airport (SNS), Naval Postgraduate School (Monterey, CA.) surface observations and GOES Satellite imagery. Favorable synoptic conditions for the formation and maintenance of stratus/fog is low- level onshore flow set up by the presence of a strong thermal surface trough in the central valley of California. However, large-scale analyses from this time period indicate that the pressure trough remained offshore throughout the period, as will be described in the next few sections.

A. CLEAR PERIOD

Clear conditions prevailed over the California coastal area from 0000 UTC 01 May until 1200 UTC 02 May 1990, which is evident from both surface hourly observations and GOES satellite imagery. The 0001, 1501, 2031 and 2231 UTC 01 May 1990 GOES visible imagery all show the California and western Pacific area as generally cloud free with no fog or stratus along the California Coast. Surface observations from Salinas (SNS) indicate clear skies and visibilities ranging from 15 to 50 miles, confirming the clear conditions during this period.

The synoptic event that initiated the clear weather seen in the 0001 UTC 01 May visible satellite image (Fig. 1) was the passage of a significant shortwave through California. The 0000 UTC 01 May 500 mb NMC analysis (Fig. 2) shows a very strong ridge dominating the Eastern Pacific Ocean and a 5550 m cut-off low centered over Southern California. This cut-off low was produced by a shortwave that moved down the coast on 30 April. The 0000 UTC 01 May NMC 500 mb vorticity analysis (Fig. 2) shows a 22×10^{-5} s^{-1} vorticity maximum associated with the Southern California cut-off low and indicates strong negative vorticity advection (NVA) along the California coast. Evidently strong subsidence is occurring due to this strong NVA over California.

During the next 36 hours, the 500 mb cut-off low shifts eastward, and a weak shortwave moves through Southern British Columbia. The 1200 UTC 02 May 500 mb NMC analysis (Fig. 3) shows the cut off low over SE Arizona, a weak shortwave trough in Eastern Washington and a shortwave ridge over Northern California/Nevada. This weak shortwave is best identified by the 14 x 10^{-5} s^{-1} vorticity maximum in Eastern Washington (Fig. 3). The passage of this shortwave has shifted the tilt of the long-wave ridge axis westward at 50° N and decreased its amplitude, but has not significantly effected its position south of 40° N.

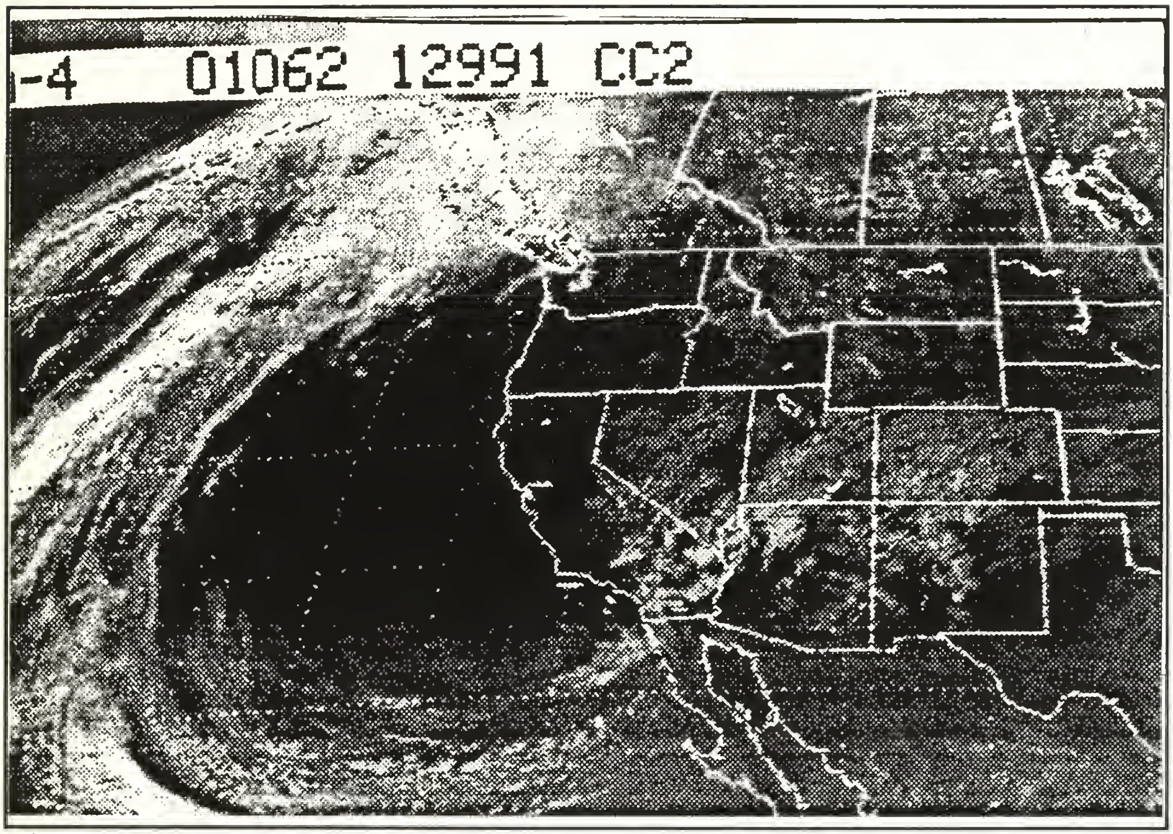

Figure 1. 0001 UTC 01 May 1990 GOES visible satellite imagery.

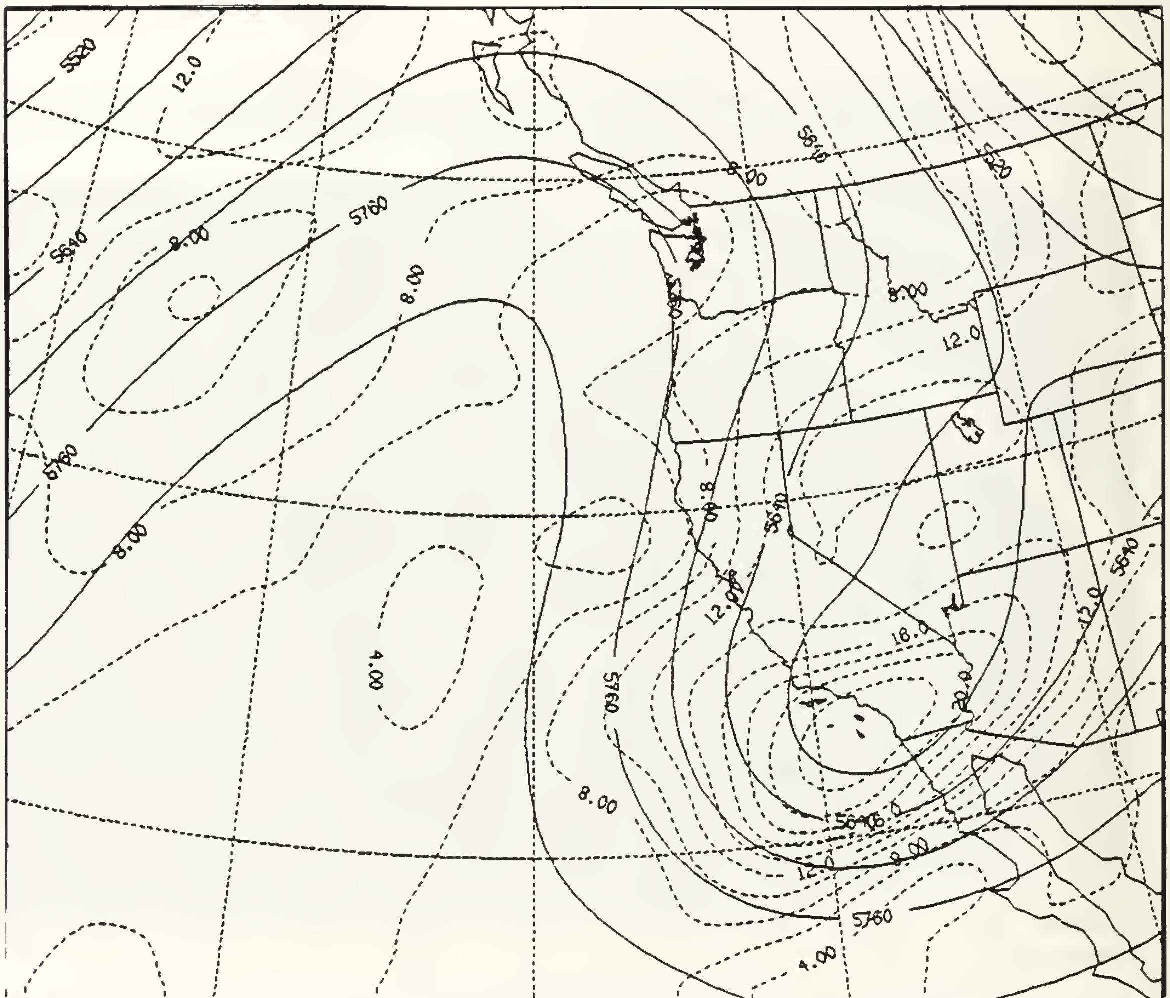

Figure 2. 0000 UTC 01 May 1990 NMC 500 mb analysis. Heights (m, solid) and absolute vorticity, (10^{-5}/s, dashed).

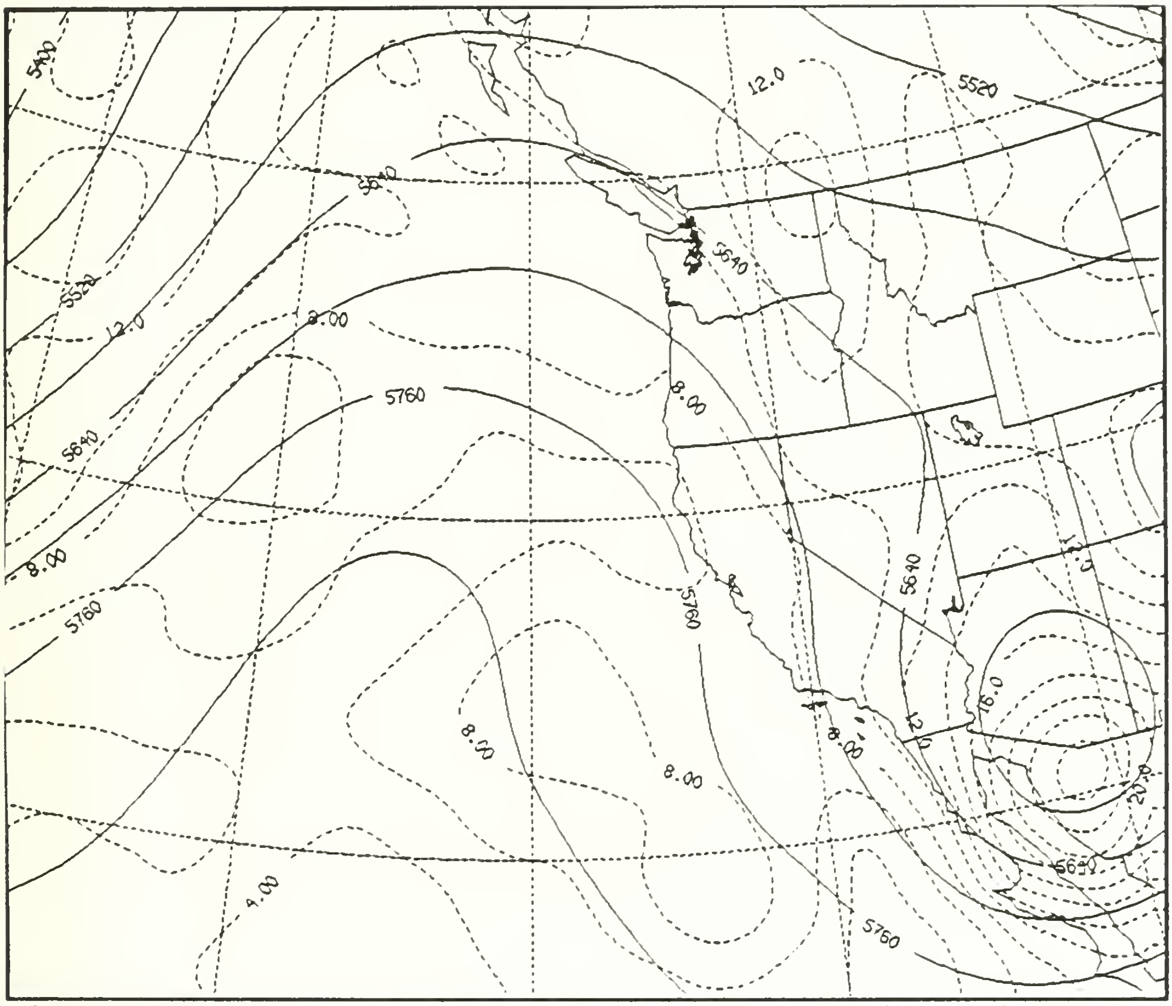

Figure 3. 1200 UTC 02 May 1990 500 mb analysis. Heights (m, solid) and absolute vorticity (10^{-5}/s, dashed).

According to Felsch (1990), the surge potential is based on the existence of stratus clouds in Southern California. At this time, there are no clouds in Southern California, therefore the potential for a stratus surge is low.

The 0000 UTC 01 May 1990 NMC surface analysis (Fig. 4) shows a 1004 mb low over Arizona and a weak inverted trough that extends from Arizona to northwestern California. A 1030 mb high pressure system dominates the Eastern Pacific Ocean off the California/ Oregon/Washington coasts with some high pressure ridging extending into Oregon and Nevada. During the next 36 hours, the high off the coast weakens 7 mb and the low over Arizona fills.

The 1200 UTC 01 May 1991 NMC surface analysis (Fig. 5) indicates a strong diurnal effect as the inverted trough extending from Arizona to northwestern California has strengthened and moved westward off the California coast. The strengthening of this coastal trough is due to increased surface ridging over northeastern California/northwestern Nevada. The 0000 UTC 02 May 1991 NMC surface analysis (Fig. 6) confirms the diurnal nature of these surface features. This diurnal effect is likely the result of the reduction to sea level pressure at higher elevations. GDAS extrapolation to sea level uses temperatures from two levels (Kanamitsu 1989), which would result in a diurnal variation in reduction to sea level. The strong inverted trough has moved eastward and is again positioned over the California coast, and the high pressure ridging over Northern California/Nevada has weakened and retreated northwestward. The 1200 UTC 02 May 1991 NMC surface analysis (Fig. 7) shows the same diurnal westward shift of the thermal trough and suggests that the thermal trough has intensified somewhat. According to Felsch (1990), this is one of the conditions normally present for a stratus surge.

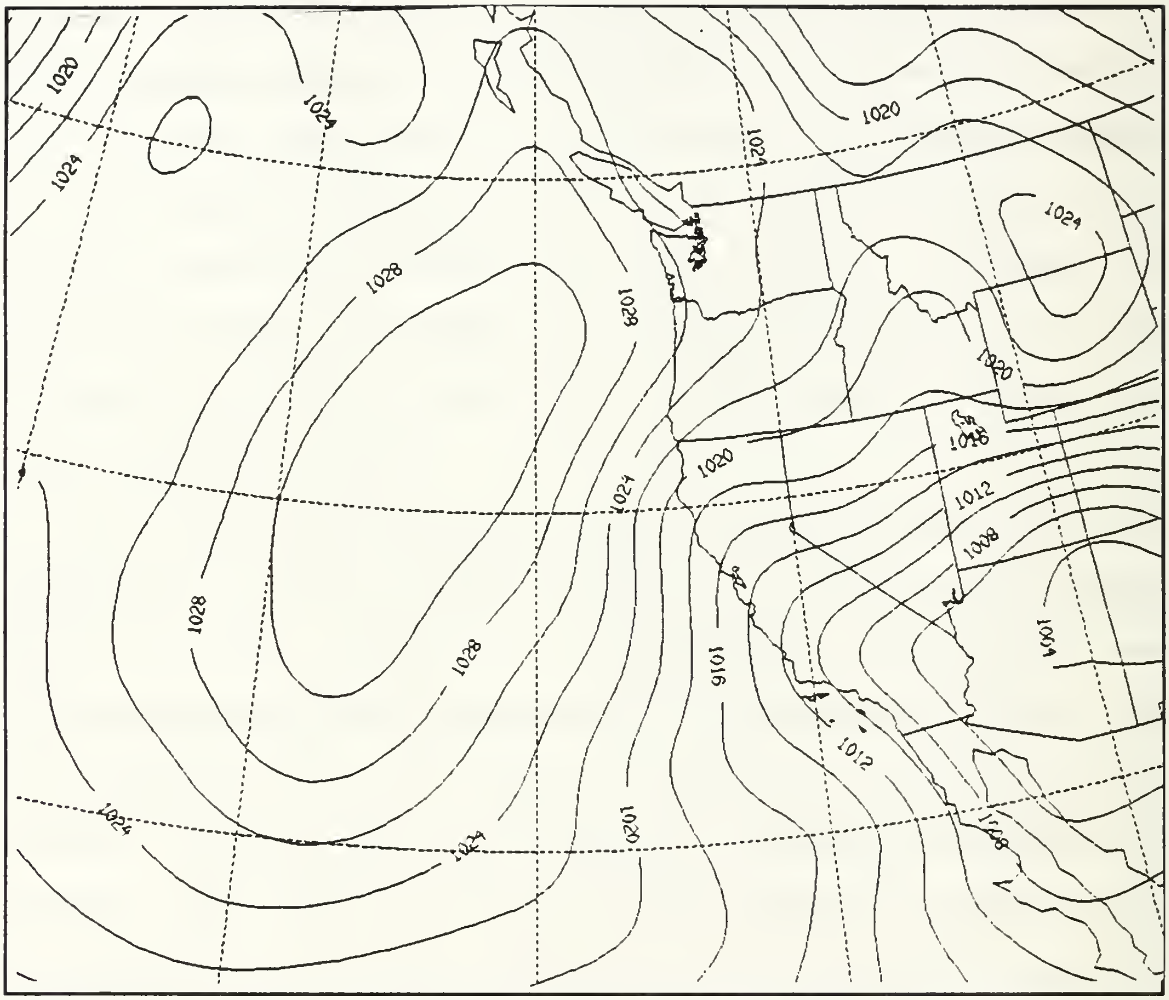

Figure 4. 0000 UTC 01 May 1990 NMC Sea Level Pressure (mb) Analysis.

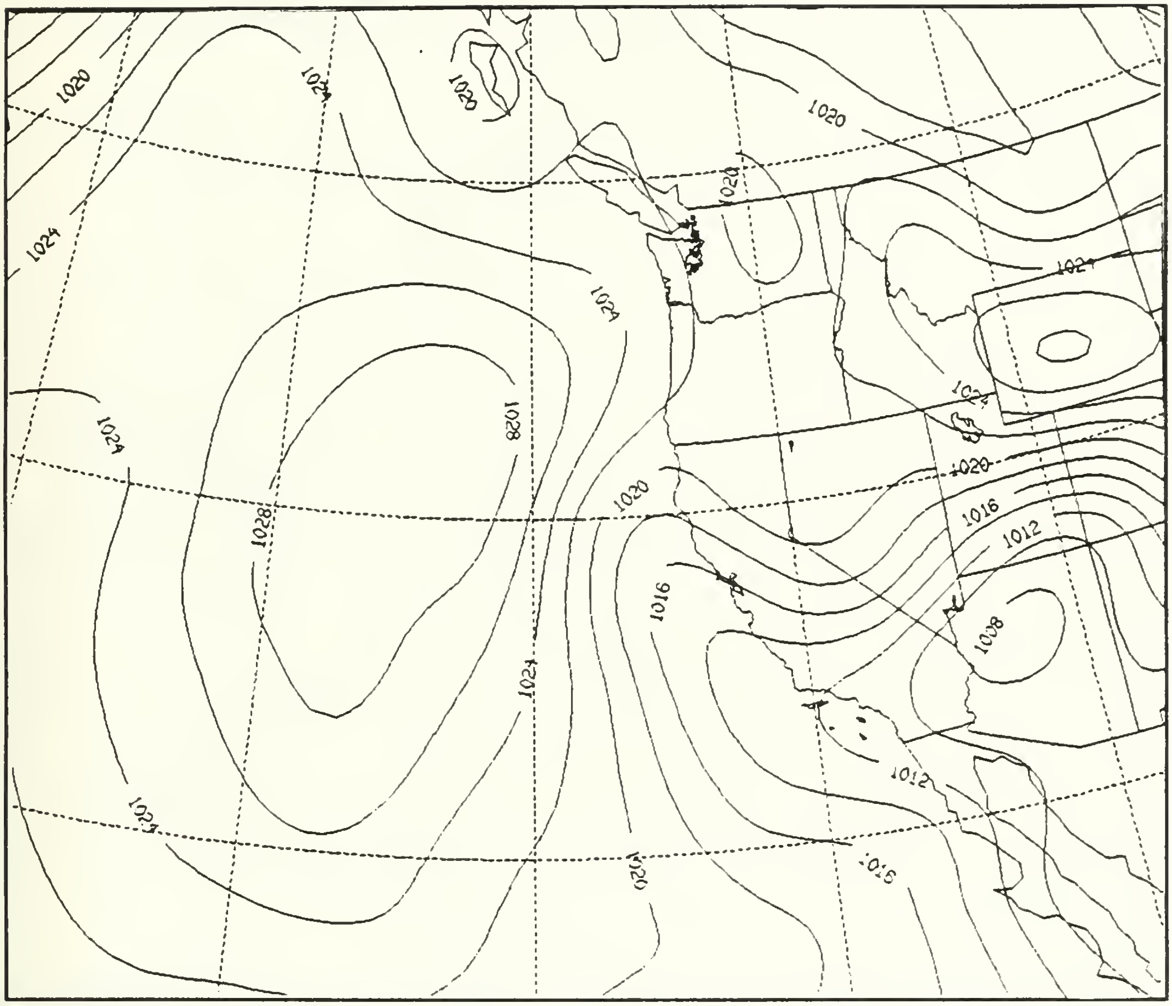

Figure 5. 1200 UTC 01 May 1990 NMC Sea Level Pressure (mb) Analysis.

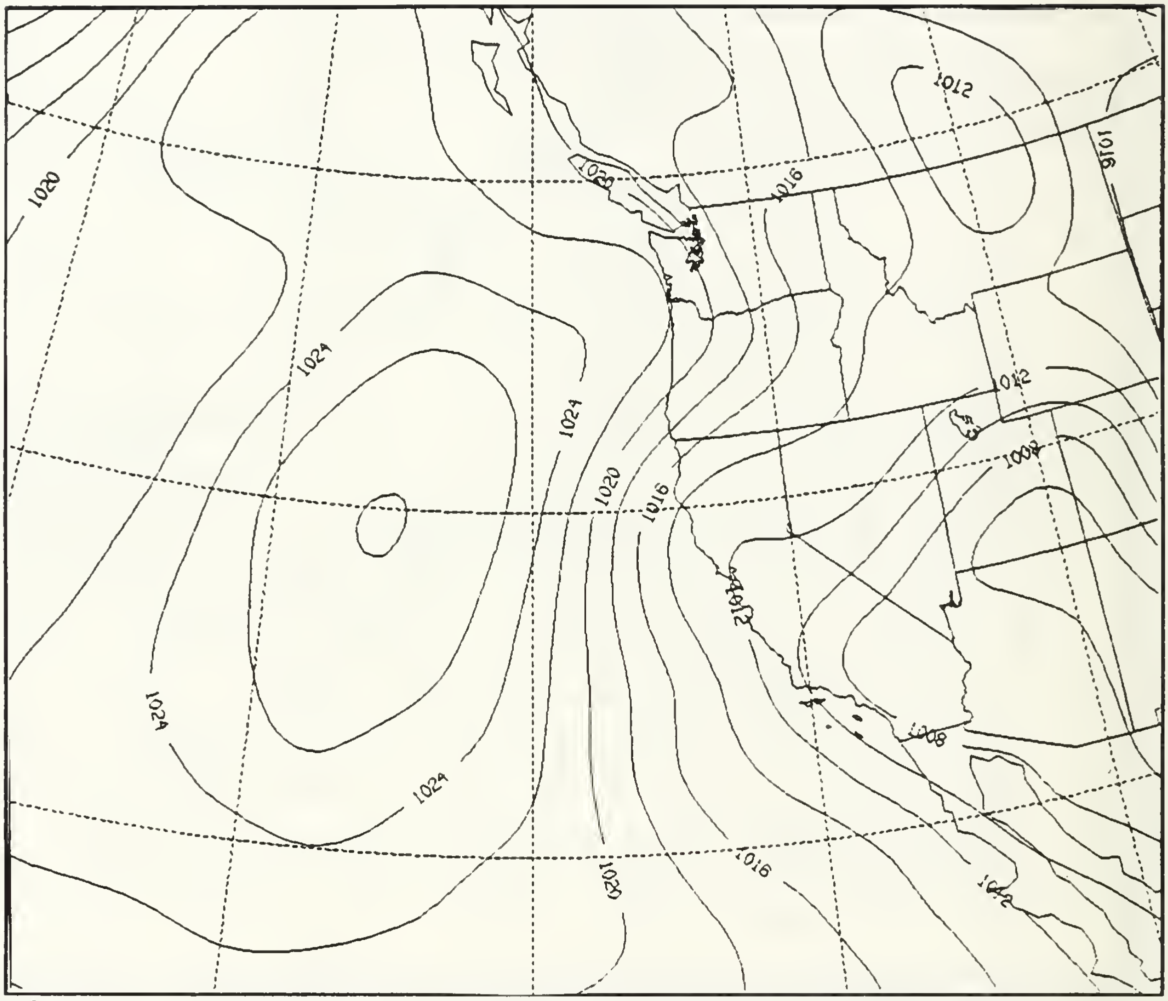

Figure 6. 0000 UTC 02 May 1990 NMC Sea Level Pressure (mb) Analysis.

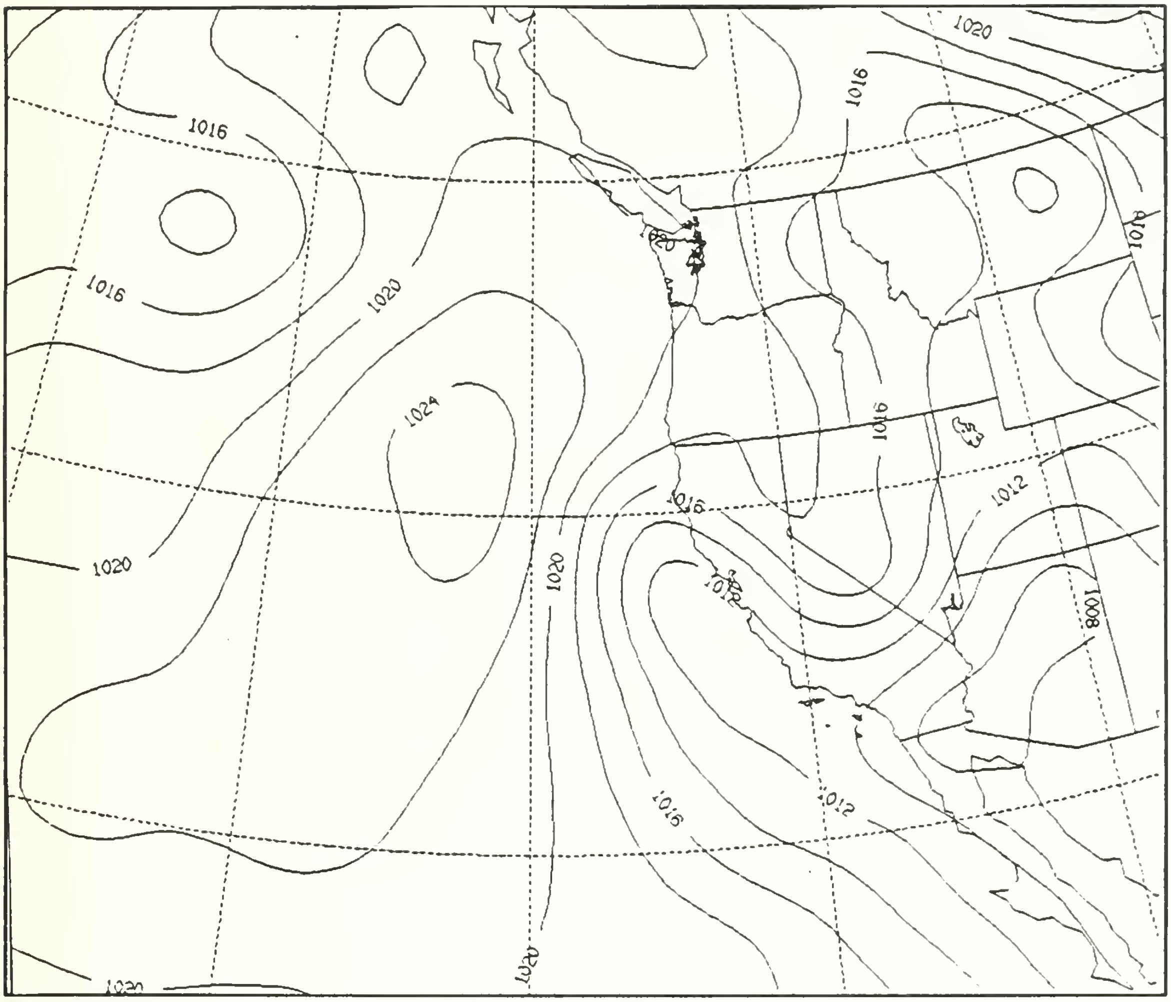

Figure 7. 1200 UTC 02 May 1990 NMC Sea Level pressure (mb) analysis.

B. TRANSITION PERIOD

The period from 1200 UTC 02 May to 1200 UTC 03 May represents the transition from no coastal stratus and fog to extensive stratus and fog along the Central and Southern California Coast. The 1501 UTC 02 MAY GOES visible image (Fig. 8) shows stratus or fog along the Central California Coast from Monterey Bay to Point Conception, with patchy stratus south of Point Conception. The 2031 and 2231 UTC 02 May visible GOES images (not shown) show that the stratus/fog has moved away from the California coast, except from Monterey Bay south to Morro Bay. The Salinas surface observations show that the fog formed around 1200 UTC on 02 May and burned off by 1600 UTC on 02 May, but this may have been radiation fog. Monterey observations as well as the satellite imagery indicate that stratus persisted along the coast. By 0500 UTC on 03 May, the stratus has returned to Salinas and other inland locations. By 1200 UTC 03 May the stratus is very extensive along the coast from San Francisco to Los Angeles as shown by the 1501 UTC 03 May satellite imagery (Fig. 9).

The synoptic surface analyses from 1200 UTC 02 May (Fig. 7) to 1200 UTC 03 May (Fig. 10) show the same patterns but indicate that the surface ridge has intensified in Northern California and Nevada. The inverted coastal trough at 1200 UTC 03 May is positioned off the California coast, farther west than has been the trend for the previous 60 hours. This sea level pressure pattern suggests relatively strong offshore flow in Northern and Central California.

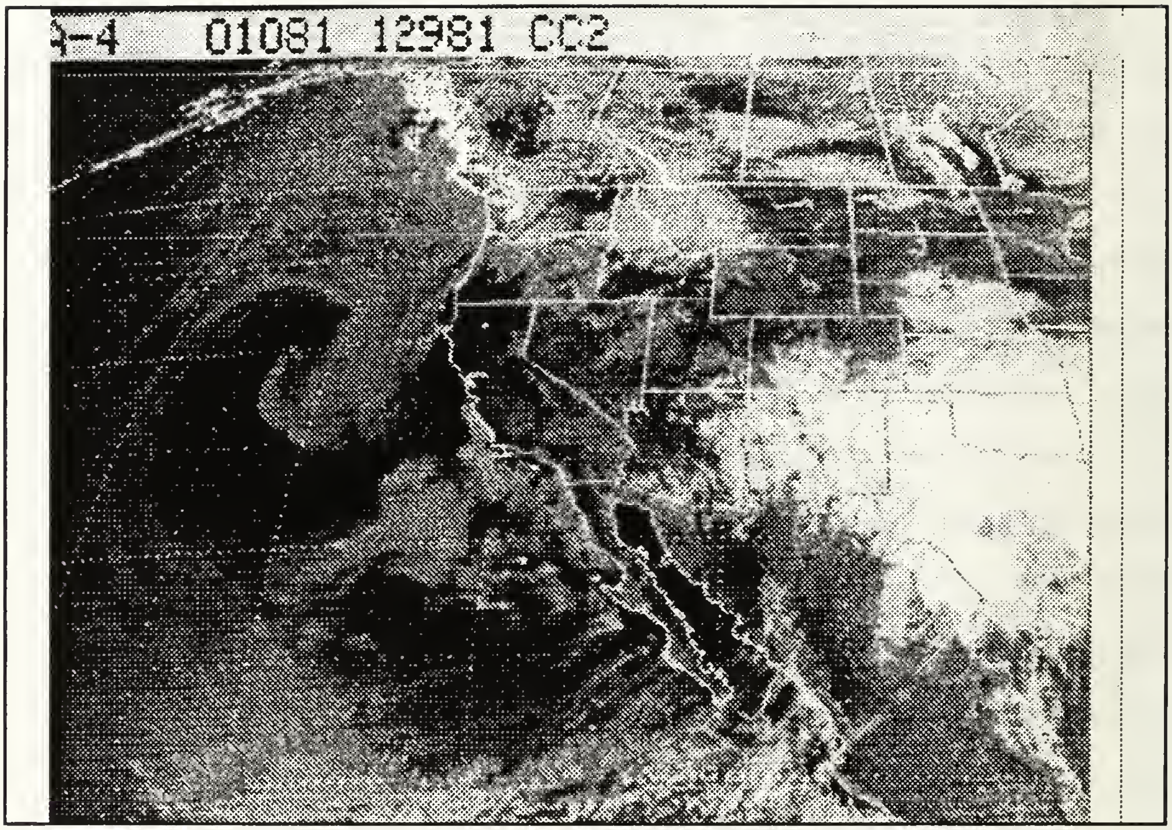

Figure 8. 1501 UTC 02 May 1990 GOES visible satellite imagery.

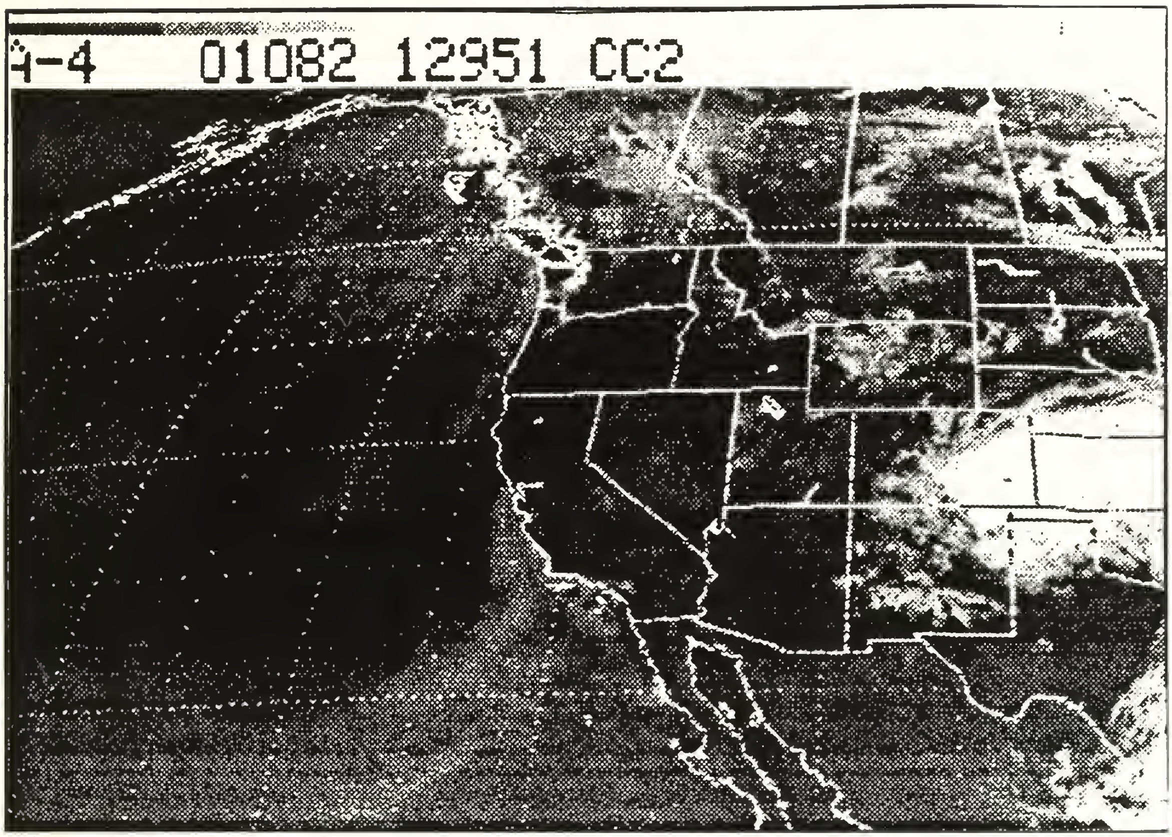

Figure 9. 1501 UTC 03 May 1990 GOES visible satellite imagery.

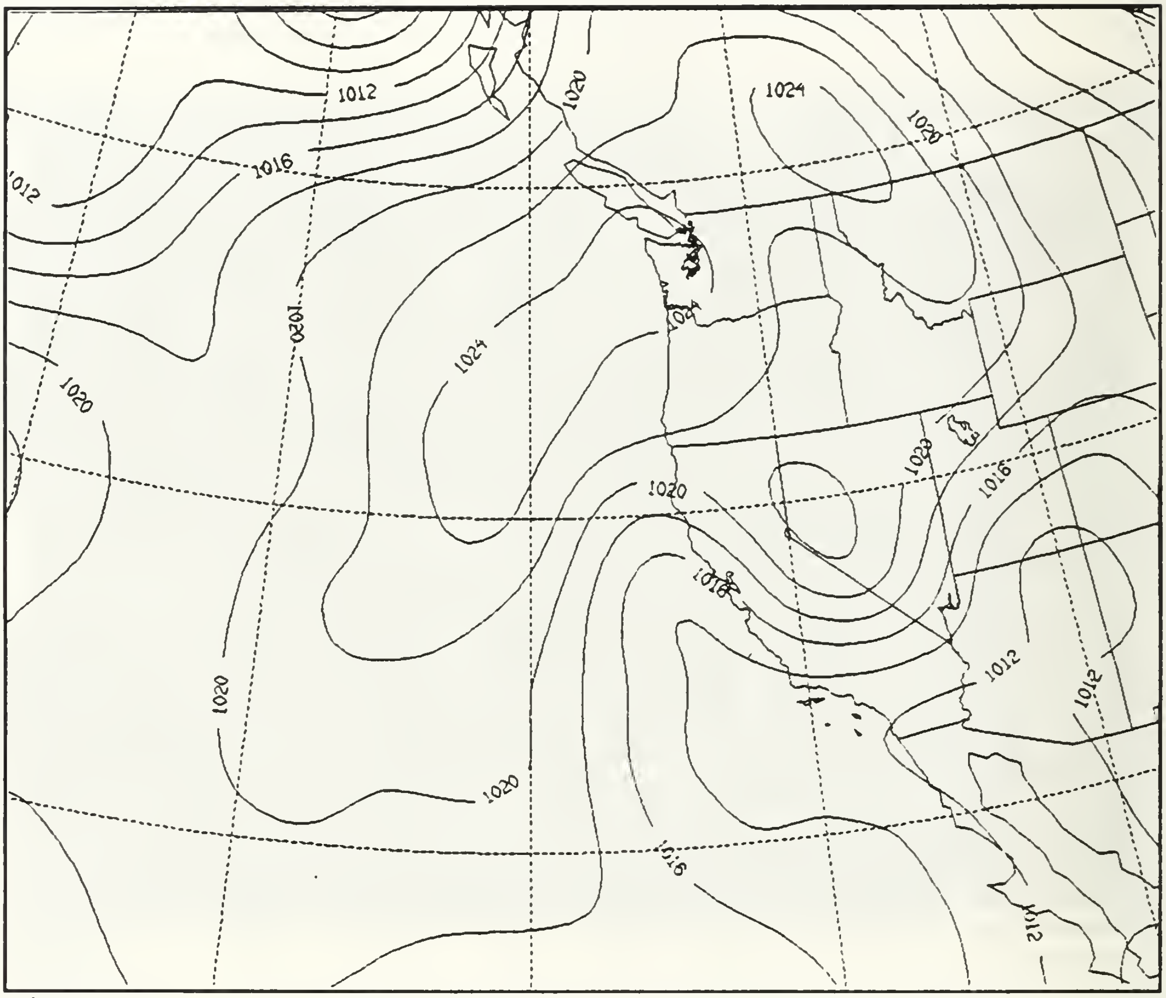

Figure 10. 1200 UTC 03 May 1990 NMC Sea Level Pressure (mb) Analysis.

The 0000 UTC (not shown) and 1200 UTC 03 May 500 mb NMC analyses show the Eastern Pacific ridge building northeastward, although it weakened between 0000 UTC 01 May and 1200 UTC 02 May, and the 500 mb cut off low over Arizona moving eastward and weakening. The shortwave over Washington at 1200 UTC 02 May (Fig. 3) has moved south with the maximum vorticity located in Northern Utah (Fig. 11). This northern shortwave trough produces weak negative vorticity advection along the Central California Coast due to the north to northeasterly flow over Northern California. The shortwave trough extending into Southern California is producing positive vorticity over Southern California.

While it is true that some of the same conditions are present in this case as were present in Felsch (1990), there is no stratus formation present in Southern California prior to the formation in Central California (i.e., there is no indication of a surge of stratus from Southern California northward). Additionally, at the beginning of this period the location of the upper-level low is well east of the normal initial location of the upper-level lows discussed in Felsch (1990).

C. STRATUS/FOG PERIOD

After 1200 UTC 03 May, coastal stratus and fog was well established and remained in place until the next significant

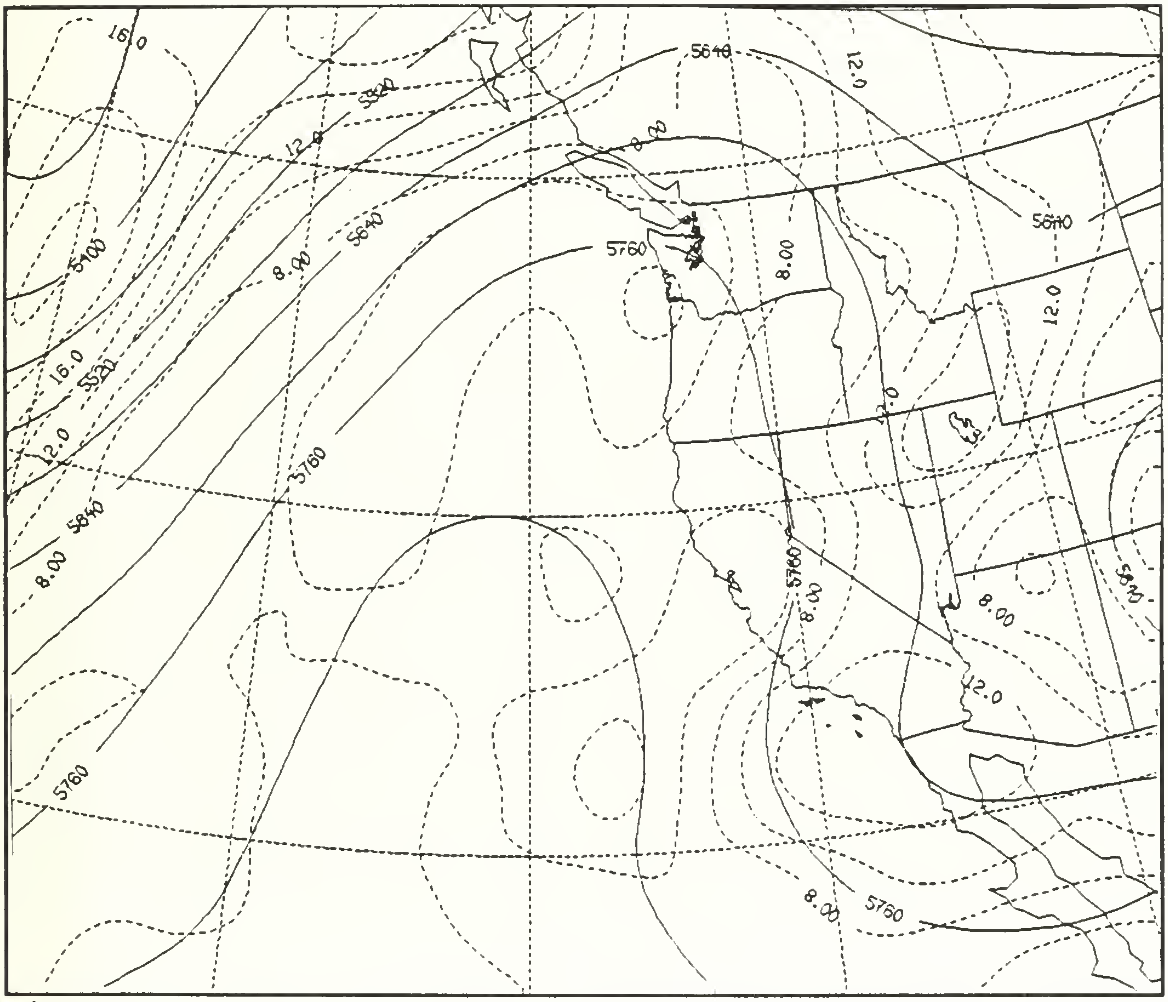

Figure 11. 1200 UTC 03 May 1990 NMC 500 mb analysis. Heights (m, solid) and absolute vorticity (10^{-5}/s, dashed).

shortwave passed the coast after 05 May. All GOES visible imagery for 3 and 4 May show stratus or fog extending along the California coast from north of San Francisco to the southern border of California and west several hundred miles off the coast of California. The 1501 UTC 04 May GOES visible imagery (Fig. 12) demonstrates the extent of the coastal stratus during this period.

During this stratus/fog period, the primary upper-level large-scale features shift eastward in response to a shortwave approaching from the west. The 1200 UTC 04 May 500 mb NMC analysis (Fig. 13) shows the high pressure ridge in the eastern Pacific continuing to build northeastward. The ridge axis has passed the coast in Washington and Oregon and is approaching the coast in Northern California.

Associated with this eastward movement of the upper-level ridge, the Pacific Northwest surface high moves eastward and the surface pressures increase southward into Northern California/ Nevada. The 1200 UTC 04 May NMC surface analysis (Fig. 14) shows that the inverted coastal trough has extended northward although the pressure has increased compared to 24 hours earlier. By 0000 UTC 05 May, the inverted trough has pushed all the way north to Washington along the California and Oregon coasts. The trough has weakened significantly as well but remains offshore on the large-scale analyses.

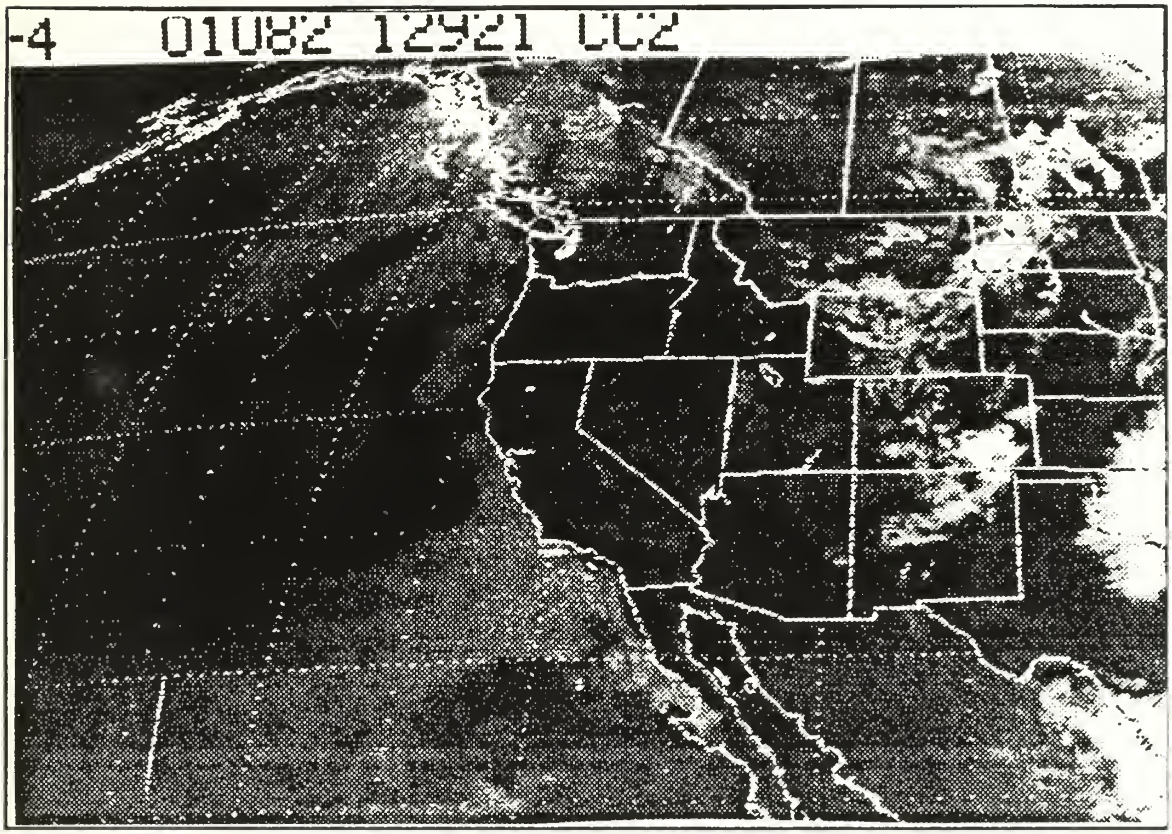

Figure 12. 1501 UTC 04 May 1990 GOES visible satellite imagery.

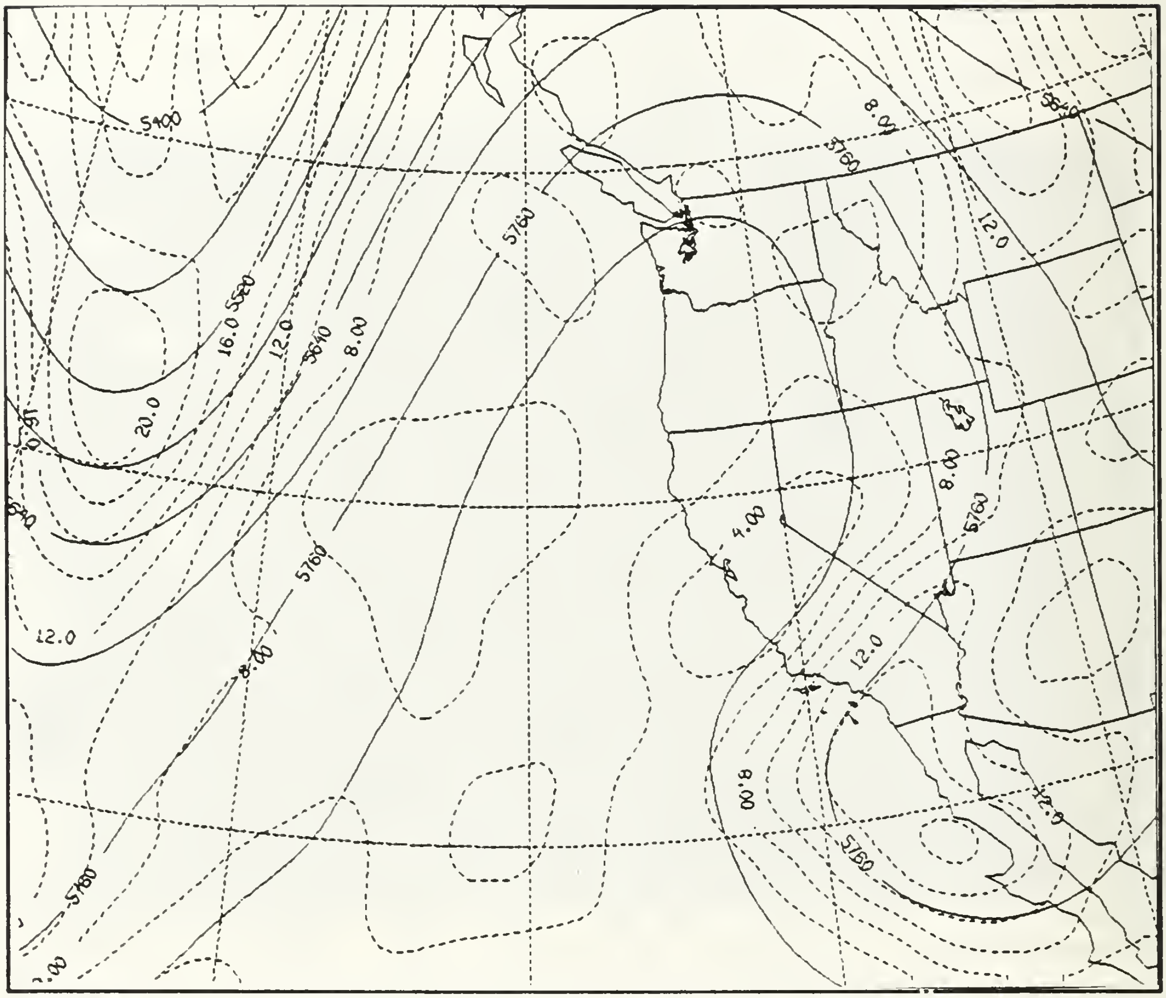

Figure 13. 1200 UTC 04 May 1990 NMC 500 mb analysis. Heights (m, solid) and absolute vorticity (10^{-5}/s, dashed).

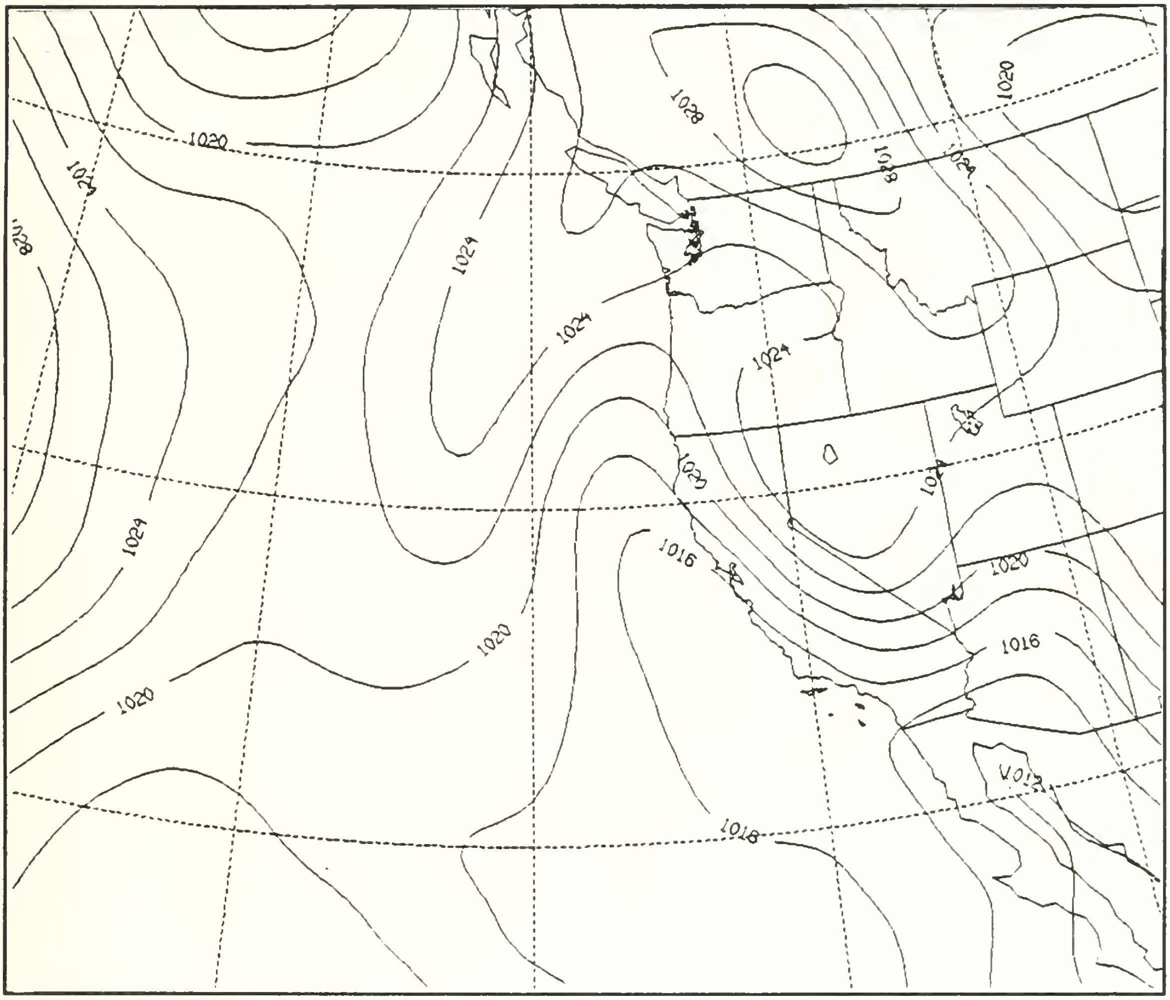

Figure 14. 1200 UTC 04 May 1990 NMC Sea Level Pressure (mb) Analysis.

D. SYNOPTIC SUMMARY

The significant large-scale evolution can be summarized as follows:

1) A very high amplitude 500 mb ridge became established just off the west coast after a shortwave trough moved south through California. Throughout most of this period the dominant feature was this eastern Pacific (EPAC) ridge, which remained stationary along 130° W during the period from 0000 UTC 01 May 1990 up to 1200 UTC 02 May. Strong subsidence following the initial trough passage through California produced dry, clear conditions over the California coastal area. A weak shortwave passed through the Pacific Northwest, which may have contributed to subtle low-level changes that lead to the onset of coastal stratus and fog along the Central California Coast. By 0000 UTC 03 May, after the shortwave moved through the Pacific Northwest, and for the remainder of the period, the EPAC ridge built to the northeast and crossed the coast by 1200 UTC 03 May. Significant coastal stratus was present throughout this period.

2) At the surface, the synoptic-scale evolution was less pronounced than that seen at 500 mb. The most obvious feature is the diurnal movement of the California inverted thermal trough. During the periods between 0000 UTC and 1200 UTC it is night time in California, and the thermal trough

consistently moves westward, or off shore. During the periods between 1200 UTC and 0000 UTC it is day time, and the thermal trough consistently moves eastward, or onshore. The extent of this onshore/offshore fluctuation was similar throughout the period and does not readily explain the transition from clear to stratus conditions. By the end of the evaluation period the average position of the inverted trough was farther west than it had been at the beginning of the period, which can be attributed to the eastward shift of the upper-level ridge and associated surface pressure increase inland.

3) Because almost all the surface observations received for this area were over land, the NMC sea level pressure analysis short-term changes were primarily in response to data, or pressure, changes over land. Consequently, the exact position of the trough axis is difficult to determine and provides little indication of the transition from clear to cloudy conditions. The surface winds along the coast associated with the flow around the inverted trough are from the north to slightly northwest when the trough is inland and from the southeast when the trough is offshore. This pattern of surface flow implies a sea breeze/land breeze type circulation along the coast, which is evident in the Salinas (SNS) wind observations, although the night time winds are generally calm and not southeasterly. Again, this general pattern gives no indication as to why the stratus forms as the sea/land breeze is present in the clear period as well.

Because of the shortcomings of the NMC surface analysis, mesoscale sea level pressure analysis were done and will be discussed in Chapter V.

V. MESOSCALE SURFACE ANALYSIS

To attempt to understand the subtle changes in the surface pressure and wind patterns that resulted in the formation of the coastal stratus, mesoscale surface analyses were performed. The analyses were done every three hours and suffer from a lack of offshore data. However, the coastal buoys provide enough information to indicate the sense of the offshore changes. In addition to these mesoscale surface analyses, available soundings were examined to describe the evolution of the boundary layer structure and determine conditions that support stratus along the Central California Coast.

A. CLEAR PERIOD

As mentioned in the synoptic analysis, the GOES visible imagery from 0001 UTC through 2231 UTC 01 May 1991 indicate generally clear skies along the western United States coastline with no fog or stratus present along the California coast. These conditions do not fall under the classification of a stratus surge studied by Felsch (1990) yet stratus does form.

The 1200 UTC 01 May and 02 May Oakland soundings both show surface-based inversions, indicative of subsidence resulting from the EPAC upper-level ridge. Both the 1200 UTC 01 May and 0000 UTC 02 May Oakland soundings show large areas of warming, which tends to confirm the existence of subsidence associated with the ridge (Fig. 15). Farther south at Vandenburg, the 1200 UTC 01 May and 0000 UTC 02 May both have similar large areas of warming, suggestive of subsidence, but by 1200 UTC 02 May the subsidence warming has decreased. This may signal that the subsidence over Southern California has diminished. All the Vandenburg soundings between 0000 UTC 01 May and 1200 UTC 02 May show inversions, or deeper, cooler marine layers, even during clear periods. Since surface air at Vandenburg is cooler than at Oakland and the Oakland soundings do not continually show inversions, the surface pressure is higher at Vandenburg than at Oakland. The presence of the cooler marine layer, coupled with increased subsidence near Vandenburg, act to support higher pressure at Vandenburg than at Oakland.

The dominant feature on all the mesoscale sea level pressure analyses is the inverted trough, which originates southeast of California and extends northwestward. Several low-pressure centers are evident within this trough with the most northern located near Merced (MER), as seen on the 0000 UTC 01 May pressure analysis (Fig. 16). The 0000 UTC 01 May

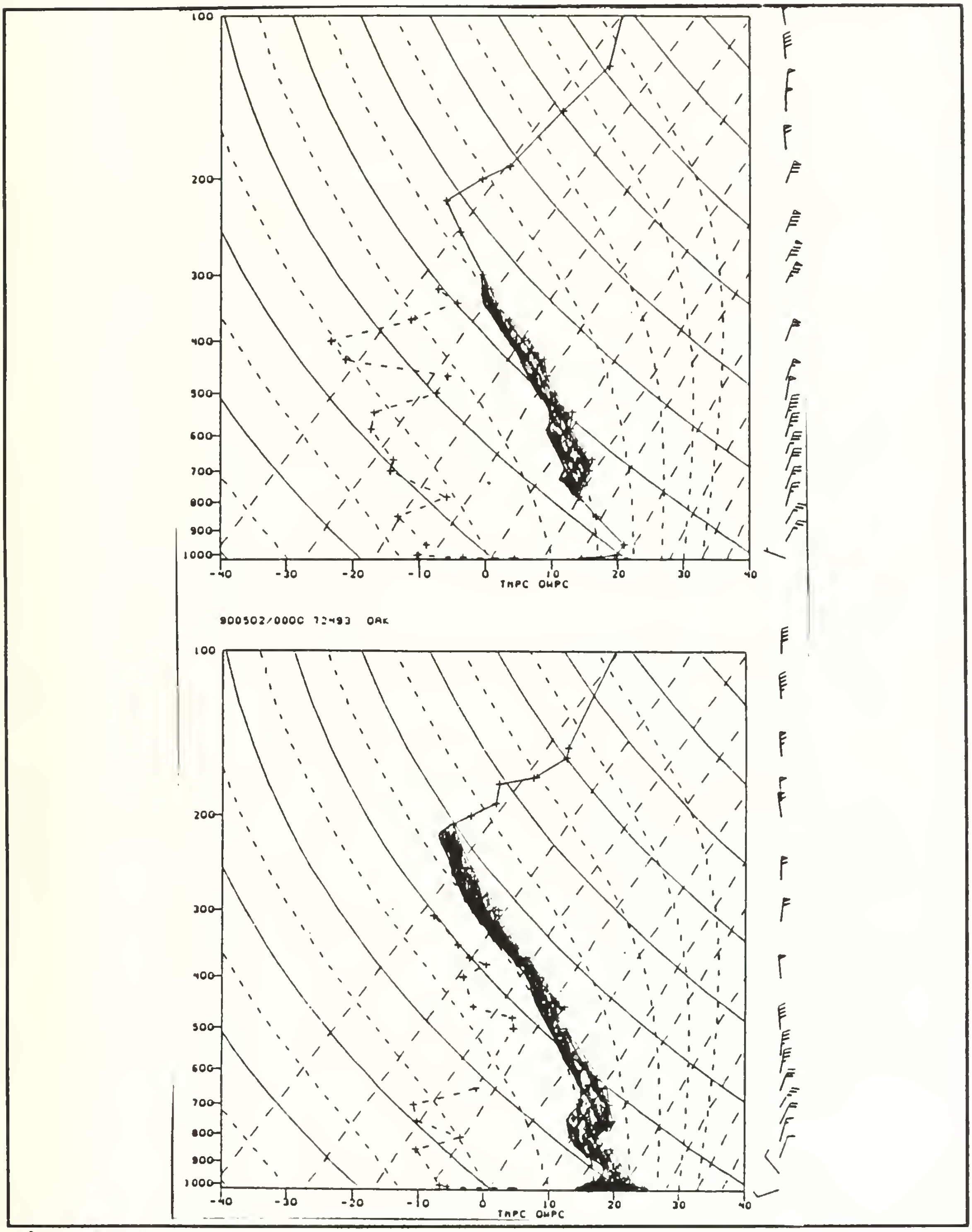

Figure 15. 1200 UTC 01 May 1990 and 0000 UTC 02 May 1990 upper air soundings for Oakland, CA. Shaded areas represent warming since the previous sounding.

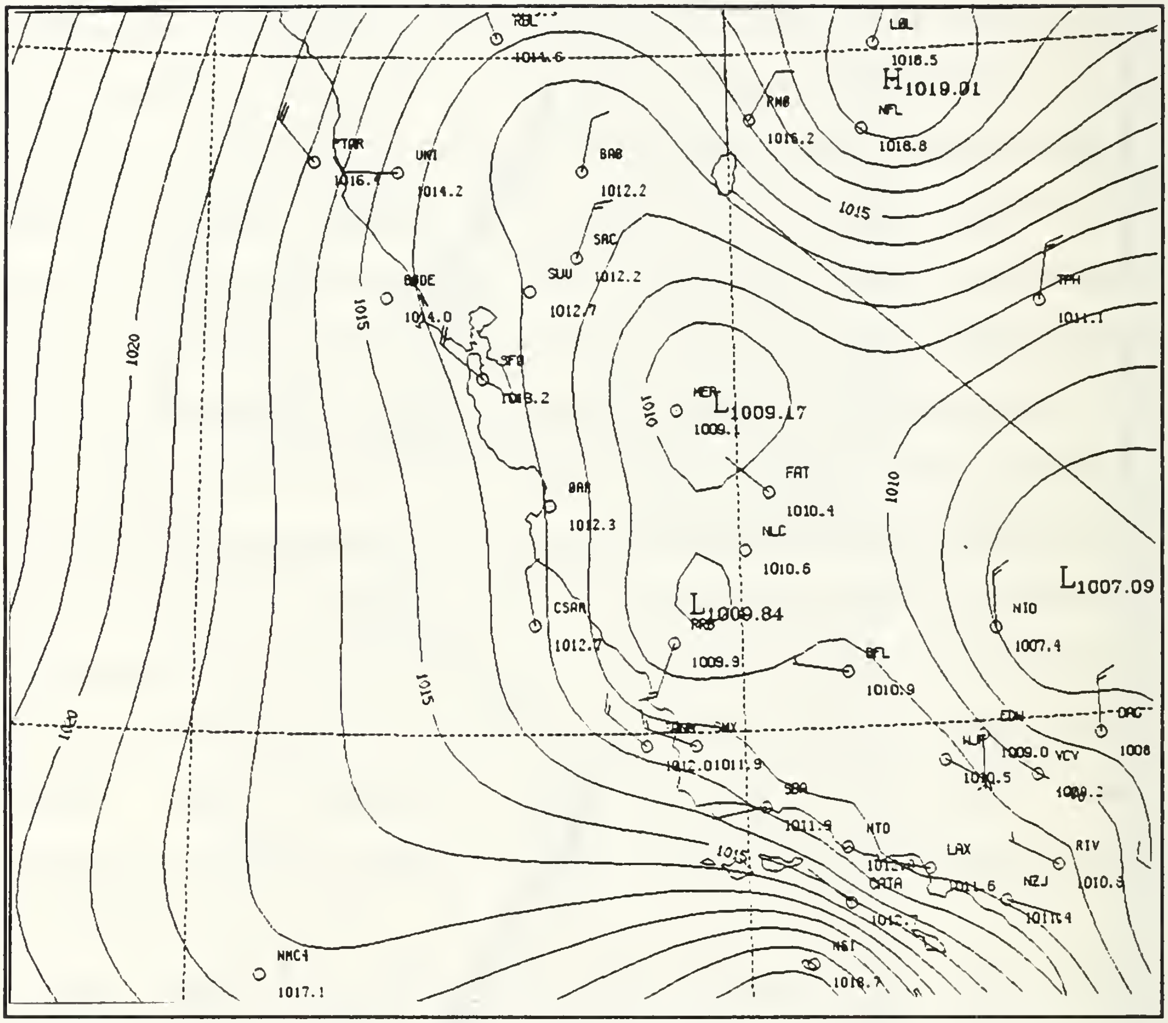

Figure 16. 0000 UTC 01 May 1990 Mesoscale Sea Level Pressure (mb) Analysis.

mesoscale surface wind analysis (not shown) shows the wind flow along the Central California Coast generally from the northwest parallel to the coast with north to northeast winds in the interior. The 0600 - 2100 UTC 01 May mesoscale sea level pressure analyses (not shown) show the diurnal effects of heating and cooling on the thermal low pressure systems. The flow continues to remain along shore or slightly onshore from the northwest until 0900 UTC 02 May, with the exception of the period between 1800 UTC 01 May and 0000 UTC 02 May, when the flow alternated between onshore and offshore for brief periods. The 0000 UTC 02 May mesoscale analysis (Fig. 17) shows the northward movement of the low pressure system in the Central Valley, indicative of the weakening of the subsidence in Northern California.

The 0000 02 May mesoscale winds (Fig. 18) shows the surface divergence to the south along the Southern California Coast where high pressure will eventually form and, through continuity, corresponds with the convergence and subsidence aloft. Because of the characteristic difficulties that exist in calculating the surface divergence, small maxima are present in the analysis, which are supported by only one or two observations. While these features are subject to question, one can have confidence with the larger scale pattern. This weakness of the surface divergence analyses is present throughout the period and is not discussed for each analysis presented in the remainder of this chapter.

The 0600 - 1200 UTC 02 May mesoscale sea level pressure analysis (not shown) show the night time cooling effects decreasing, compared to the previous 12 hours, and winds becoming light and variable. The 0600 UTC 02 May mesoscale sea level pressure analysis (Fig. 19) shows the pressure gradient weakening and the beginning of the higher pressure present to the south, setting the conditions for the possible onset of stratus and fog. The 0600 UTC 02 May mesoscale wind analysis (Fig. 20) shows the surface convergence present near

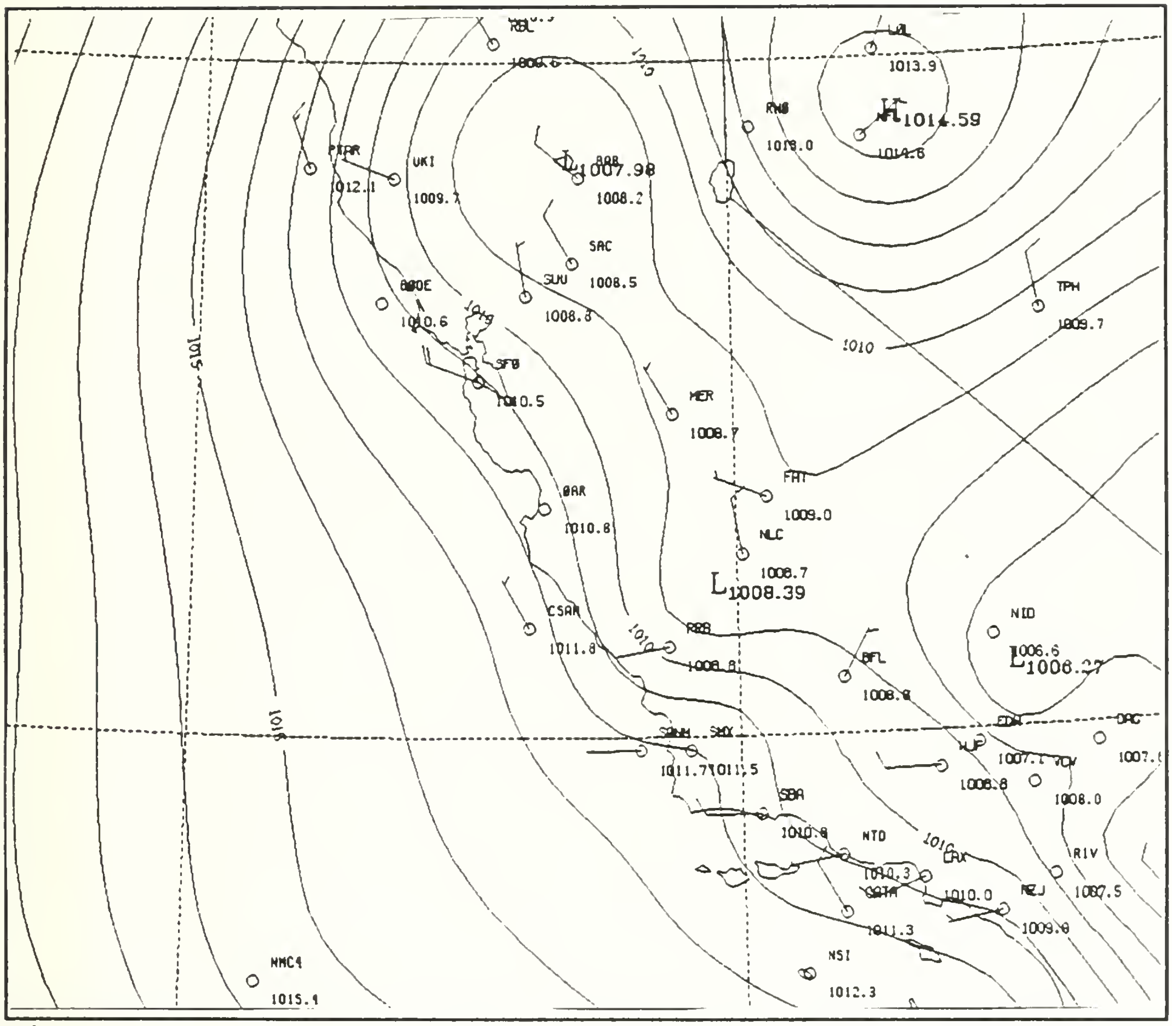

Figure 17. 0000 UTC 02 May 1990 Mesoscale Sea Level Pressure (mb) Analysis.

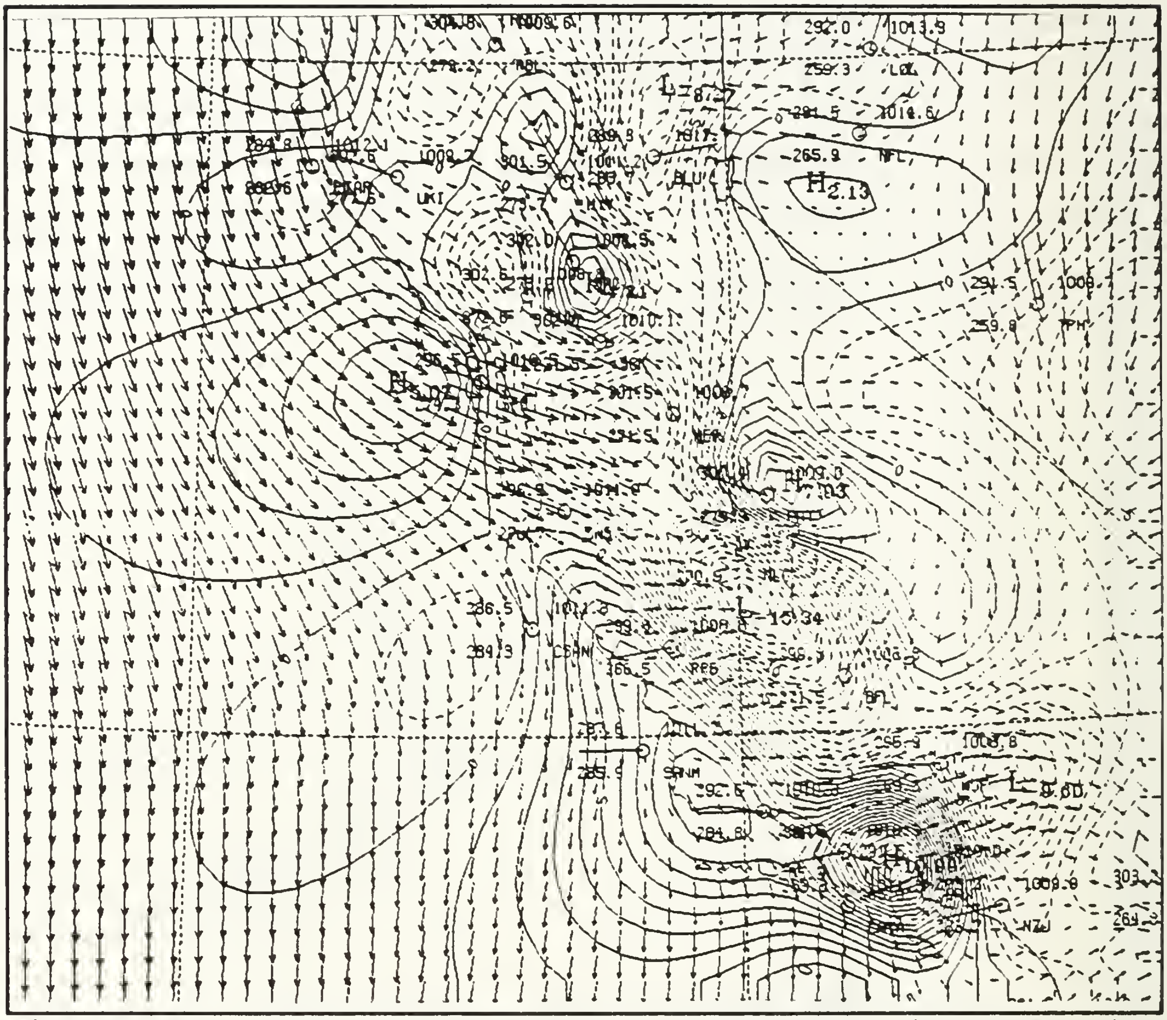

Figure 18. 0000 UTC 02 May 1990 mesoscale wind analysis. Contours from 1.5 x 10^{-5}/s to 1.9 x 10^{-5}/s. "H" represent areas of divergence and "L" represents areas of convergence.

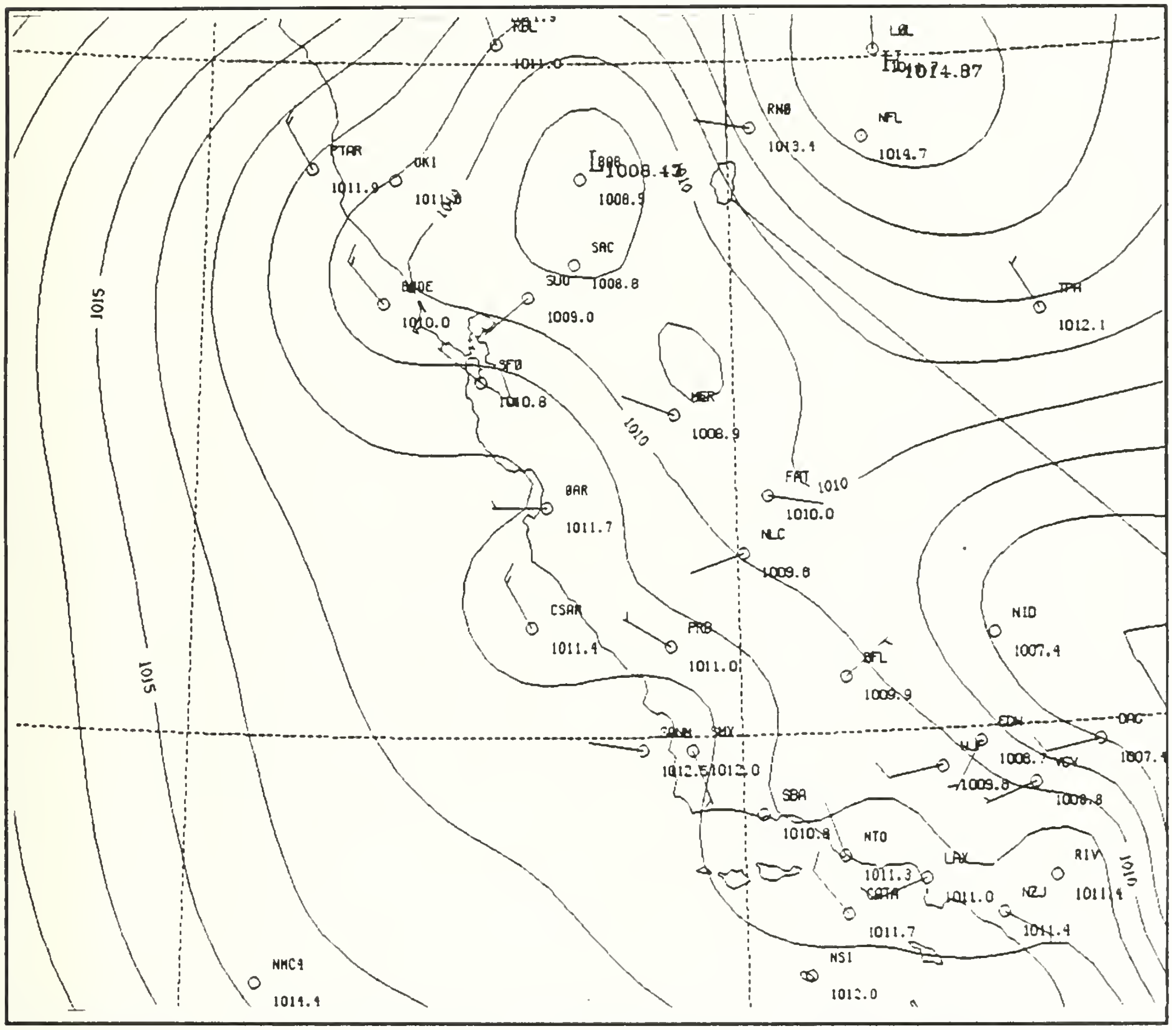

Figure 19. 0600 UTC 02 May 1990 Mesoscale Sea Level Pressure (mb) Analysis.

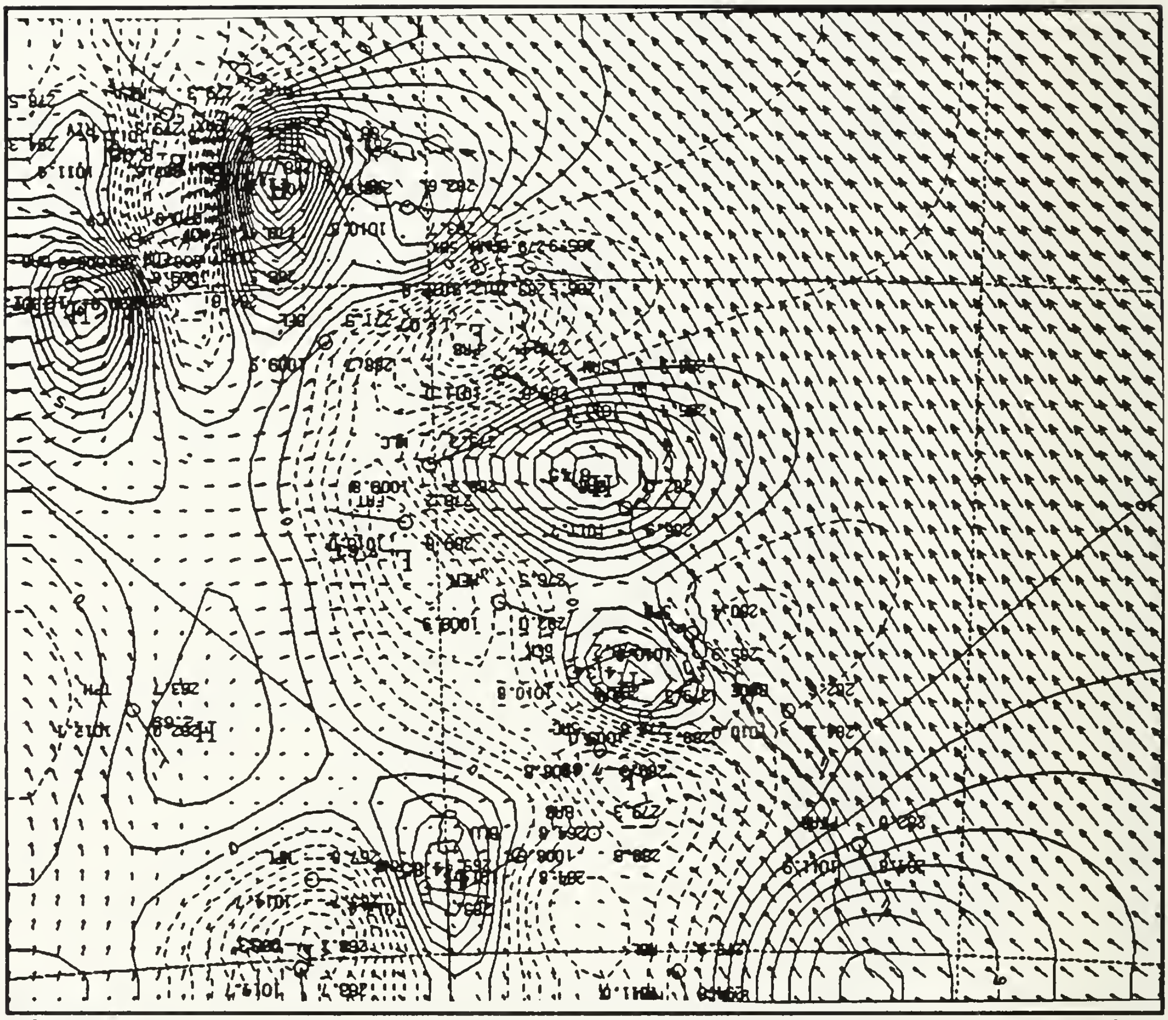

Figure 20. 0600 UTC 02 May 1990 mesoscale surface wind analysis. Contours from 1.5×10^{-5}/s to 1.9×10^{-5}/s.

Point Conception, deepening the marine layer which may also help initiate the stratus and fog formation. This relaxation in the pressure gradient is similar to the Felsch (1990) condition for a stratus surge, but the along shore pressure gradient does not suggest a southerly flow, as was the case in Felsch (1990).

B. TRANSITION PERIOD

As mentioned earlier, the period from 1200 UTC 02 May to 1200 UTC 03 May represents the transition from no coastal stratus and fog to extensive stratus and fog along the Central and Southern California Coast. A thorough evaluation of this transition period would include an understanding of what caused the stratus to suddenly form along the Central California Coast, vice travel north from Southern California as a surge.

Other than the inverted trough extending northwest from Arizona, the most significant feature shown on the 1200 UTC 02 May to 1200 UTC 03 May mesoscale analysis is the building of a mesoscale surface ridge along the Central California Coast and extending as far north as San Francisco. The 2100 UTC 02 May mesoscale sea level pressure analysis (Fig. 21) shows the developing high/low pressure pattern along the coast. The 2100 UTC 02 May mesoscale surface wind analysis (Fig. 22) shows the actual sea breeze pattern and flow from the south, in contrast to the northerly offshore flow on the NMC surface

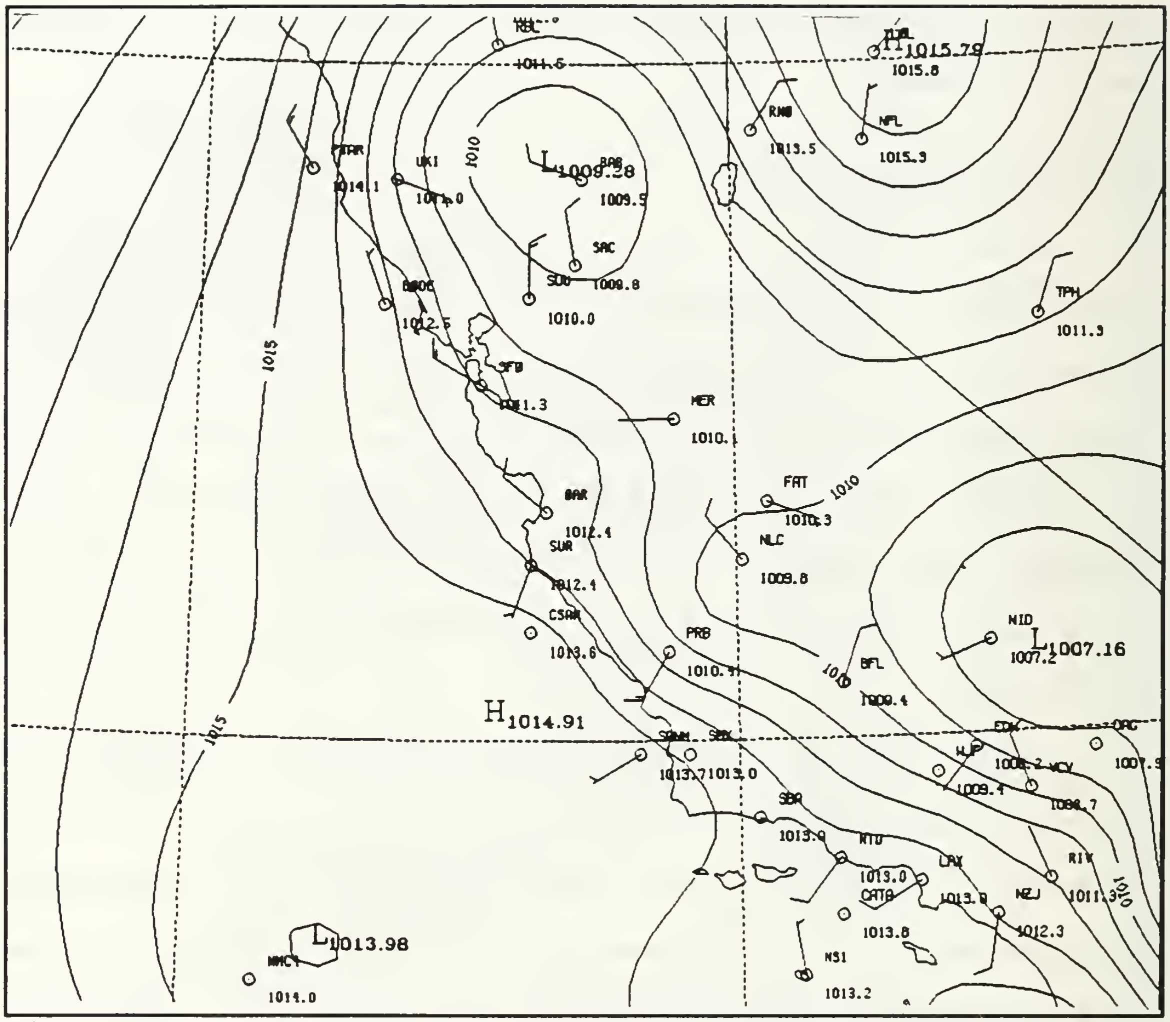

Figure 21. 2100 UTC 02 May 1990 Mesoscale Sea Level Pressure (mb) Analysis.

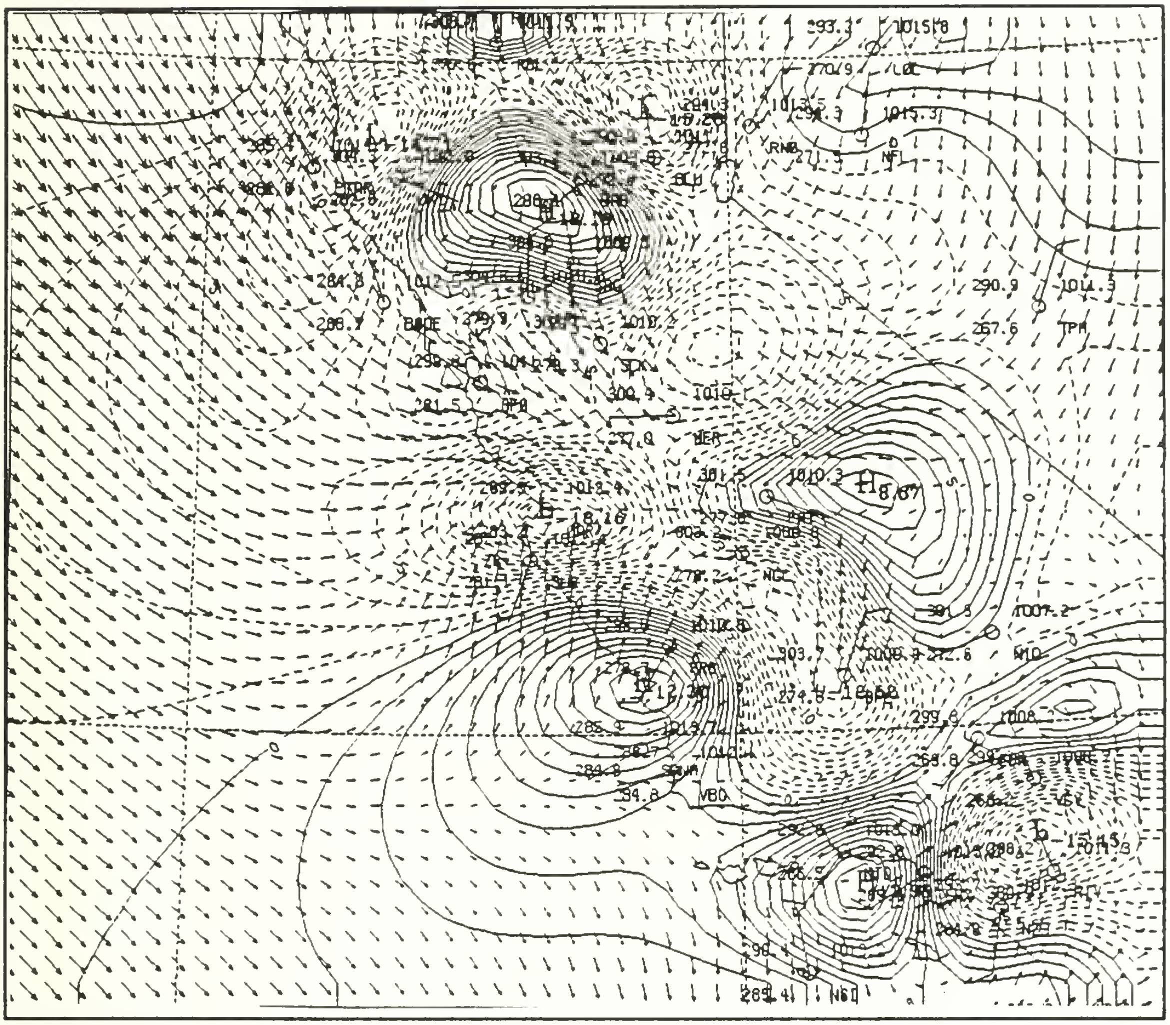

Figure 22. 2100 UTC 02 May 1990 mesoscale wind analysis. Contours from -1.8×10^{-5}/s to 1.3×10^{-5}/s. "H" represents areas of divergence and "L" represents areas of convergence.

pressure analyses presented in Chapter IV. The mesoscale surface ridge, seen on the 0600 UTC 03 May mesoscale sea level pressure analysis (Fig. 23), corresponds to the stratus covered area and evidently represents the pressure increase due to a deeper, cooler marine layer in this region. The 1200 03 May mesoscale analysis (Fig. 24) shows the classic stratus and fog surface features similar to the Mass and Albright (1987) and Dorman (1985) cases, but this is a characteristic feature of any stratus situation. The difference between this study and these other two is the meteorological situation that led up to the stratus and fog formation. Once the stratus and fog have formed the scenarios become similar in appearance.

One feature that potentially initiated the formation of this surface ridge is the large-scale eastward movement of the upper-level system. This pushed the shortwave ridge over the Pacific Northwest southward and the cut-off low over Southern California eastward (Figs. 3 and 26), allowing the area of NVA downstream of the shortwave ridge to move past Oakland and over Vandenburg (near SMX), leaving neutral advection over Oakland. The NVA over SMX produced increased pressure at Vandenburg, and the decrease in NVA from the shortwave ridge resulted in a decrease in pressure at Oakland. Although the NMC 500 mb charts do not necessarily show the shortwave ridge moving over Oakland during the period 0000 UTC to 1200 UTC 02 May, a graph of the 500 mb heights (Fig. 25) at Oakland shows

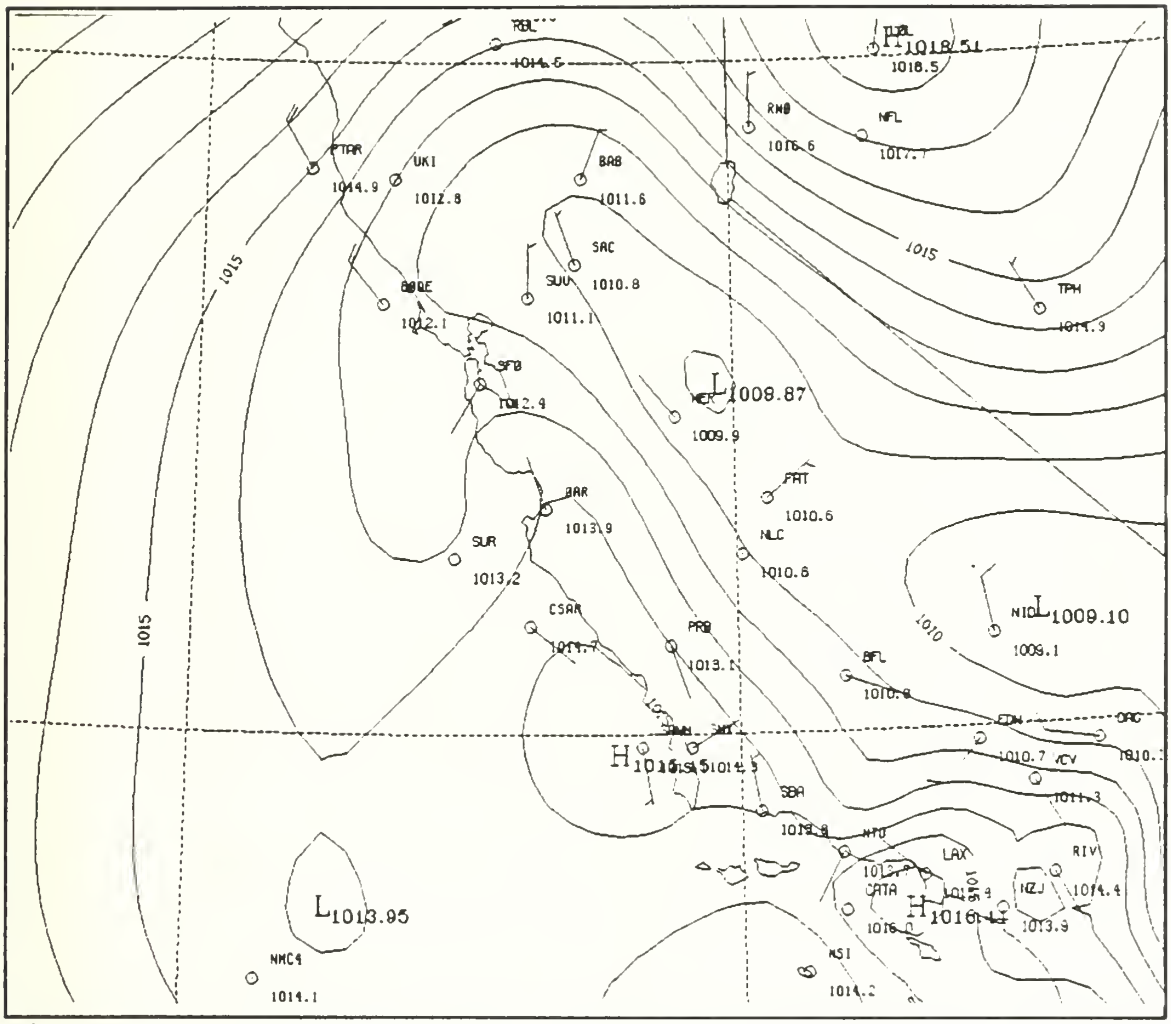

Figure 23. 0600 UTC 03 May 1990 Mesoscale Sea Level Pressure (mb) Analysis.

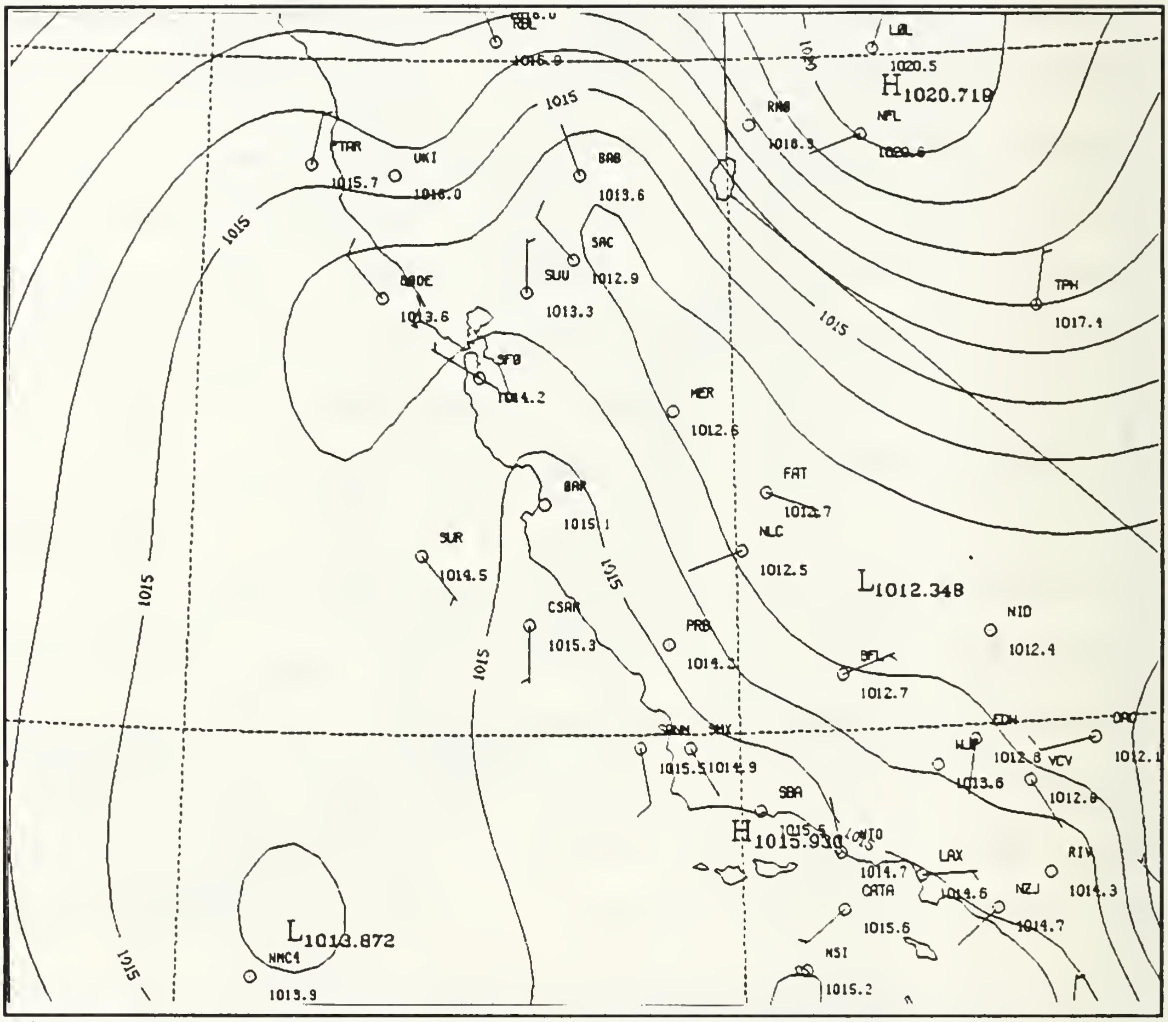

Figure 24. 1200 UTC 03 May 1990 Mesoscale Sea Level Pressure (mb) Analysis.

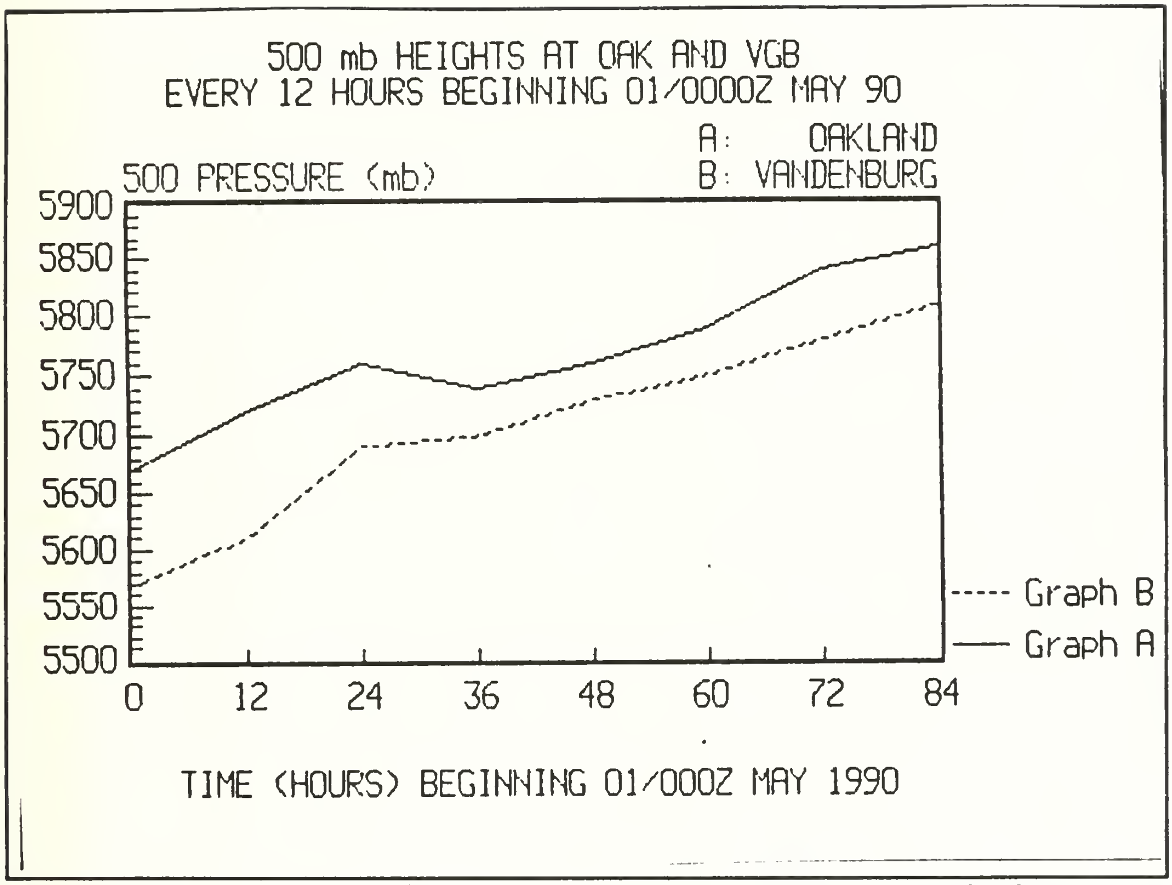

Figure 25. 500 mb heights from Oakland, CA and Vandenburg, CA upper air soundings plotted every 12 hours from 0000 UTC 01 May 1990 through 1200 UTC 04 May 1990.

a height decrease between 0000 UTC and 1200 UTC 02 May, indicating an area of PVA over Oakland. This height decrease indicates that the upstream side of the shortwave ridge is over Oakland, vice the downstream side of the ridge, as indicated on the 0000 UTC 02 May 500 mb NMC Analysis (Fig. 26).

This explains why the surface pressure near Oakland (BODE, which is a buoy) decreased while the pressure increased near Vandenburg (SANM, which is a buoy) between 0000 UTC and 0600 UTC 02 May, as seen on the surface pressure plots for BODE and SANM (Fig. 27). We would normally expect a decrease in surface pressure associated with a decrease in the upper-level heights. The increased pressure at Vandenburg and decrease in pressure at Oakland set up a north/south pressure gradient that resulted in the flow from the south. A plot of the sea level pressures at 1200 UTC on 01, 02 and 03 May for the four buoys off the California coast (PTAR, BODE, CSAN, and SANM) (Fig. 28) shows a pressure reversal from higher pressure near Oakland (BODE) to lower pressure relative to SANM (near Vandenburg). A plot of the sea surface temperature and air temperature at the CSAN buoy (Fig. 29) show the air temperature decreasing after 24 hours into the period (0000 UTC 02 May) and then the sea and air temperatures generally remain about the same after 1200 UTC 02 May. This indicates that the stratus and fog probably formed between 0000 and 1200

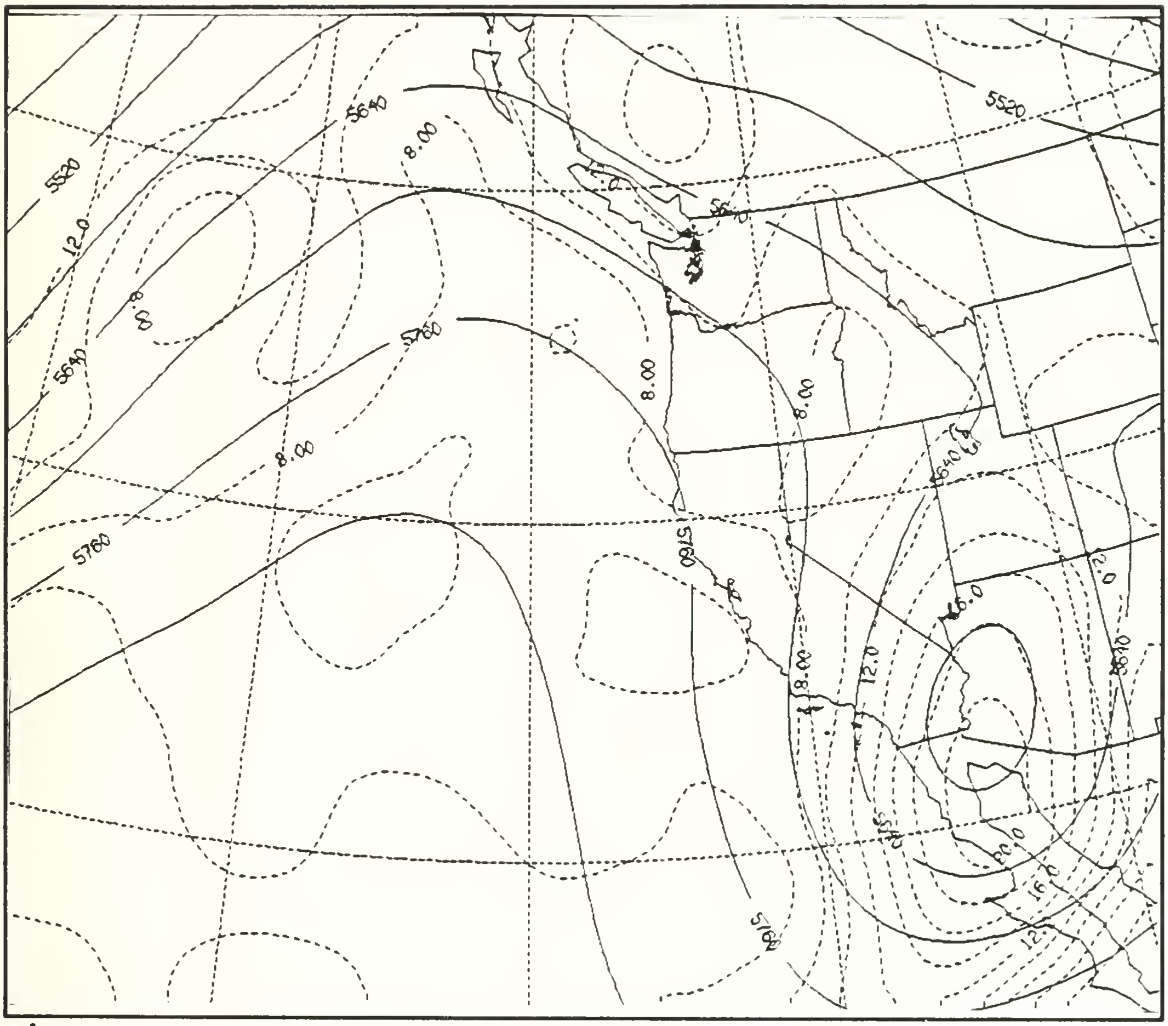

Figure 26. 0000 UTC 02 May 1990 NMC 500 mb analysis. Heights (m, solid) and absolute vorticity (10^{-5}/s, dashed).

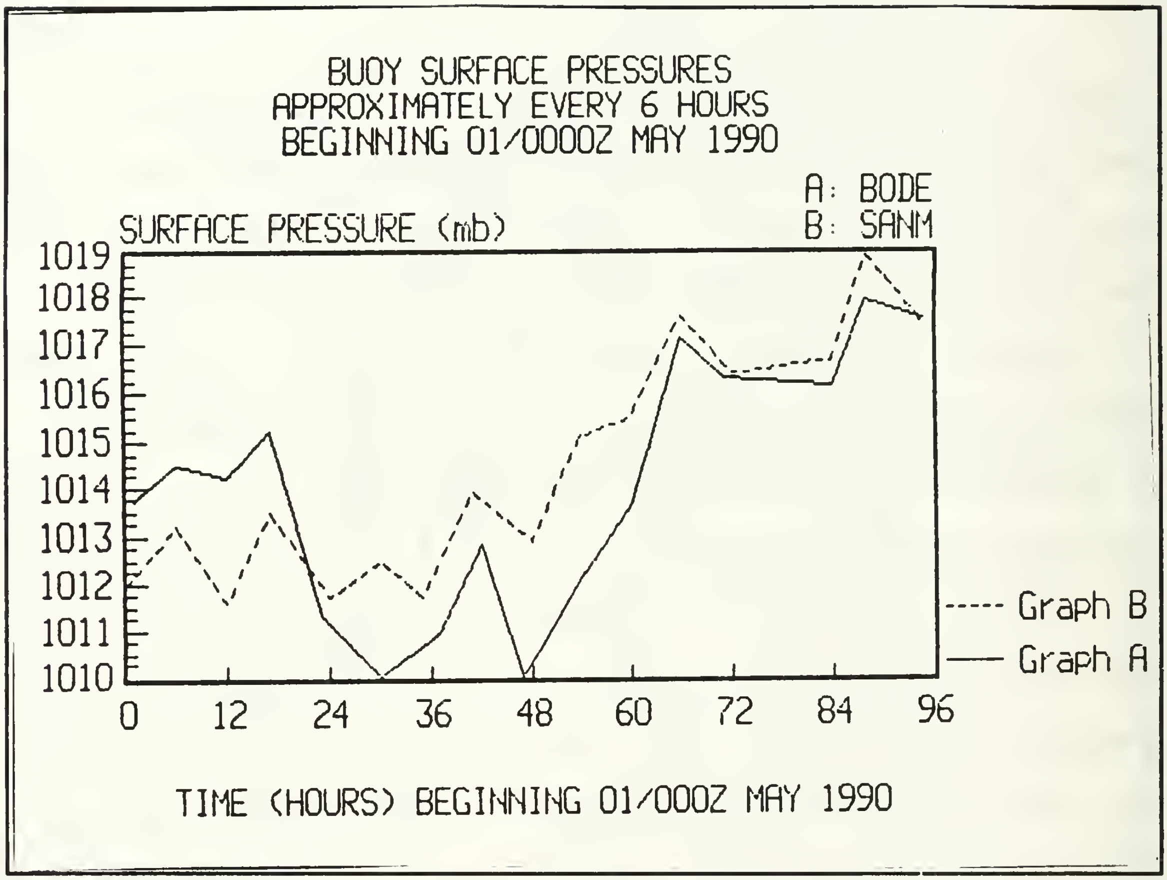

Figure 27. Surface pressure for BODE and SANM buoys plotted approximately every 6 hours from 0000 UTC 01 May 1990 through 2300 UTC 04 May 1990.

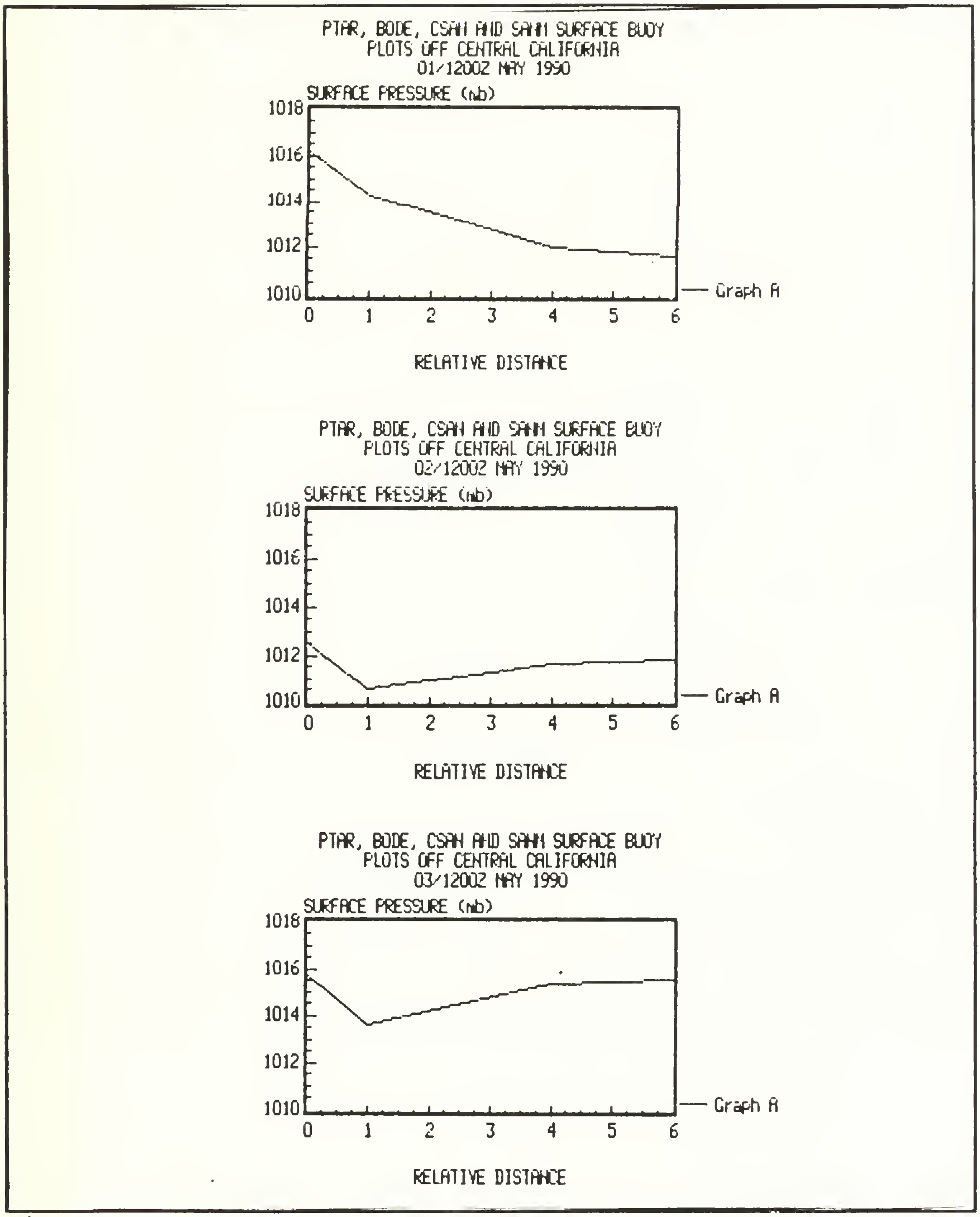

Figure 28. Surface pressure for PTAR (farthest north), BODE, CSAN and SANM (farthest south) buoys plotted every 24 hours beginning 1200 UTC 01 May 1990. X axis (distance) is scaled relative to the separation distance between the buoys.

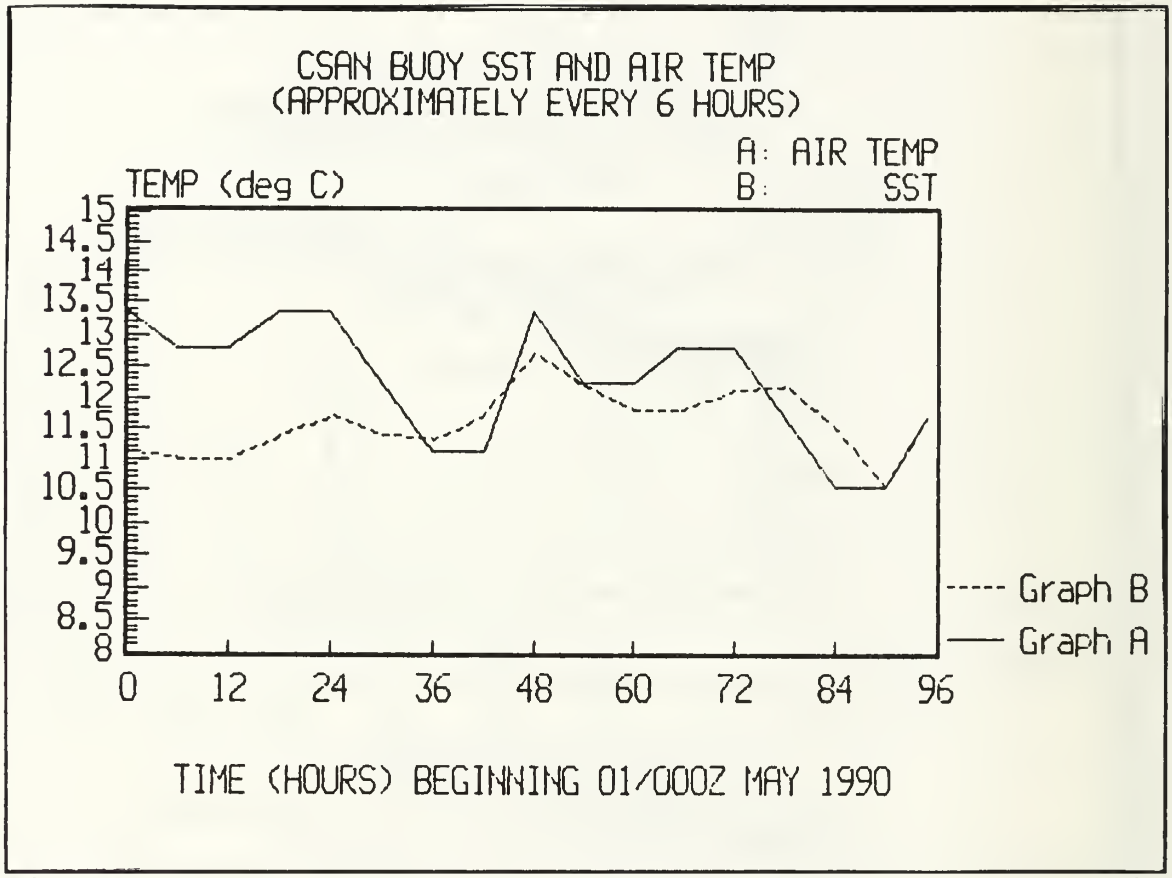

Figure 29. Sea surface temperature (deg C) and air temperature (deg C) for CSAN buoy plotted approximately every 6 hours from 0000 UTC 01 May 1990 through 2300 UTC 04 May 1990.

UTC on 02 May and continued at the CSAN buoy for the remainder of the period.

As seen on the 0900 UTC 03 May surface winds analysis (Fig. 30), the surface ridge produces southerly flow south of the Monterey Bay and, because of the already present northerly flow above the Monterey Bay, results in surface convergence near the Monterey Bay and later north of San Francisco. A comparison with the 1200 UTC 02 May wind analysis shows a complete reversal of the coastal wind flow south of San Francisco from north to south. This indicates that the pressure gradient has also reversed and the higher pressure is now south of the low pressure. The warmer southerly flow produces additional surface convergence at the ridge axis, elevating the marine layer. The 0000 UTC 03 May Oakland sounding shows the surface inversion rising to 975 mb, indicative of a weakening of the subsidence aloft and the surface convergence on the edge of the high pressure tongue. The 2031 and 2231 UTC 03 May GOES visible imagery show a tongue of stratus and fog co-located with this surface convergence, elevated marine layer and the ridge axis seen on the 0000 UTC 04 May mesoscale sea level pressure analysis (Fig. 31). The 1200 UTC 02 May to 0000 UTC 03 May mesoscale analysis show a relatively strong low located over SAC, indicating the presence of a strong daytime sea breeze. At this point the stratus is "surging" up the California coast to

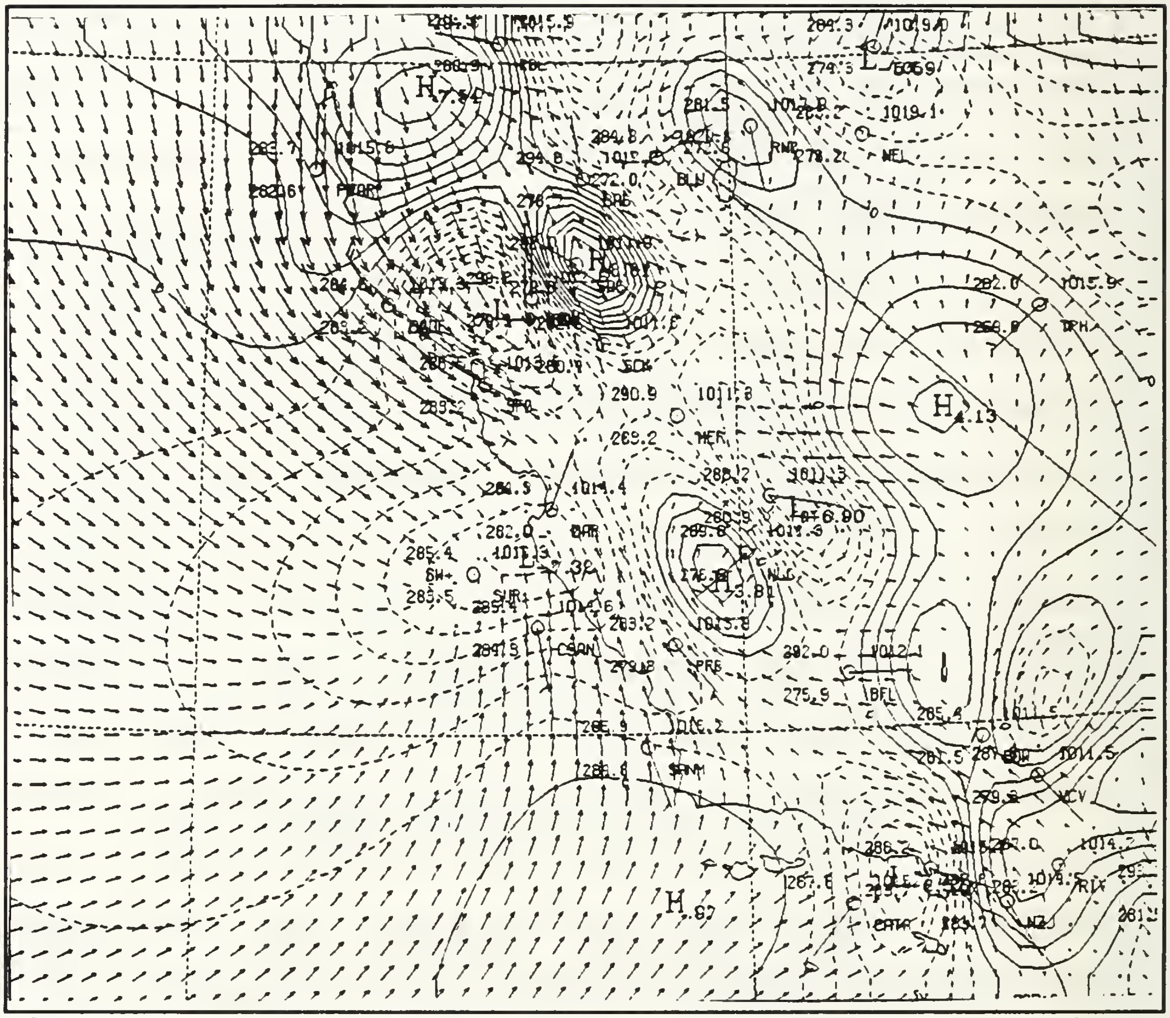

Figure 30. 0900 UTC 03 May 1990 mesoscale surface winds. Contours from .9 x 10^{-5}/s to 1.0 x 10^{-5}/s. "H" represents areas of divergence and "L" represent areas of convergence.

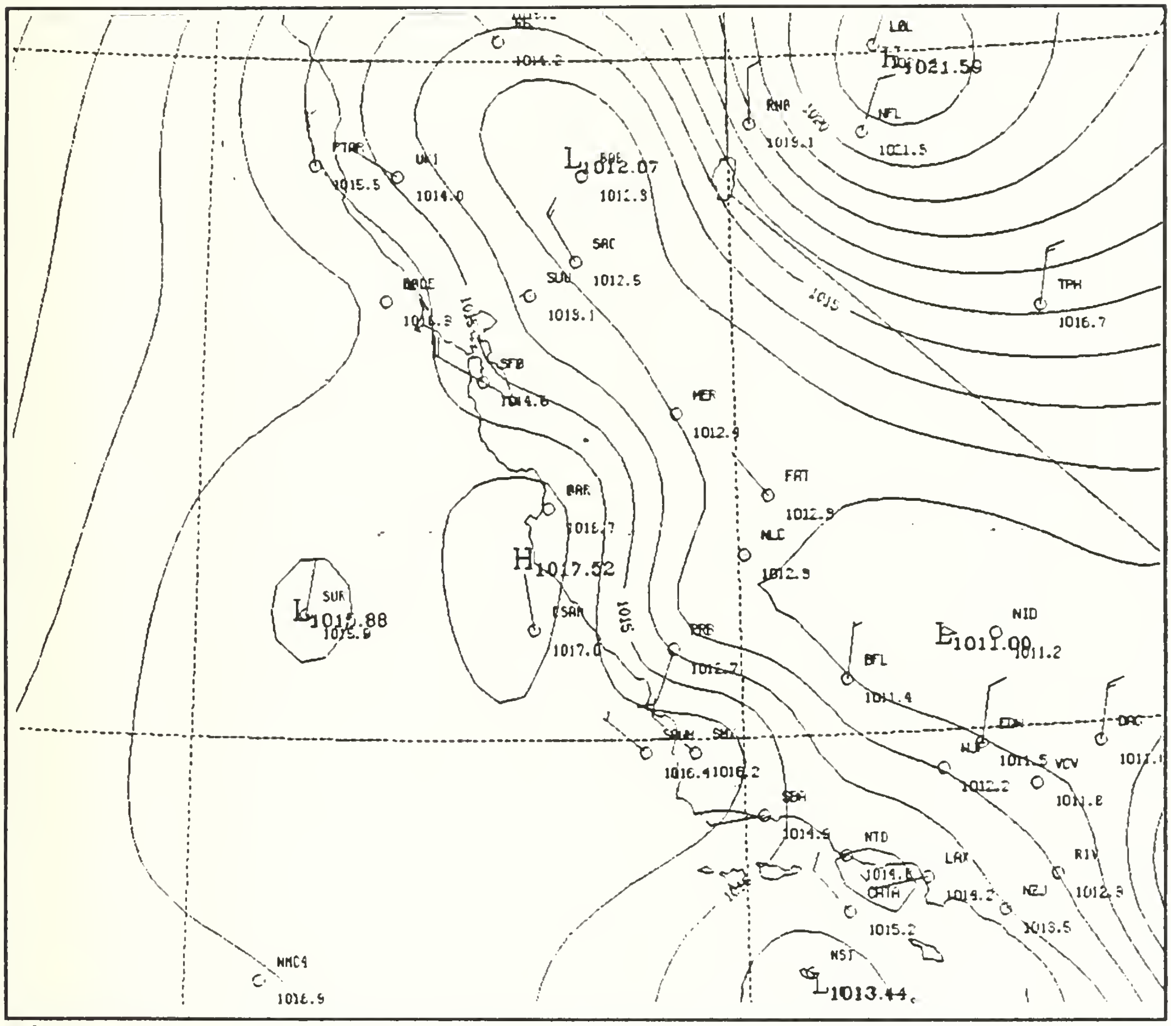

Figure 31. 0000 UTC 04 May 1990 Mesoscale Sea Level Pressure (mb) Analysis.

a small degree, similar to the Mass and Albright and Dorman cases discussed earlier.

C. STRATUS/FOG PERIOD

As mentioned in the synoptic discussion, after 1200 UTC 03 May, coastal stratus and fog are well established and remain in place through the end of this period, although moving north later in the period. The movement is similar to that described in Mass and Albright (1987), who referred to the movement as a stratus surge.

The 1200 UTC 03 May to 0900 UTC 04 May mesoscale analyses show the onshore flow and area of convergence moving north of San Francisco. The 04 May satellite imagery confirms that as the surface ridge moves up the coast, so does the convergence area, stratus and fog. This movement, as mentioned before, is similar to that discussed by Mass and Albright (1987). During the later period, this case is similar to the Mass and Albright 1982 case. In fact, the Mass and Albright case took place during the same time of year (03 - 08 May 1982).

The 0600 - 2100 UTC 04 May mesoscale analyses show the decrease of the sea breeze due to the movement of the large-scale upper-level high-pressure system inland, as represented by the 2100 UTC 04 May mesoscale sea level pressure analysis (Fig. 32). This marks the breakdown of this stratus event as the cold front offshore moves through during the next day.

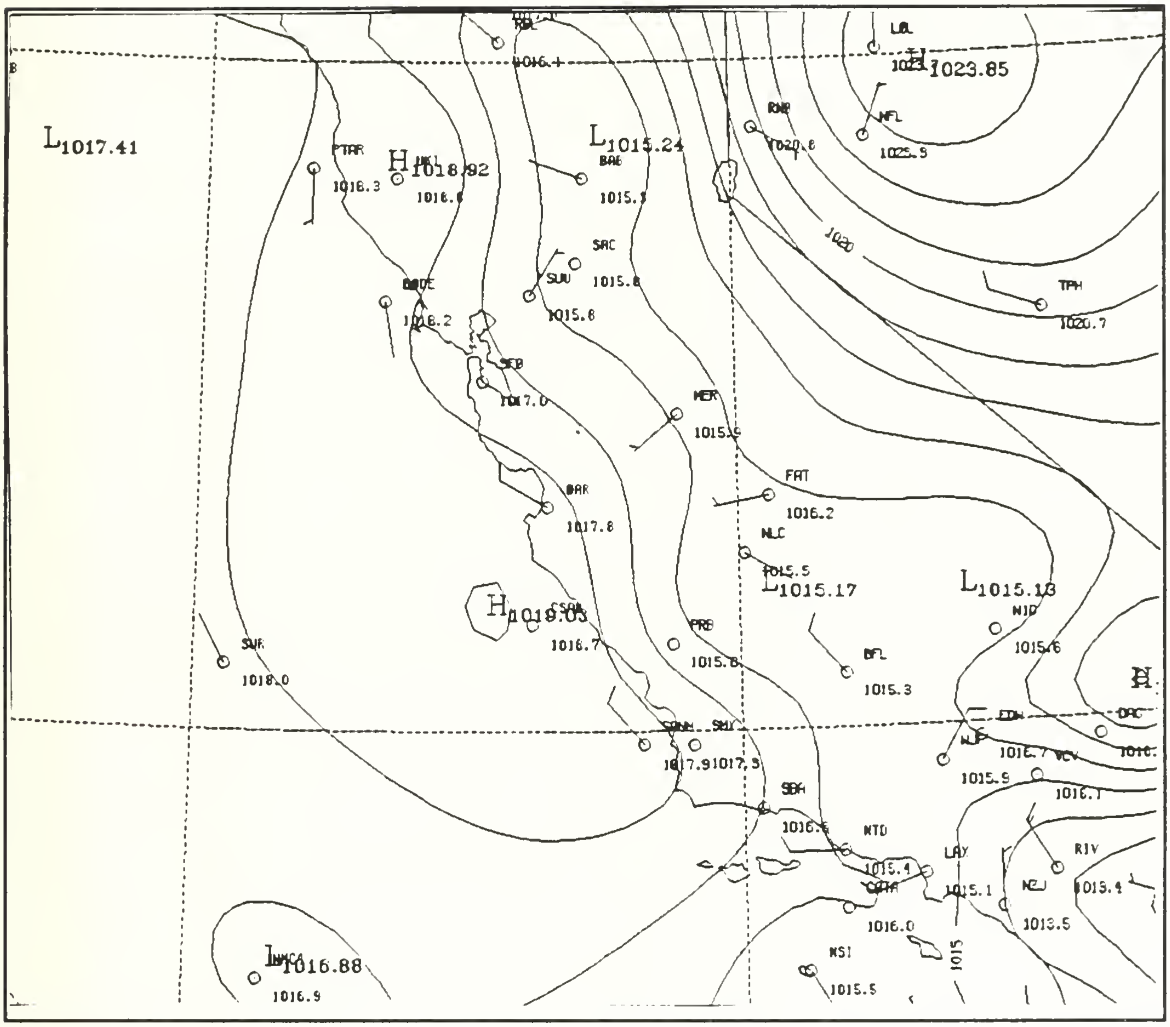

Figure 32. 2100 UTC 04 May 1990 Mesoscale Sea Level Pressure (mb) Analysis.

The 0000 UTC 04 May Oakland sounding shows the marine layer elevated between 990 mb and 960 mb. Prior to 1200 UTC 04 May, the subsidence, along with the night time cooling, was strong enough to bring the mixed layer down to the surface by 1200 UTC each day. However, at 1200 UTC 04 May the Oakland sounding shows the elevated marine layer persisting, indicating a weakening of the subsidence aloft.

D. MESOSCALE ANALYSIS SUMMARY

Between 0000 and 2100 UTC 01 May the flow around the Monterey Bay was either along shore or slightly onshore from the cooler north, neither of which are particularly favorable for fog or stratus formation. As discussed earlier this is the result of the eastward movement of the upper-level cut-off low and ridge and the southern movement of the shortwave ridge over Oregon. This sets up the north/south pressure gradient and southerly flow. By 1200 UTC 02 May the flow is from the south around the Monterey Bay and a surface ridge began building around the San Francisco/Monterey Bay area. By 2100 UTC 02 May the flow was onshore from the southwest around the Monterey Bay area and by 0300 UTC 03 May the surface ridge was well established at San Francisco and the Monterey Bay area.

The presence of the surface ridge, or high pressure, along the Central California Coast for the remainder of the evaluation period resulted in continued surface convergence at the leading edge of the ridge and onshore southerly flow along the Central California Coast. As the surface ridge built and moved north, so did the stratus and fog. From 1200 UTC 03 May to 0900 UTC 04 May the onshore flow from the south continued, providing surface convergence and warm air flow over cooler water, which are favorable conditions for fog or stratus formation.

Between 0900 and 2100 UTC 04 May the eastward movement of the upper-level ridge decreased the sea breeze somewhat in Central and Northern California allowing the stratus and fog to move farther up the coast. The presence of the higher pressure and cooler marine air at Vandenburg helped sustain the stratus and fog.

Prior to the weakening of the subsidence, the Oakland soundings, which are taken over land, clearly showed a diurnal change in the lower atmosphere between a surface and an elevated inversion layer. The weakening of the subsidence resulted in a continual elevated marine layer after 0000 UTC 04 May.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY AND CONCLUSIONS

During this case study the following events occurred:

1) On the synoptic scale: an upper-level ridge moved from the Eastern Pacific through the Pacific Northwest; an upper-level cut-off low moved south through eastern California and then east through the Southern United States; and a upper-level shortwave ridge moved south through Eastern Washington, Oregon and California.

2) On the meso-scale: the north/south pressure gradient along the Central California Coast reversed, setting up a southerly onshore/along shore flow; and a surface pressure ridge formed along the Central California Coast and moved northward along the coast.

This case differed from previous case studies which analyzed the California coastal stratus and fog formation. In the Mass and Albright 1985 case (Mass and Albright 1987) the movement of the upper-level high and low systems differed from this case. In the Mass and Albright 1982 case (Mass and Albright 1987) and (Dorman 1985) the location of the upper-level high and low pressure systems were different than for this case. What is important to note is that the upper-level features are the primary factors that produced the stratus and fog. Because the movement and locations are different in this case than cases examined in other studies, the conditions which cause the stratus and fog formation is different for this case.

In Mass and Albright (1989) the formation of the Catalina Eddy contributed to the upper-level shortwave trough which moved eastward through the northwestern United States. Mass and Albright felt this weakened the surface pressure gradient in Northern California, thereby setting up the north-south pressure gradient conducive for southerly flow along the California Coast. Although a similar upper-level shortwave trough moved eastward through the Northwestern United States in this case study, it was not dynamically important and did not have a significant influence on the Central California Coastal wind flow.

Felsch (1990) found that the presence of either an upper-level shortwave ridge over Northern California, or the presence of an upper-level low southwest of California, were necessary for a stratus surge event. In this case both were present, but in different locations. Again, because the location and movement of the upper-level ridge and low are different in this case study, and the stratus and fog did not form offshore, move onshore and surge up the California Coast, the findings from Felsch do not apply.

In conclusion, the formation of the stratus and fog was initiated by the movement of the upper-level cut-off low and the shortwave ridge. Their movements provided increased subsidence and upper-level NVA over the Southern California, which, in turn, produced higher pressure over the Vandenburg region and, coupled with relatively lower pressure over Oakland, set up the conditions that lead to the formation of the stratus and fog. The Vandenburg/Oakland pressure gradient produced southerly flow which carried warm moist air over relatively cooler water. The moist air condensed and stratus and fog developed.

If routine surface observations were plotted and analyzed on the meso-scale, along with upper-level systems closely associated with the surface features, it would be possible to identify features which are similar to the ones in this case. Forecasting the movement of the upper-level systems would provide the capability to forecast stratus and fog formation.

B. RECOMMENDATIONS

Further research and a more detailed examination of the surface observations up and down the California Coast would be required to fully characterize the actual onset time of the stratus and fog formation. Although there are only a few 24 hour surface reporting stations along the California Coast, a detailed look at those continually reporting would provide a better understanding of **exactly** when the coastal stratus and fog forms. The exact time of formation is important to fully understand whether the Southern California surface high sets up the conditions for the formation of stratus and fog, or whether the stratus and fog formed first, setting up the higher pressure in Southern California. Satellite imagery is insufficient to determine the time because the stratus and fog usually form during the night time when only IR imagery is available. Because stratus cloud temperatures are very close to ocean temperatures, it is difficult to distinguish between the stratus and the ocean using IR imagery. Additionally, a more detailed study, with more observations offshore would help to better characterize the offshore pressure and wind features.

Since the NMC real-time surface and upper-level analyses do not provide sufficient detail to accurately depict the mesoscale situation in Central California, a detailed mesoscale examination is necessary to accurately depict the surface and upper-level features and their interaction. This could be done using a fine-scale numerical model assuming that the synoptic-scale features are properly depicted over the data-sparse Pacific Ocean. Given the lack of mesoscale observational data, an intensive observing program would be needed to provide these data.

Finally, the results from this case study using routine observations should be extended. Careful examination of many other stratus/fog events might help to generalize these results.

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