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FOG RELATED TO STRATUS CLOUDS IN SOUTHERN CALIFORNIA

Multisensor observations of fog and analysis of mesoscale and radiosonde data provide evidence that radiational cooling from the top of stratus clouds is a significant process leading to fog formation and that mesoscale variability of fog producing mechanisms is great

12 August 1976

Research, January 1974 – December 1975

Prepared for
NAVAL AIR SYSTEMS COMMAND

NAVAL ELECTRONICS LABORATORY CENTER
SAN DIEGO, CALIFORNIA 92152

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER NELC Technical Report 1989 (TR 1989) ✓	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER ⑨
4. TITLE (and Subtitle) ✓ ⑥ FOG RELATED TO STRATUS CLOUDS IN SOUTHERN CALIFORNIA. Multisensor observations of fog and analysis of mesoscale and radiosonde data provide evidence that radiational cooling from the top of stratus clouds is a significant process leading to fog formation and that mesoscale variability of fog producing mechanisms is great.		5. TYPE OF REPORT & PERIOD COVERED Research rept. Jan 1974 – Dec 1975,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) ⑩ V.R. Noonkester and L.E. Logue		8. CONTRACT OR GRANT NUMBER(s) ⑯ WR033-02
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Electronics Laboratory Center San Diego, CA 92152		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS ⑰ 61153N, WR03302, WR0330200 (NELC M111)
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Systems Command Washington, DC 20782		12. REPORT DATE ⑪ 12 August 1976
		13. NUMBER OF PAGES 68
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) ⑫ 69p.		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution is unlimited. ⑭ NELC/TR-1989

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Fog	Mesoscale weather
Remote sensors	Acoustic echosounding
Stratus clouds	Weather radar
California weather	Fog forecasting

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Many fog events have been observed at the coast of San Diego during the presence of a stratus-cloud deck using a set of remote (eg, FM-CW radar and acoustic echosounder) and direct (eg, radiosondes) atmospheric sensors. The sensor observations and analysis of mesoscale and radiosonde data provide evidence that radiational cooling from the top of the stratus clouds is a significant process leading to fog formation and that mesoscale variability of fog producing mechanisms is considerable.

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PREFACE

Marine fog investigations have been in progress at the Naval Electronics Laboratory Center since 1974 using a coastal multisensor system at San Diego. Although the pertinent physics and meteorological-oceanographical elements are likely to be similar, the data analysis has proceeded by dividing fog occurrences into two basic types, namely, fog associated with stratus clouds and fog associated with Santa Ana conditions. The results of the marine fog investigations are being discussed in two separate reports according to the fog type. This report considers fog related to stratus clouds. A subsequent report* will consider fog related to Santa Ana conditions. Both reports contain identical information from the INTRODUCTION through SENSORS and SUPPORTING DATA (see CONTENTS) so that each report is complete and can be examined without the necessity of acquiring the companion report for supportive information.

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*Naval Electronics Laboratory Center Technical Report 2000, *Fog Related to Santa Ana Conditions in Southern California*, by VR Noonkester and LE Logue (in process)

OBJECTIVE

Investigate the structure of the lower atmosphere in the mesoscale region using remote sensors. In particular, investigate the nature of marine fog occurring along the coast of Southern California using the measurements from a unique set of sensors at the Naval Electronics Laboratory Center's (NELC's) coastal site and relating observations to methods of improving fog forecasting techniques.

RESULTS

1. The NELC coastal sensor site has proved to be a good site from which to observe marine fog. Many cases of fog have been observed by the multiple sensor system during the two primary fog producing atmospheric conditions, namely, stratus-cloud and Santa Ana weather regimes. This report considers observations of fog related to stratus clouds occurring primarily during the months from May to October 1974-1975.
2. The sensors used were capable of revealing many important features of marine fog episodes. Both the acoustic echosounder and the FM-CW radar revealed the depth of the marine layer; the radar observed drizzle in and below the stratus clouds; the lidar or ceilometer observed the stratus-cloud base height; and the visiometer measured the visibility during fog episodes. A new method of recording the ceilometer output provides considerable details of the cloud/fog height.
3. All observed stratus-cloud related fog has been capped by a temperature inversion.
4. Stratus-cloud related fog forms when the base of the stratus descends to the surface. The descent to the ground occurs primarily by an increase in the thickness of the stratus cloud deck but occurs occasionally when the cloud deck is displaced toward the ground by a decrease in the thickness of the marine layer. These processes are considerably more effective in maintaining fog at night.
5. The aerosols appear generally to be of marine origin during fog events associated with stratus clouds when the visibilities are usually greater than 1/4 mile (0.4 km).
6. The observations support a model which contains a continuous descent of the stratus-cloud base toward the ground through intermediary processes initiated by radiational cooling at the top of the stratus cloud. One of the intermediary processes, drizzle fallout immediately below the stratus top, is often observed by the FM-CW radar during fog events. The likelihood of fog appeared to increase significantly when the top of the stratus was below about 400 metres. These observations would be expected according to the model just mentioned.
7. An analysis of radiosonde data (0400 PST) taken at stations along the coast of California shows the presence of a convectively unstable layer at the surface primarily during the midcalendar months when stratus clouds are

prevalent. The unstable surface layer is considered to be a consequence of events producing cooling above the sea surface (at near-constant temperature) which is initiated by radiational cooling at the stratus top. A convectively unstable layer immediately below the inversion base was found to be associated with the surface-based unstable layer at San Diego for the month of June 1974 at 0400 PST. This radiosonde analysis supports the stratus-cloud related fog model requiring appreciable radiational cooling at the stratus-cloud top.

8. Climatological data for North Island, San Diego, California, indicate that the processes producing fog beneath a stratus deck are cumulative throughout the night until sunrise. This supports the stratus-cloud fog model featuring cloud-top radiational cooling.
9. The mesoscale variability of visibility restrictions by fog and the stratus-cloud base heights is considerable. This suggests considerable mesoscale variability of the factors controlling the stratus-cloud thickness and height.
10. An analysis of objective fog forecasts at the Naval Weather Service Facility at North Island for fog conducive days (days when fog is observed or forecast) shows that the success rate for forecasting fog was 53 percent for 1975. The analysis is continuing to determine the importance of trends in the objectively determined factors and to evaluate the critical values of the factors.
11. Improvements in fog forecasting in Southern California appear to be dependent on mesoscale studies for fog associated with stratus clouds.

RECOMMENDATIONS

Studies should be designed to measure the horizontal variability of the important fog producing factors in the mesoscale range and then to determine how the new knowledge can be applied to daily fog forecasting using regularly available data. The studies should exploit new measuring devices including electro-optical and particle measuring devices. A combination of coordinated measurements aboard an aircraft, ship, and from satellites should provide a comprehensive data base to determine the mesoscale features influencing fog formation and dissipation.

The reliability of fog forecasts should be determined in other important areas of naval operations so that an assessment of the problem can be made and proper studies designed to improve fog forecasting.

Significant advances in the understanding of the marine layer behavior off the coast of California are not expected until dynamical models are developed and used in conjunction with a comprehensive measurement program. The models should be developed to aid in the design of measurement programs. Progress is expected to be tedious until joint theoretical and measurement programs are completed.

ADMINISTRATIVE INFORMATION

This work was performed under Air Task A370370C/003A/4R03302001, Element 61153N, Project WR03302, Task WR0330200 (NELC M111) by members of the Propagation Division, Electromagnetic Systems Department, for the Naval Air Systems Command. This report covers work performed from January 1974 through December 1975 and was approved for publication on 12 August 1976.

ACKNOWLEDGMENTS

The authors are indebted to DR Jensen, ML Phares and WK Horner for their diligence in operating the sensors during the fog measurement periods and to JS Woodward and L Kincheloe for the careful processing of the data. Special thanks are extended to JH Richter for providing continuous guidance and suggestions throughout the project.

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INTRODUCTION

Marine fog creates naval problems concerning aircraft carrier operations, coastal and port navigation, aerial reconnaissance, target identification, task force maneuvers, rendezvous, and optical propagation. Wheeler (1974)[1] has reviewed some significant wartime naval engagements seriously affected by fog, and has listed general naval operations affected by fog and ship and aircraft accidents for which fog was a cause or contributory factor. He has given the number of fatalities and cost estimates of damage to ships or aircraft for accidents associated with fog. His data suggest that improvements in marine fog forecasting can save many lives and dollars and are likely to increase the probability of success of naval operations.

According to the Meteorological Glossary,[2] fog is an "obscurity in the surface layers of the atmosphere which is caused by a suspension of water droplets, with or without smoke particles, and which is defined, by international agreement, as being associated with visibility less than 1 km." For operational considerations, fog intensity is usually measured by the horizontal visibility when restricted by suspended water droplets. Hence, marine fog is associated with the sea and its intensity is measured by visibility. Based on microphysical considerations, fog may be classed as ice fog, supercooled fog, or warm fog. Warm fog (air temperature $> 0°C$) poses the greatest threat to naval operations (Naval Air Systems Command 1970)[3] and is the type of fog considered in this study. For the purposes of this study, a fog episode is associated with the events prior to, during, and following a period of time when an observer indicates a visibility restriction by "fog" or when an instrument indicates a visibility of 1 mile (1.6 km) or less.

The Navy has need to improve the climatological data base on the world-wide occurrence of marine fog for planning purposes and fog forecasting capabilities for operations. The improvement of the climatological data base for the Navy is being pursued by the Naval Postgraduate School (Renard et al, 1975),[4] other Government facilities, and civilian agencies.

An accurate fog forecast would include details concerning the three-dimensional structure of visibility and its change with time. The requirements on forecast accuracy obviously vary considerably depending on the application. Verifications of naval fog forecasts are not generally available but the forecasting capability of the time-space details appear to be inadequate.* This apparent lack of capability is considered to be primarily caused by insufficient basic knowledge and meteorological data, and not generally from weaknesses in forecasters' skills.

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[1] Wheeler, SE, *Marine Fog Impact on Naval Operations*, Thesis, Naval Postgraduate School Report NPS-58Wh74091, September 1974

[2] Meteorological Glossary, edited by DH McIntosh, Chemical Publishing, New York, 1972

[3] Naval Air Systems Command (Research and Technology Group), *Research Prospects (Marine Fog Science and Engineering)*, prepared under Contract No N66001-70-C-0713, April 1970

[4] Renard, PJ, RE Englebretson, and JS Daughenbaugh, *Climatological Marine-Fog Frequencies Derived from a Synthesis of the Visibility-Weather Group Elements of the Transient-Ship Synoptic Reports,* Naval Postgraduate School Report NPS-51Rd75041, April 1975

*Studies to determine the fog-forecasting skill scores for all naval forecasting units might reveal significant climatological geographic dependent variations in forecasting capabilities. These results could be used as an aid in the determination of the type of research most likely to improve fog forecasting and in the selection of regions where forecasting improvements are most urgently needed.

The atmospheric and ocean surface conditions conducive for fog formation or dissipation involve a continuum of processes from the macroscale (synoptic scale, ~ 3000 km) to the microscale (particle interaction). The macroscale conditions controlling the general moisture and condensation nuclei distribution provide the setting for the microscale processes. Subtle changes associated with mesoscale circulation and ocean surface conditions (⩾ 300 km) appear to create the final important processes for fog conditions. Continuous and simultaneous measurements of mesoscale and microscale features associated with fog must be made to fully understand the physics of marine fog. However, independent measurements using either scale can provide important insight into fog processes. This report describes the results of continuous measurements by remote sensors during marine fog episodes on the coast of San Diego and the interpretation of the sensor data relative to mesoscale processes. The remote sensor data were supplemented by intermittent mesoscale surface (standard observations) and upper air (radiosonde observations) data. The results indicate that mesoscale processes associated with marine fog episodes are significant and complex but tenable.

BACKGROUND

In 1931, JB Anderson[5] presented results of aircraft flights over the ocean region near San Diego pertaining to velo clouds,* fog, temperature structures, and humidity structure. He identified two types of fog occurring in Southern California: namely, fog related to velo clouds and fog related to Santa Ana conditions. He indicated that the velo-cloud tops must be below about 1200 feet (304 m) for fog to form by cloud-base depression and stressed the potential importance of radiational cooling at the top of the clouds. He did not offer any phenomenology for Santa Ana related fog but indicated that the marine layer (cool moist layer of air below the warmer, drier air above created by subsidence) was usually present a few miles offshore and was essentially unmodified during Santa Ana conditions. He found the region below the velo-cloud top to be conducive to mixing and that inversion does not create the clouds. Sea-surface temperature was indicated to be an important factor in forming stratus and fog. He concluded by stating "there appear to be no good reasons why, with additional knowledge, not only the height and thickness of the clouds and the height of the base, but also the other features which are of vital importance to the aviator and navigator will be forecast with confidence and accuracy."

Petterssen (1938)[6] concluded that fog related to stratus was not a direct result of the cool water along the coast. The depth of the layer and mixing below the layer were found to be the most important features to consider in fog formation. Instability below the fog or cloud top (at the top of the marine layer) was found to be a predominant feature. Radiational cooling from the top of the cloud or fog was suggested as

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[5] Anderson, JB, "Observations from Airplanes of Cloud and Fog Conditions along the Southern California Coast," *Monthly Weather Review*, p 264-270, July 1931

[6] Petterssen, S, "On the Causes and the Forecasting of the California Fog," *Bulletin of the American Meteorological Society*, v 19, p 49-55, 1938

*The stratus clouds which drifted overland from the ocean each night and dissipated each day during the summer months in Southern California were called velo clouds by Californians in 1931.

being important to the maintenance of the inversion and the instability. Leipper (1948)[7] found that some of Petterssen's conclusions were not valid for all years because his sample size was inadequate and presented data showing the importance of sea-surface temperature in stratus and fog formation.

Neiburger (1944)[8] concluded that radiational cooling from the stratus top was important for the maintenance of mixing below the cloud. He suggested that investigations to determine the long-term (days) and short-term (diurnal) depth of the marine layer were necessary to improve forecasts of weather associated with the stratus and marine layer. This suggestion was supported by Blake (1948)[9] who found that the inversion base-height and maximum surface temperatures were closely related and that this relationship was most likely to be caused by large-scale subsidence.

In 1948, Leipper (1948)[10] presented data on Santa Ana related fogs and gave some objective guides/indices for forecasting these fogs. Santa Ana fogs had been generally ignored in previous research. Leipper discussed the stages of the Santa Ana fog formation and showed the significance of his forecast indices. These indices were also found to be applicable to summer-type fogs related to stratus. They are still used by forecasters at the Naval Weather Service Facility at North Island, San Diego. An evaluation of the fog-forecasting skill resulting from using these indices at North Island is given in FOG FORECASTS AT NORTH ISLAND. In a more comprehensive report on this investigation, Leipper (1948)[11] emphasized the importance of radiational cooling from the top of the fog or stratus cloud. He states that this cooling would explain "why isolated patches of fog over the sea could be colder than the underlying surface when the air outside of the fog patch is warmer than the surface, why the lapse rate through the fog is super-adiabatic, why a layer of fog once formed can move over warmer water without dissipating, and why a radiation index (a measure of the moisture gradient of the air above the fog) is important in determining the probability of fog formation." He further states ". . ., in many cases a cold surface is needed for the initial formation of fog or stratus, but after formation radiation maintains the cloud in spite of other adverse conditions." These results encouraged Leipper to suggest that most of the California stratus is formed by the lifting of fog banks. He again stresses these ideas in a later paper when discussing fog and smog banks in Southern California (Leipper, 1968)[12].

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[7] Leipper, D, "California Stratus Forecasting Correlations," 1935 and other years, *Bulletin of the American Meteorological Society*, v 29, p 294-297, 1948

[8] Neiburger, M, "Temperature Changes During Formation and Dissipation of West Coast Stratus," *Journal of Meteorology*, v 1, p 29-41, 1944

[9] Blake D, "The Subsidence Inversion and Forecasting Maximum Temperature in the San Diego Area," *Bulletin of the American Meteorological Society*, v 29, p 288-293, 1948

[10] Leipper, D, "Fog Development at San Diego, California," *Sears Foundation: Journal of Marine Research*, v 8, p 337-346, 1948

[11] Leipper, D, *Fog Forecasting on Coasts*, final report on the Fog Project, Office of Naval Research, Contract No N6oni-111, 31 August 1948

[12] Leipper, D, "The Sharp Smog Bank and California Fog Development," *Bulletin of the American Meteorology Society*, v 49, p 354-358, 1968

Although the literature on California stratus and fog decreased after about 1950, there were a number of studies related to the stratus-fog conditions. Edinger (1959, 1963)[13-14] showed that the destructive modification of the marine layer moving inland is a combination of terrain effects and surface heating. The severe control on the properties of the invading marine layer upon land by the terrain was clearly shown in Justham (1974)[15] who critically analyzed the motion of the marine layer far inland into a valley in Northern California. The marine layer depth along a coast was shown to be controlled by the synoptic pattern in the San Francisco region by Fosberg and Schroeder (1966).[16]

Advancement on the theory of the formation of the inversion capping the marine layer was made by Neiburger (1960).[17] He showed that the major characteristics of the temperature structure in the eastern Pacific Ocean near California are caused by large-scale subsidence in the eastern portion of the subtropical high. Changes in the depth of the marine layer off the coast of Los Angeles were found to be up to 500 feet (160 m) during the day by Edinger and Wurtele (1971).[18] They found that the offshore islands created appreciable wave structure downwind when the stability was suitable. They also outlined a dynamical model of the lower atmosphere which could be pursued to further our understanding of the marine layer and overlying inversion. This model included horizontal gradients and moving synoptic patterns.

Recent studies on California stratus and fog by Calspan Corporation (1974, 1975)[19,19a] using the research ship ACANIA and aircraft observations have revealed a number of important features, namely: (a) the marine air must be "conditioned by turbulent exchange of heat and moisture with cold underlying water" before fog can be formed; (b) widespread fog has been observed to occur at the surface by a depression of the base of stratus clouds; (c) fog can form in cool, nearly saturated air advecting over warmer water; (d) radiative cooling at the top of thin fog promotes the upward development of the fog and creates an inversion of temperature at the fog top; (e) widespread fog can be associated with mesoscale convergence; (f) fog patches have been observed upwind (westward) of large-scale fog-stratus systems; and (g) bay fogs are associated with the land sea-breeze system. They found that all fogs were associated with a capping inversion and cooling by long-wave radiation at the top of the fog. The process by which fog is created when the stratus base is depressed

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[13] Edinger, JG, "Changes in the Depth of the Marine Layer over the Los Angeles Basin," *Journal of Meteorology*, v 16, p 219-226, 1959

[14] Edinger, JG, "Modification of the Marine Layer over Coastal Southern California," *Journal of Applied Meteorology*, v 2, p 706-712, 1963

[15] Justham, SJ, *The Spatial Distribution of Fog/Stratus in Northern California, A Descriptive and Statistical Analysis: Summer, 1970,* thesis, University of Illinois at Urbana-Champaign, 1974

[16] Fosberg, MA and MJ Schroeder, "Marine Air Penetration in Central California," *Journal of Applied Meteorology*, v 5, p 573-589, 1966

[17] Neiburger, M, "The Relation of Air Mass Structure to the Field of Motion Over the Eastern North Pacific Ocean in Summer," *Tellus*, v 12, p 31-40, 1960

[18] Edinger, JG and MG Wurtele, *Marine Layer Over Sea Test Range*, final report for Commander Pacific Missile Range, Contract N123(61756)56992A, Pacific Missile Range Report TD 71-2, 1971

[19] Calspan Corporation, *The Microstructure of California Coastal Stratus and Fog at Sea*, Second Annual Summary Report on Project Sea Fog, prepared for Naval Air Systems Command, Contract No N00019-74-C-0045, July 1974

[19a] Calspan Corporation, *Marine Fog Studies off the California Coast*, Third Annual Summary Report on Project Sea Fog, prepared for Naval Air Systems Command, Contract No N00019-75-C-0053, March 1975

((b) above) is considered to follow a sequence of processes in the following order: radiative cooling at the top of the cloud → increase of liquid, water content at the cloud top and creation of turbulent mixing → fallout and turbulent transport of moisture, drizzle and droplets downward to below cloud base → increase of humidity below the cloud base until saturation → cloud base approaches the ground to form fog. These findings provide excellent support of earlier findings and hypotheses on California coastal fog and should form the basis for further studies. The Calspan studies did not include information on a type of Santa Ana related fog which is a significant type of fog appearing south of Los Angeles during the winter months.

Important studies on the California inversion and associated stratus and fog conditions are being conducted by San Jose State University using the instrumented TV tower at Mt Sutro in San Francisco (Miller, 1975).[20] The tower, with a base at 254.3 metres MSL, has sensors at six levels up to 473 metres MSL. The basic sensors include wind (three vectors), temperature, wet bulb temperature, and pressure. Using the tower data to study fog, Goodman (1975)[21] determined the variations in the drop-size distribution and concentration for several fog events and found that these factors were strongly dependent on the surface air trajectory (over land or sea or both). She found that the upper boundary (near stratus or fog top) played a crucial role by supporting radiational cooling and mechanical mixing. These processes create droplets which settle as drizzle or are turbulently transported downwind to lower the stratus base or to maintain the fog in a sequence of events indicated above.

Some preliminary results of the tower data by Miller (1976)[22] on the flux of momentum, moisture and temperature, average inversion properties, and spectra of variables, show properties which cannot be easily explained but are basic to the understanding of the important physics related to stratus clouds, fog, and visibility. He concludes: "The intensity and depth of vertical mixing within the maritime air that is required over the extremely cold ocean water (average July temperature of 10°C) cannot be explained in terms of the usual energy sources of convection – surface heating and/or evaporation/radiative cooling at the top of the marine layer." Subsequent results should prove significant for marine fog studies along the coast of California.

CLIMATOLOGY OF FOG NEAR SAN DIEGO

The sensors used to observe atmospheric features during the fog episodes discussed in this report are located on the coast of Southern California near San Diego and as called out in figure 1. Although fog is observed more frequently in coastal regions farther north in California, it is present sufficiently often in San Diego to ensure the use of the NELC sensors that can operate continuously and unattended during periods when fog is most likely.

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[20] Miller, A, "Project Stable," *Bulletin of the American Meteorological Society*, v 56, p 52-59, 1975

[21] Goodman, JK, *The Microstructure of California Coastal Fog and Stratus*, San Jose State University, Meteorology Dept Report 75-02, October 1975

[22] Miller, A, *Wave Properties in the West Coast Inversion*, San Jose State University, Meteorology Department Report supported by the National Science Foundation, February 1976

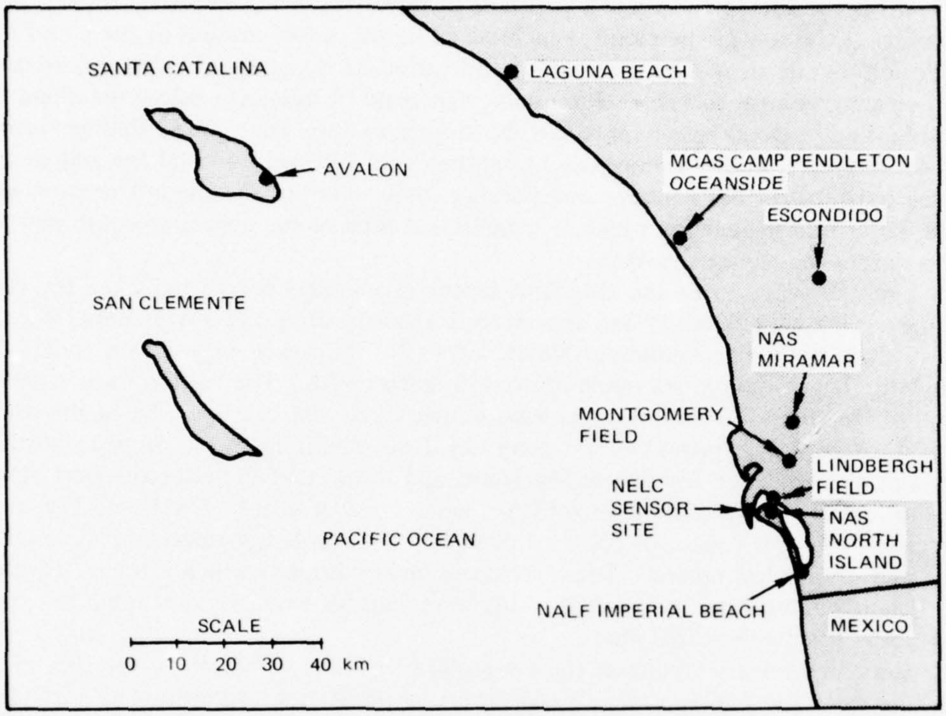

Figure 1. Map showing location of NELC sensor site.

Figure 2, data taken from records of the Naval Weather Service Facility at North Island[23] over a 22 year period, shows the number of days fog was observed with visibility less than 1 mile for the called out period. The figure shows that the least number of "fog days" occurred during the summer when the stratus related fog was predominate and the maximum number of "fog days" occurred when the Santa Ana fog was predominate. Fog is observed more often at NELC than at North Island because surface heating over the land (Pt Loma, primarily) tends to dissipate the fog as it is carried eastward from the ocean by westerly winds and because thin decks of fog are prevented from moving inland by the rapid rise in the elevation (maximum elevation about 120 m MSL) of the land immediately east of the sensor site.

Figures 3 and 4 show the percentage of time the visibility is less than 5 miles (8 km) over the ocean region off the coast of California.[23] These data are based on hundreds of ship's observations between 1946 and 1968 and show that reduced visibilities, assumed to be associated with fog, are a coastal phenomenon (Fleet Weather Facility, 1971[24]). The frequency of reduced visibilities (< 8 km) is greater in the summer than in the winter near San Diego. This seasonal difference, as shown in figures 3 and 4, appears to be opposed to the data presented in figure 2. Apparently, dense fogs with visibilities less than 1 mile (1.6 km) are more likely in the winter while light fog conditions

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[23] Fleet Weather Facility, San Diego, *Local Area Forecaster's Handbook*, March 1969

[24] Fleet Weather Facility, *Climatological Study – Southern California Operating Area*, prepared by NWSED Asheville, March 1971

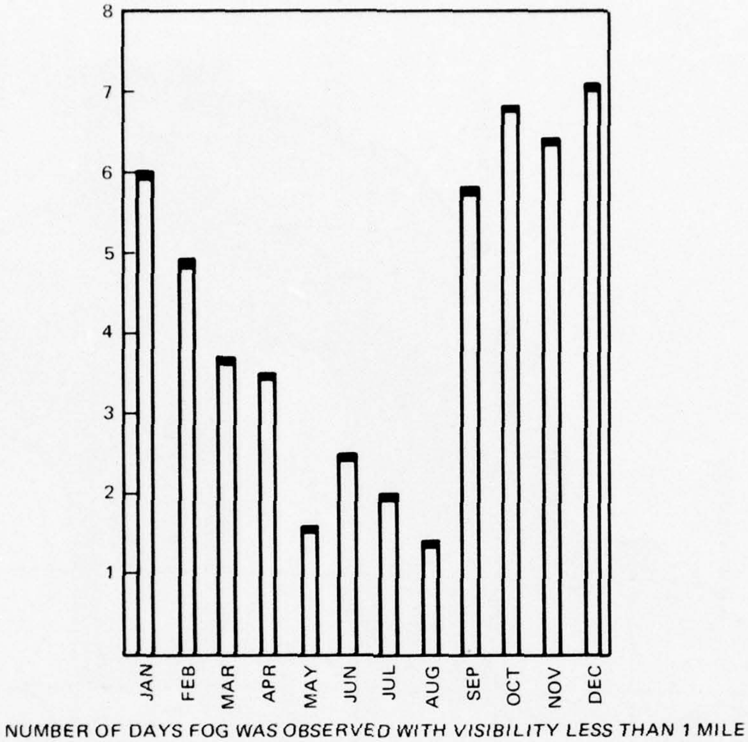

Figure 2. Distribution of fog days by month at North Island (San Diego) January 1946 through July 1968.

producing visibilities between 1 and 5 miles (1.6 and 8 km) are more likely in the summer. This indicates that visibilities between 1 and 5 miles (1.6 and 8 km) are more likely in stratus cloud related fogs than in Santa Ana related fogs. When Santa Ana related fogs occur visibilities are most likely to be less than 1 mile (1.6 km). These deductions agree with observations noted at the NELC sensor site.

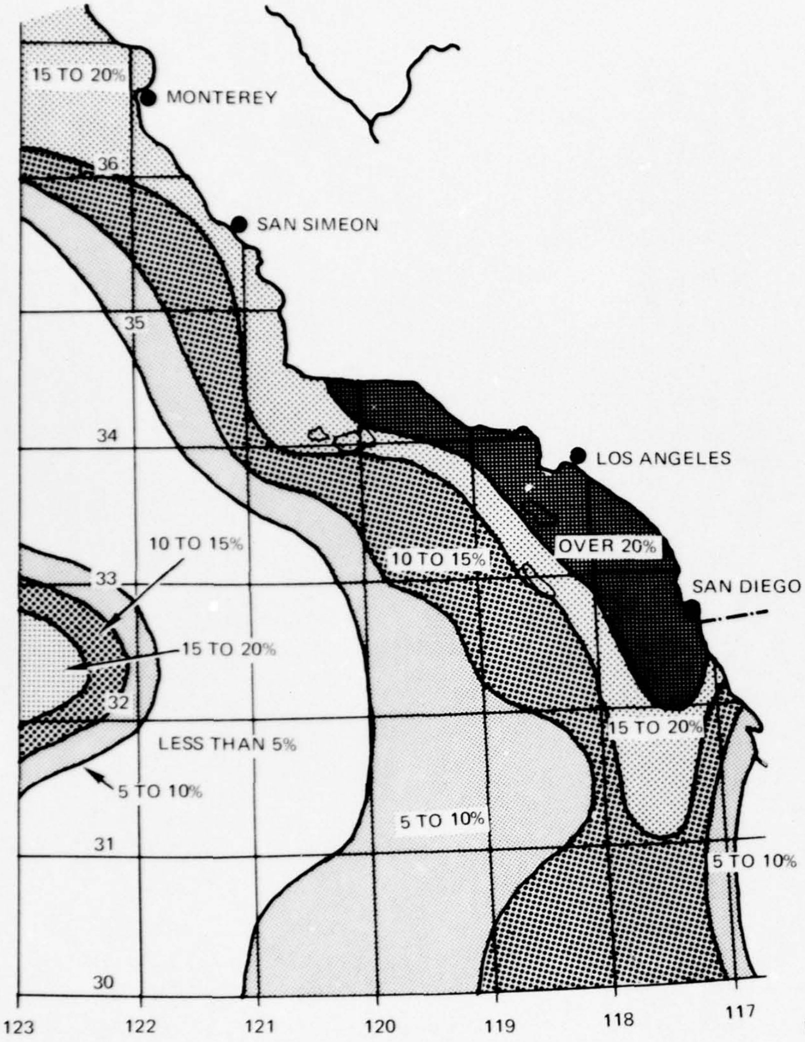

Figure 3. Spatial distribution of the percentage of time visibility is less than 5 miles (8 km) over the ocean region near San Diego during the summer months.

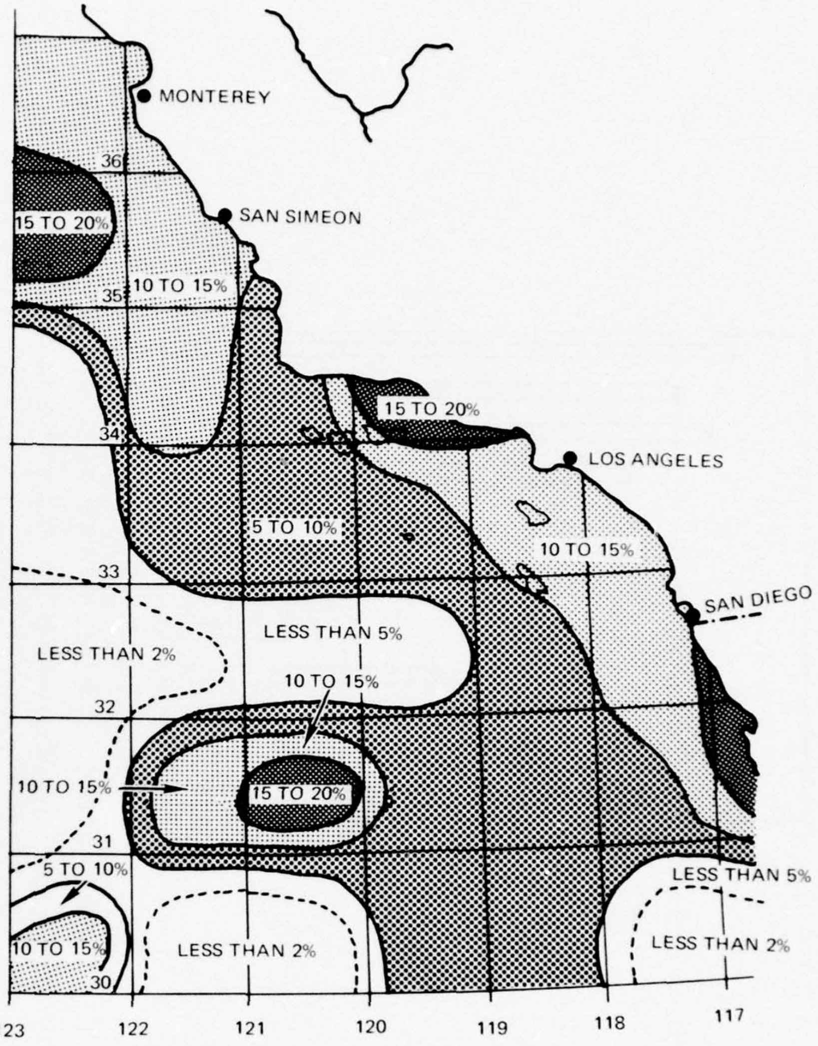

Figure 4. Spatial distribution of the percentage of time visibility is less than 5 miles (8 km) over the ocean region near San Diego during the winter months.

FOG CLIMATOLOGY OF NORTH ISLAND FOR 1975

Fog occurrences for North Island in 1975 were casually examined to determine features not made evident by normally available climatological data.

Figure 5 shows the number of days with fog (visibility ≤ 3 mi, 4.8 km) by month for 1975 at North Island. Comparison of figure 5 to figure 2 (for visibilities ≤ 1 mi, 1.6 km) indicates that the annual variation of fog in 1975 does not represent the long-term average. A deviation of a short-term average from the long-term average is typical of many meteorological parameters. Thus, fog forecasts, like most meteorological elements, must be given individual consideration for each synoptic situation.

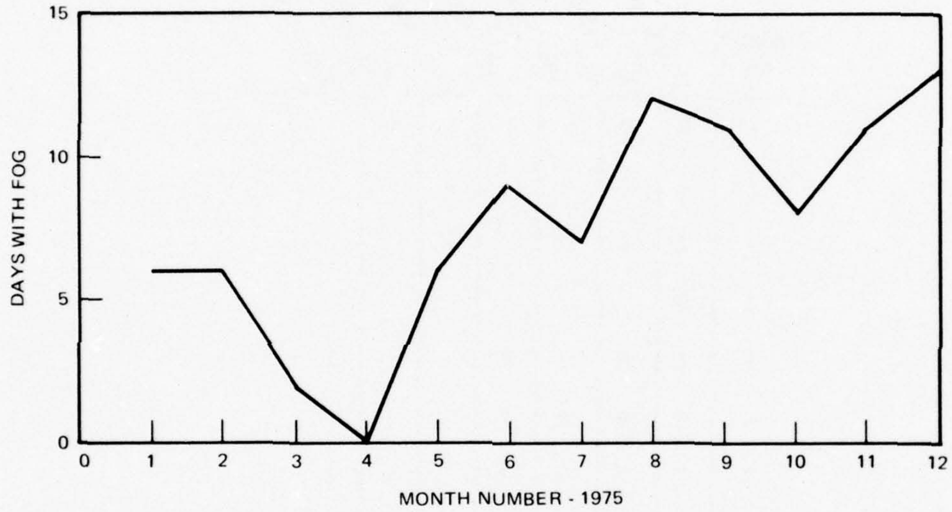

Figure 5. Distribution of the number of days with fog (visibility ≤ 3 mi) by month at North Island (San Diego) during 1975.

Table 1 gives the distribution of fog periods by month for 1975 according to type and the number of fog episodes occurring in sequences of 2, 3, or 4 days. Sixty-two percent of the fog days occurred in sequences of up to 6 days. Apparently, synoptic conditions conducive for fog formation can prevail for several days once they are established. This tendency for fog to be repetitive is heeded by the forecasters at the Naval Weather Service Facility at North Island.

Figure 6 shows the number of days fog (visibilities ≤ 3 mi, 4.8 km) occurred at North Island in 1975 according to the hour of the day for both fog types, Santa Ana (SA) related fog and stratus cloud (SC) related fog. The figure shows that fog at North Island is predominately a nighttime phenomenon particularly for SC fog. SA fog is only slightly more likely at night. The rapid decrease in the number of days with fog after 0700 PST shows the great influence of solar heating. The steady increase in the days with SC fog after 1800 PST until 0500 PST supports a continuous cooling process during the night for SC fog. The plateau of the number of days with SA fog after 2100 PST indicates little dependence on time after sunset.

TABLE 1. DISTRIBUTION OF FOG DAYS BY MONTH, TYPE, AND SEQUENCE DAYS AT NORTH ISLAND (SAN DIEGO) DURING 1975. (FOG OCCURRENCE BETWEEN 1800 PST ONE DAY AND 0600 THE NEXT DAY.)

Month No	Total no of fog days	No of stratus fog days	No of Santa Ana fog days	Fog, 1 day only	Fog, 2-day sequence	Fog, 3-day sequence	Fog, 4-day sequence
1	6	0	6	1	1	1	
2	6	6	0	2	2		
3	2	2	0		1		
4	0						
5	6	6	0	2			1
6	9	9	0	7	1		
7	7	7	0	3			1
8	12	12	0	5		1	1
9	11	10	1	9	1		
10	8	5	3	1	1		1 (6 days)
11	11	5	6	3			2
12	13	2	11	4		3	

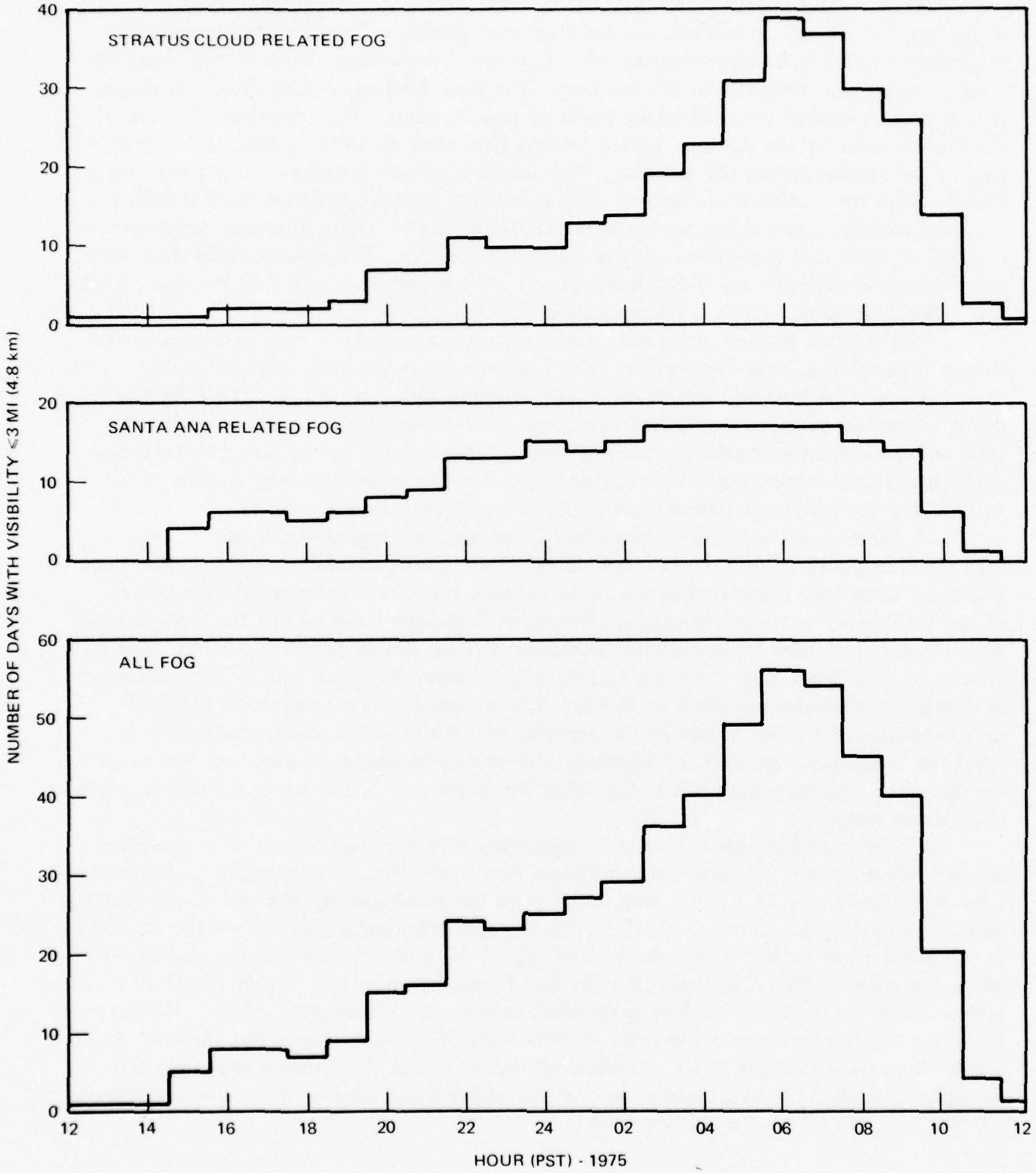

Figure 6. Distribution of the number of days with fog (visibility ≤ 3 mi) by hour at NELC during 1975 according to the type of fog.

FOG TYPES IN SOUTHERN CALIFORNIA

An extensive stratus-cloud deck often exists over a vast ocean region off the coast of Southern California in a weak, low-level pressure gradient along the eastern part of the Pacific's subtropical high-pressure cell. This cloud deck often forms inland along the coast at night and dissipates in the morning. The land, heating-cooling cycle contributes to this coastal diurnal cloud coverage cycle by two methods. The convective heating of the marine layer by the daytime heated ground (Noonkester, 1974[25]) aids in the dissipation of the stratus during the morning. This daytime surface heating creates a sea breeze which causes the marine layer to flow inland, become thinner, and heat adiabatically by a sinking motion, thus, aiding to dissipate the stratus deck. These processes are somewhat reversed at night and the stratus deck is regenerated inland. The coastal cloud deck may not dissipate during the day if the marine layer is deep and has thick stratus clouds at its top. (See discussion by Calspan Corporation, 1974 p 20.[19])

Fog is often formed along the coast when the stratus-cloud base decreases in elevation until the base is at the surface. The visibility is usually never reduced to less than 1/4 mile (0.4 km) and this often occurs in Santa Ana related fog. The difference in the visibilities between the stratus cloud and Santa Ana related fog is caused by the type and number of aerosols (particularly condensation nuclei) in the air. Evidence indicates that stratus related fog involves condensation nuclei of oceanic origin while Santa Ana related fog involves condensation nuclei of continental origin.

A Santa Ana condition occurs when a high-pressure region builds up over the high elevated plateau along the western states. This usually transpires in the winter when migratory lows with associated fronts move through the area. The normal subsidence of the air flowing westward toward the Southern California coast out of the high-pressure region is supplemented by additional downslope motion out of the high plateau. The air arrives dry and hot along the coast and the marine layer is pushed out to sea, reduced in depth, or otherwise modified by the dry, hot air which tends to override the cool moist marine layer. The nature of the modification is not well known. Santa Ana related fog forms near the coast of Southern California and Baja California and moves into the San Diego region within a few days after the onset of a Santa Ana condition (a weakened Santa Ana).

Cyclonic eddies appear to have a significant effect on fog formation and motion south of Pt Arguello, California, during Santa Ana conditions. The behavior of the eddies (like the "Catalina eddy") is not well understood but local convergence-divergence patterns and coastline configuration are likely to play a major role, particularly when the fog forms in a definite front or band. A thin deck of fog (< 30 m deep) often moves northward along the coast of Baja California into the San Diego region (either day or night) and appears to be controlled by a mesoscale wind field (pressure trough or eddy). The method by which the fog forms over the coast of Baja California is not known but the cool water along the coast is thought to be a controlling factor. Santa Ana related fog appears to be strongly controlled by horizontally varying atmospheric and oceanic mesoscale conditions which are yet to be even roughly modeled.

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[25] Naval Electronics Laboratory Center Technical Report 1919, *Convective Activity Observed by FM-CW Radar*, by VR Noonkester, 10 May 1974

Although stratus-related fog exhibits considerable horizontal variability, a horizontally independent model has emerged which appears to have considerable merit. Figure 7 shows a sequence of processes (outlined in the section BACKGROUND) considered to lead to fog formation beneath a stratus base. Considerable data have shown that the cloud top must be below about 400 metres before the cloud base will lower to form fog. Apparently this process cannot maintain a saturated condition in a layer greater than about 400 metres.

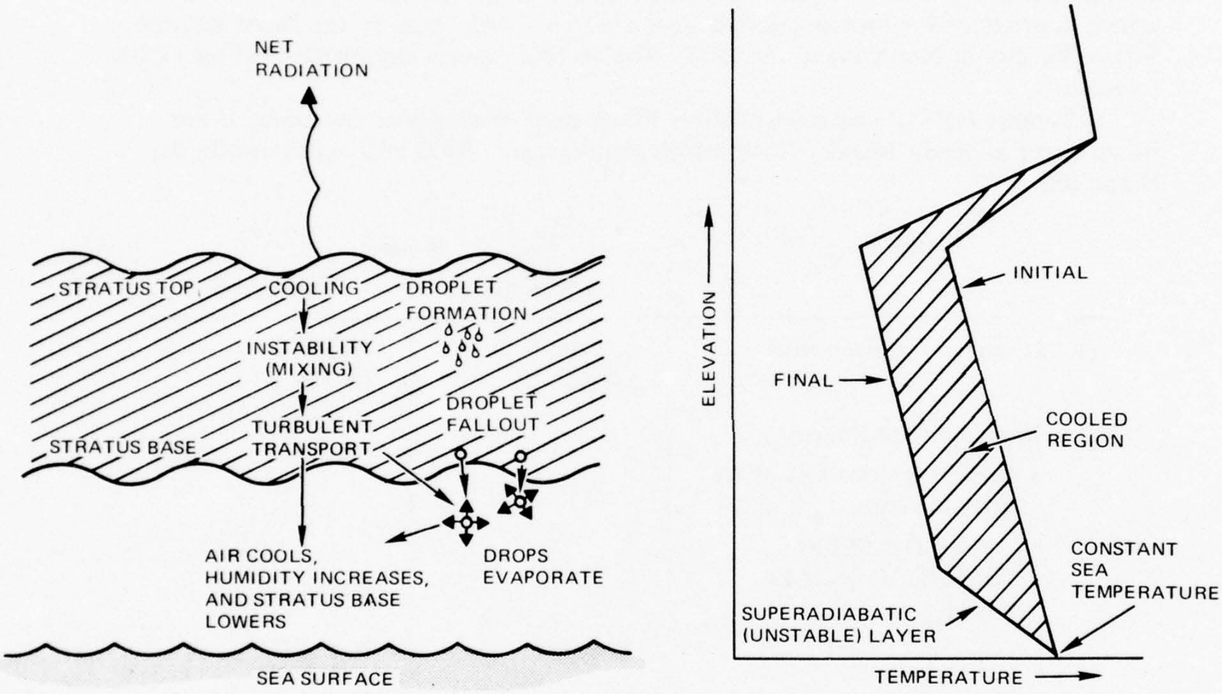

Figure 7. Sequence of processes considered to be creating fog and low-level cooling during the presence of stratus clouds over Southern California.

The sequence of events in the qualitative model, as given, is independent of sea-surface temperature and does not suggest potentially important factors like mesoscale divergence patterns or wind shear turbulence effects, but observations (eg, Calspan Corporation, 1974[19]) support the basic features of the model. An apparent consequence of continual operation of the processes would be the creation of a surface-based superadiabatic layer over the water. Data from several sources indicate that such an unstable layer is often present and are discussed in the section MARINE LAYER STRUCTURE.

FOG FORECASTS AT NORTH ISLAND, SAN DIEGO, CALIFORNIA

The adequacy, reliability, or success of environmental forecasts is difficult to evaluate. One practical method would be to determine the loss of lives, money, operational effectiveness, and material due to an inadequate forecast but this would be exceedingly difficult. Wheeler (1974)[1] gave details on losses associated with fog but did not indicate if a fog forecast was sought or obtained, and if one was obtained, was it heeded or was it partially or wholly inadequate. Because a forecast can be adequate for one purpose and inadequate for another, an evaluation of a fog forecasting technique may result in several measures of merit. This section will discuss a simple reliability analysis of an objective, four-factor fog forecasting technique used on a daily basis by the Naval Weather Service Facility at North Island for 1975. The analysis ignores any operational use of the forecasts.

Leipper (1948)[11] gave four indices which were developed to determine if fog would occur at North Island. These indices, based on the 0400 PST radiosonde in San Diego, are:

Index	Range	
	Favorable	Unfavorable
1) Height of inversion base	$\leqslant$ 1300 ft ($\leqslant$ 397 m)	$\geqslant$1300 ft ($\geqslant$ 397 m)
2) Upper-air temperature		
a. *Highest temperature above* inversion base, T_a =__°C		
b. Scripps Pier SST at 0800 PST on preceding day, T_w =__°C		
c. Calculate: $X = T_a - T_w$	$X \geqslant 0°C$	$X < 0°C$
3) Surface moisture index		
a. Dew point for North Island at 1630 PST on preceding day, T_c =__°C		
b. Calculate: $Y = T_c - T_w$	$Y \geqslant -5°C$	$Y < -5°C$
4) Radiation index		
Mixing ratio w at 10 000 ft (3050 m)	$w \leqslant 3.5$ gm/kgm	$w > 3.5$ gm/kgm

If all four indices are favorable fog is expected to occur between 1800 PST that evening and 0600 PST the following morning at North Island. A forecaster may make a fog forecast opposed to the indices (favorable or unfavorable for fog) if he considers the synoptic conditions to be changing appropriately. The analysis of the fog forecast was made based entirely on the indices and surface observations at North Island. Fog was considered to be present at North Island if the visibility was $\leqslant$ 3 miles (4.8 km) and fog was given as the reason for the restriction at any time between 1800 PST and 0600 PST. Detailed fog forecasts made by North Island forecasters concerning specifics of time of occurrence and visibilities were not considered in this analysis.

Table 2 contains a breakdown of the success of the fog indices for stratus cloud (SC) or Santa Ana (SA) related fog. Frontal and radiation fog were not considered in this analysis. The associated meteorological conditions, prior to SC or SA type fog, were determined from North Island surface observations. The presence of stratus and the apparent lowering of the stratus base were used as criteria for identifying SC conditions. SA conditions were identified by low humidities, clear skies, and synoptic pressure pattern.

TABLE 2. SUCCESS OF FOG FORECASTS BY CATEGORY AT NORTH ISLAND (SAN DIEGO) DURING 1975. (FOG OCCURRENCE BETWEEN 1800 PST ONE DAY AND 0600 PST THE NEXT DAY.)

	All Indices Favorable				One or More Indices Unfavorable			
	Fog Forecast		No Fog Forecast		Fog Forecast		No Fog Forecast	
	Fog Observed?				Fog Observed?			
Fog Type Observed for Forecast	Yes	No	Yes	No	Yes	No	Yes	No
All cases	28	15	1	8*	21	11	17	136*
Stratus type fog	20	7	1	2*	10	5	13	–
Santa Ana type fog	8	8	0	6*	11	6	4	–

Number of fog forecast periods (1 per day):	237
Number of fog periods with fog:	67
Percent of forecast periods with fog:	28
Number of fog conducive periods (see text):	93
*Number of periods not considered conducive for fog:	144
Number of periods fog forecast was successful for fog conducive periods:	49

If all forecast days (237 days – table 2) were forecast to have no fog, then the success of this "safe" forecast would be (1-67/237) X 100 or 72 percent. This high success rate might suggest that attempts to improve fog forecasts could not increase the forecast success rate appreciably. This is misleading because there are many days which essentially do not have meteorological conditions favorable for fog that can be easily identified. A realistic evaluation of fog forecasts should only consider those days (or fog forecast periods) conducive for fog. These are days where a forecaster's skill is challenged. For the purpose of this analysis a fog conducive day is defined as a day when fog is observed (hindsight) or forecast to occur. The method by which fog conducive days are selected is crucial in the test on the success rate of fog forecasting. The days selected (by the definition) are intended to represent days which the majority of forecasters experienced in fog forecasting at North Island would prudently select, and which must be considered as potential fog days. Both the guidance of the indices plus the skill of the forecasters in accepting or rejecting the indices are tested on fog conducive days. There are 93 fog conducive days.* If all fog conducive days are forecast to have no fog, the forecast success rate is (1-67/93) × 100 or 28 percent. Reliable fog forecasts on fog conducive days could obviously make an improvement in the success rate. There were 49 successful fog forecasts made on fog conducive days. The success rate of these forecasts is (49/93) × 100 or 53 percent. Thus, the combined guidance of the indices and subjective talents of the forecasters have increased the success rate by 25 percent above a "no-fog" forecast. A success rate of 53 percent is still too low to be considered more than a "guess" or "chance" forecast. A success rate near 75 percent is sometimes considered to be the success rate of general meteorological forecasts. Methods should be developed to increase the success rate of the fog forecasts from 53 percent to approximately 75 percent.

The success rate of fog forecasting can be evaluated for the categories "indices favorable" and "indices unfavorable" as shown in table 3. When all indices were favorable, the success rate was 56 percent for all fog days, 70 percent for SC days, and 36 percent for SA days. The success rate for SC fog days is comparable to the general meteorological success rate (~75%) while the success rate for SA fog days is low. When the forecasters decided to forecast contrary to the indices, the success rate was 89 percent for all forecast days. The combined success rate within the category of all "indices favorable" was 69 percent for all fog days, 73 percent for SC days, and 64 percent for SA days. Forecasting improvement is particularly needed during SA conditions when all indices are favorable for fog.

TABLE 3. EVALUATION OF FOG FORECASTING AT NORTH ISLAND (SAN DIEGO) FOR 1975 USING FOG INDICES AS A GUIDE.

	Indices Favorable for Fog						Indices Unfavorable for Fog					
Fog Category	No Days Indices Favorable	No Days Indices Succeeded	Success of Indices (%)	No Days Indices Not Accepted	Success on Change (%)	Total Success (%)	No Days Indices Unfavorable	No Days Indices Succeeded	Success of Indices (%)	No Days Indices Not Accepted	Success on Change (%)	Total Success (%)
All fog days	52	29	56	9	89	69	185	147	79	32	66	85
Stratus fog days	30	21	70	3	67	73	–	–	–	15	67	–
Santa Ana fog days	22	8	36	6	100	64	–	–	–	17	65	–

When one or more indices were unfavorable, the success rate was 79 percent for the indices alone. Upon changing the forecast indicated by the indices, the forecaster was successful 66 percent of the time (32 days). Thus, the overall success rate was 85 percent. A high success rate was expected in this situation because most days can be easily

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*There were 18 days when fog was observed but not forecast, 26 days when fog was forecast but not observed, and 49 days when fog was both forecast and observed.

identified as poor candidates for fog and the indices would often indicate unfavorable fog conditions. The success rate would be 79 percent if no fog were forecast for all the days when the indices were unfavorable. The SC or SA categories were not identified under the no-fog forecast because neither fog condition could be easily identified.

In general, the overall capability of fog forecasts (for visibilities $\leqslant$ 3 mi, 4.8 km) at North Island needs improvement (53%) when both the indices and the forecaster's skills are considered on fog conducive days. When all indices were favorable, changes by the forecaster made definite improvements (56% to 69% for all fog cases) although the small number of changes reduces confidence in this conclusion. When the indices were unfavorable, changes by the forecaster improved the success rate appreciably. The success rate for SC conditions was at a reasonably high level (73%) when all indices were favorable; this might not be expected because the indices were developed for SA conditions.

A similar analysis could be completed for fog having a visibility maximum of less than 3 miles (4.8 km). The resulting success rate is likely to be considerably less for other visibility maxima (eg, < 1 mi) when local naval operations are likely to be more severely affected.

A fog forecast reliability analysis should include details on the forecast and observed fog onset time, duration, and specifics on the visibility, however, this would be difficult to accomplish.

An analysis is being completed on the values of the indices used to make the forecasts (237 days – table 2) to determine (a) how best to make use of trends in the indices, (b) which indices are the most important, and (c) whether the critical values of the indices (favorable or unfavorable category) should be changed. These results will be published in another report.

The major factor for consideration in this analysis is the relatively low-overall success rate (53%) of fog forecasting for North Island. This is clearly not a weakness of the forecasters because they made an excellent attempt to utilize the only objective technique available. The four-factor objective technique appears to be a good forecast guide relative to most objective meteorological aids. Improvements in the objective technique might be expected using mesoscale dependent parameters and continuous assessments of atmospheric conditions. Use of the 1600 PST radiosonde at Montgomery Field, San Diego, California, to make a short-range fog forecast (commencing 2 hours later) should increase the forecast success rate.

METHOD OF STUDY

The objective of the observational program of this project was to observe many fog episodes representing conditions throughout the year at San Diego. The primary atmospheric information was obtained by the sensors at the NELC sensor site. A fog episode is considered to be the sequence of events prior to, during, and after fog has occurred. For this purpose, fog is considered to be present at the sensor site when the visibility measurements are indicated to be below about 1 mile at least part of the time during periods when visibility is reduced by water droplets. Measurements of fog episodes for a period of at least a year were desired because the processes of fog formation and dissipation vary during a year according to the annual change in the synoptic patterns of meteorological and oceanographic parameters.

An attempt to maximize the probability of observing fog episodes by the sensors was made by making sensor observations during numerous conditions conducive to fog. These conditions were determined partly by the synoptic pattern and by the fog forecast made at the Naval Weather Service Facility at North Island. Observation periods extended from 1 day to over a month. Many fog episodes representing a large number of synoptic conditions have been experienced since commencing the study in 1974. Table 4 gives the fog measurement periods considered in this report.

TABLE 4. FOG MEASUREMENT PERIODS COVERED.

From	To
1974	
14 Jan	5 Feb
27 Feb	28 May
6 June	23 July
13 Oct	22 Oct
4 Nov	19 Nov
26 Nov	29 Nov
10 Dec	28 Dec
1975	
3 Jan	9 Jan
15 Jan	21 Jan
1 May	23 May
10 June	2 July
20 Oct	24 Oct
3 Nov	5 Nov
12 Nov	17 Nov
26 Nov	28 Nov
3 Dec	5 Dec
17 Dec	19 Dec

SENSORS AND SUPPORTING DATA

Measurements of atmospheric features have been made during fog episodes using various combinations of the following sensors at the coastal site:

- FM-CW radar
- Acoustic echosounder
- Visiometer (MRI Model 1580A)
- Transmissometer (AN/GMQ 10C)
- Ceilometer (AN/GMQ 13C)

- Lidar
- Radiosondes
- Surface measurements of pressure, temperature, relative humidity, and wind

The characteristics of these sensors are given in several reports: Richter, 1969,[26] Richter et al, 1972,[27] and Richter et al, 1976.[28]

The primary sensors of the vertical atmospheric structure are the FM-CW radar and the acoustic echosounder. The radar receives backscatter energy from regions where the radio refractive index is varying (primarily moisture controlled) due to turbulent mixing processes along a radio refractive index gradient. The predominate echoes observed by the radar at the coastal site include returns from the top of the marine layer where waves (stable and unstable) are often present, from forced and free convection near the surface, from rain or drizzle and from insects. These echoes are usually observed below 1 kilometre. The acoustic echosounder receives backscatter energy from regions where the acoustic refractive index is varying (primarily temperature controlled) due to turbulent mixing processes along an acoustic refractive index gradient. The radar and echosounder usually receive echos from the same regions because temperature and moisture mixing usually occur in the same region; however, exceptions which may be significant have been found (fig 33). The range resolution of the radar was usually 2 metres and the range resolution of the echosounder was usually either 2 or 34 metres.

The ceilometer and lidar (Noonkester, et al, 1974[29]) receive optical radiation scattered from particulates in the atmosphere up to several kilometres. The lidar receives backscatter energy while the ceilometer receives sidescatter energy. Suspended water droplets are usually the major scattering particles. These sensors are used primarily to detect the elevation of clouds; they can observe the lowering of a cloud base to the ground during fog formation and can detect some fog structure.

The scattered energy observed by the radar, echosounder, lidar, and ceilometer are recorded by filming the signal on an intensity modulated oscilloscope using a 35 mm shutterless camera. The film shows a continuous picture of the relative echo intensity as a function of elevation and time for the medium carried through the atmospheric volume probed by the sensor.

The visiometer and transmissometer measure the visibility over short and long paths, respectively. Both instruments sense the optical effects of suspended particles which also affect the lidar and ceilometer. Again water droplets usually create the greatest variability in the measured visibility. The visiometer and transmissometer have a greater resolution in the low visibility range and their output is recorded by analogue techniques.

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[26] Richter, JH, "High Resolution Tropospheric Radar Sounding," *Radio Science,* v 4, p 1261-1268, 1969

[27] Richter, JH, DR Jensen, and ML Phares, "Scanning FM-CW Radar Sounder," *The Reviews of Scientific Instruments,* v 43, p 1623-1625, 1972

[28] Richter, JH, DR Jensen, and VR Noonkester, *A Coastal Multisensor Measurement Facility at San Diego,* Conference on Coastal Meteorology (preprints), American Meteorological Society, Boston, MA, Sept 1976

[29] Noonkester, VR, DR Jensen, JH Richter, W Viezee, and RTH Collis, "Concurrent FM-CW Radar and Lidar Observations of the Boundary Layer," *Journal of Applied Meteorology,* v 13, p 249-256, 1974

Radiosondes can be obtained with (1680 MHz) or without (403 MHz) winds at the sensor site. The rise rates of the radiosonde package are usually made to be slow and the transmitted output is often made to provide more humidity than temperature by simple rewiring of the radiosonde.

The surface dry and wet bulb temperatures are obtained from wet and dry thermistor beads placed about 44 metres MSL. The pressure is measured by a sensitive electronic device labeled "vibrotron" (Richter and Gossard, 1970[30]) and is at 35 metres MSL. The wind direction and speed are measured by a UMQ5 aerovane placed at 55 metres MSL. The measurements by these sensors are recorded on a multichannel speedomax recorder.

Standard meteorological surface observations are obtained from the Naval Weather Service Facility at North Island for each fog episode observed by the sensors. Surface observations were sometimes obtained from local stations making regular or intermittent standard observations. These stations include (fig 1): Lindbergh International Airport, NAS Miramar, NALF Imperial Beach, MCAS Camp Pendleton, and San Clemente Island. Other surface observations are obtained from a larger area in Southern California for selected times when mesoscale analyses are completed. Regular radiosonde data are obtained from the National Oceanographic and Atmospheric Administration (NOAA) weather station at Montgomery Field (fig 1). Selected maps are received from the NOAA National Weather Central by facsimile recorder to determine the synoptic weather patterns during fog episodes.

STRATUS-CLOUD RELATED FOG

Many stratus-cloud related fog events have been observed by the coastal sensor system during 1974 and 1975. This section presents selected data exemplifying particular features.

OBSERVATIONS FROM 12 TO 15 JUNE 1974

Fog, with visibility reduced to about 1/4 mile (0.4 km), was observed on the mornings of the 14th and 15th June 1974. Fog was observed between 0600 and 1100 PST on 14 June and between 0700 and 1130 PST on 15 June. The surface pressure synoptic maps appeared typical for June and showed no significant change during the 2-day period. Figure 8 gives the surface pressure pattern at 0400 PST on 14 June 1974. The eastern part of the Pacific subtropical high pressure cell, along the California coast, and the thermal low, over eastern California, create a relatively strong east-west pressure gradient which influences the influx of marine air into the coastal regions of Southern California. The 850 millibar (mb) synoptic map showed a ridge over the area at 1600 PST on 13 June which was replaced by a weak trough at 0400 on 14 June and then replaced by another weak ridge at 1600 PST on 14 June. These synoptic maps appear to provide little information on the two fog sequences.

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[30] Naval Electronics Laboratory Center Technical Report 1718, *Lower Tropospheric Structure as Seen by a High-Resolution Radar,* by JH Richter and EE Gossard, 26 June 1970

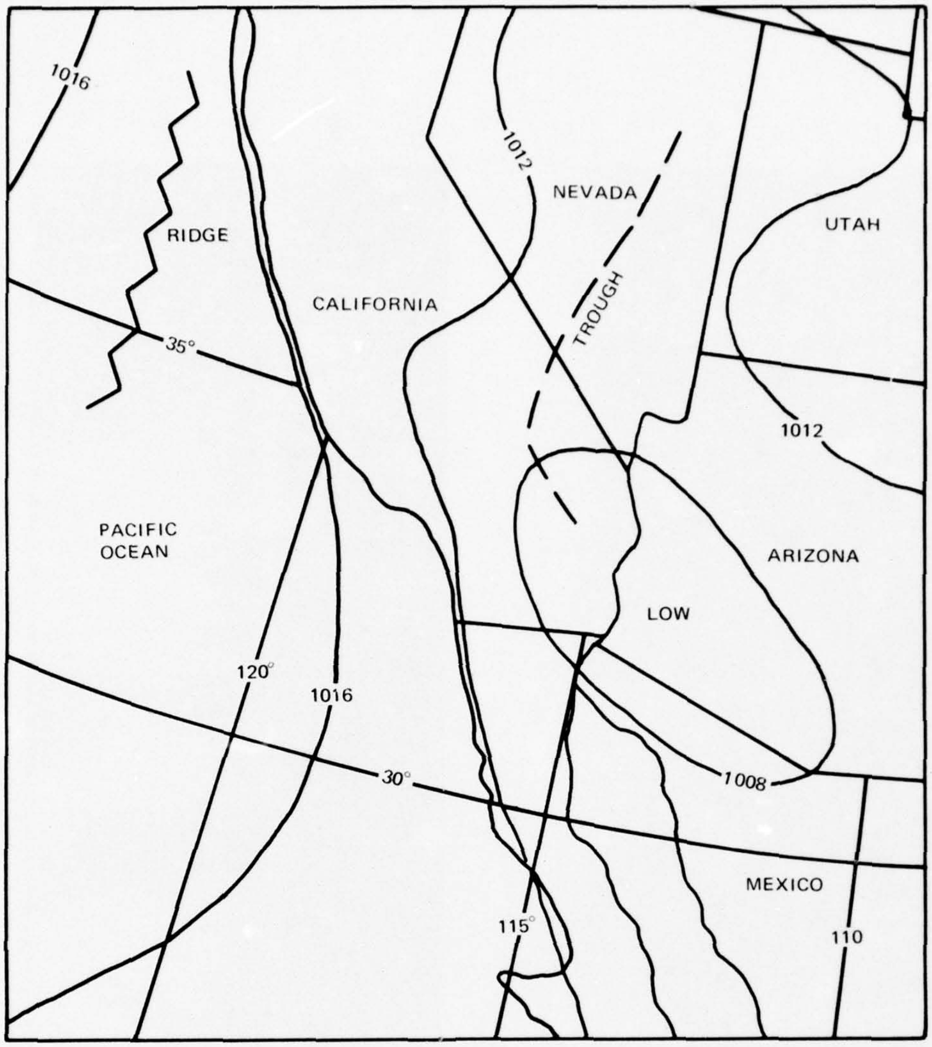

Figure 8. Surface pressure pattern at 0400 PST on 14 June 1974 near a fog event.

Figure 9 shows simultaneous acoustic sounder and FM-CW radar backscatter returns during the occurrence of drizzle in the marine layer on 12 June 1974. The continuous echo seen by both sensors near 650 metres is the echo from near the top of the marine layer where, in most cases, the temperature increases and the humidity decreases with elevation. Turbulent mixing along these gradients supports backscatter to these sensors. Drizzle creates the bright vertically oriented echoes below about 500 metres on the radar record. The drizzle does not create backscatter acoustic echoes. The occurrence of drizzle is sometimes made evident by noise spikes throughout the entire vertical depth of the acoustic record such as is shown in figure 9 at 0400 PST from the drizzle striking the receiver enclosure. The low-level acoustic echoes are considered to be mechanically induced wind noise around the acoustic backscatter receiver.

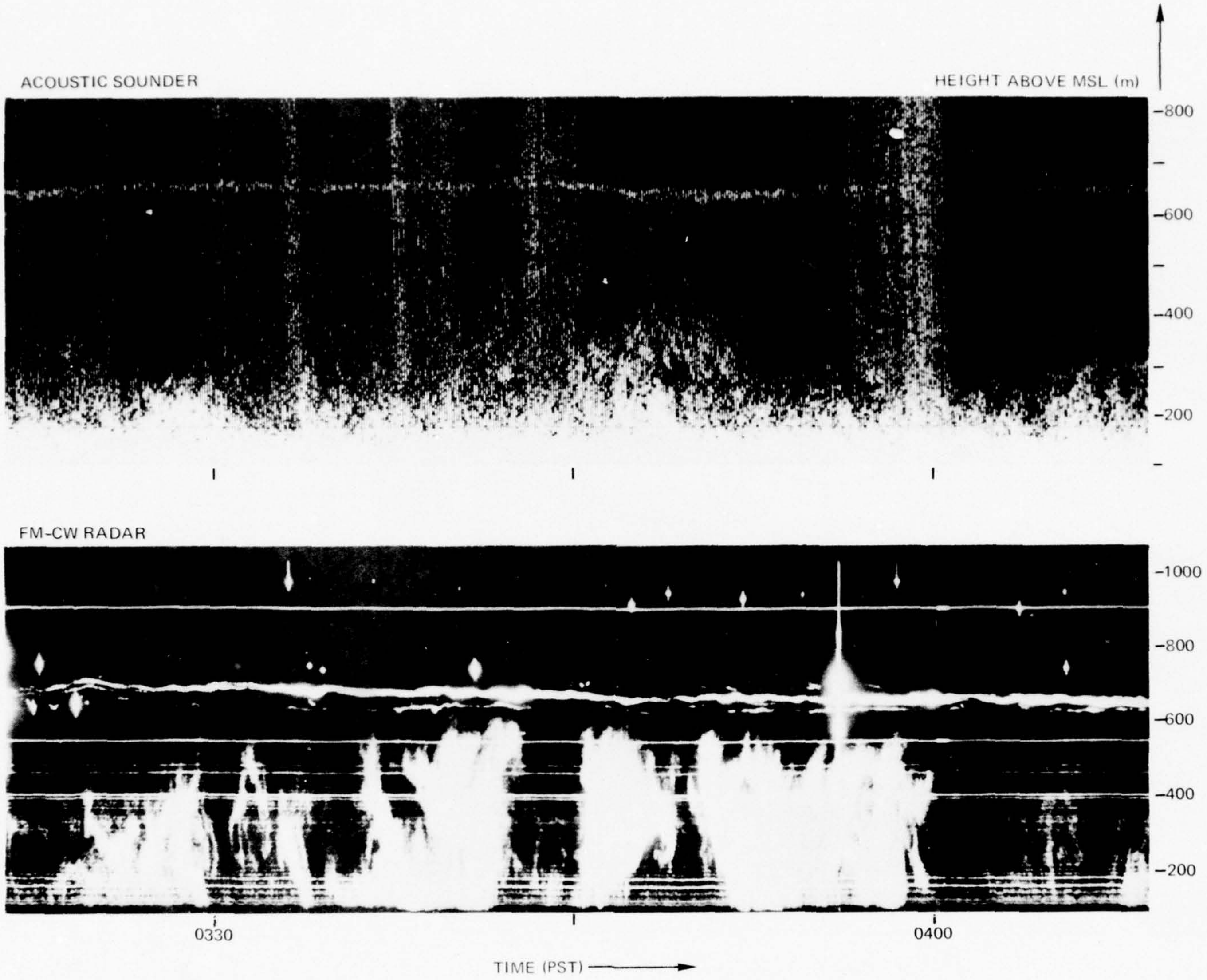

Figure 9. Sensor observations during a fog event on 12 June 1974.

Drizzle is usually observed by the radar just below (~100 m) the top of the marine layer. The model in figure 7 shows this and shows that continuous drizzle and subcloud cooling by turbulent transport of cooler air and by drizzle evaporation could lower the stratus base to the surface to form fog. This stratus-base lowering would have to occur upwind in regions not sensed by the sensors. Drizzle at the sensors can only suggest the possibility of its presence upwind. The formation of fog by this method has been found (by theoretical estimates and empirically) to be unlikely if the marine layer depth is greater than about 400 metres. Fog was not observed on this night in the relatively deep marine layer.

Figure 10 shows the vertical temperature and dew point structure between 1600 PST on 13 June 1974 and 1600 on 15 June 1974 as determined by radiosondes taken at Montgomery Field. Fog occurred in a deep marine layer (550 m) on 14 June and in a thin marine layer (200 m) on 15 June. Drizzle preceded the fog event on 14 June but did not appear to precede the fog event on 15 June.

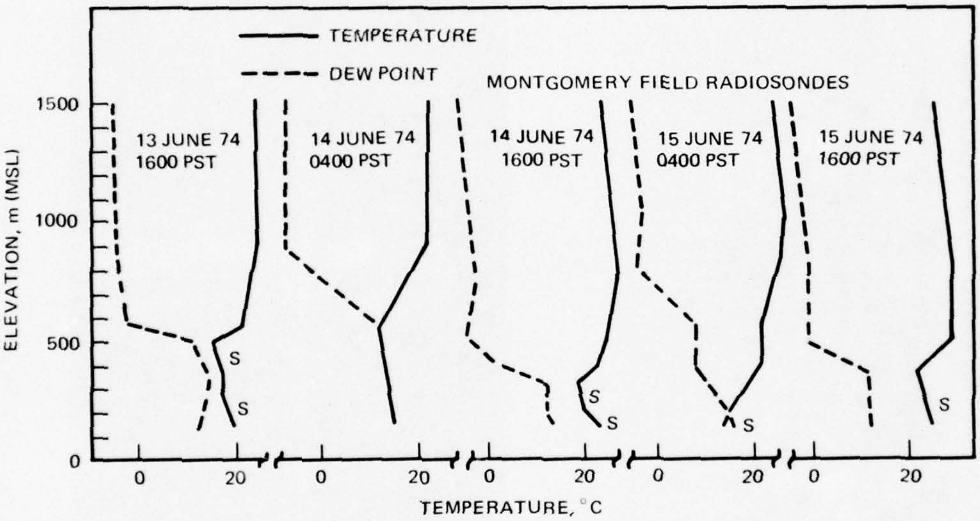

Figure 10. Vertical structure of temperature and dew point as determined by radiosondes taken at Montgomery Field (San Diego) during days having fog. The 'S' indicates superadiabatic lapse rates of the temperature.

Figure 11 shows simultaneous acoustic and radar echoes about 2 hours before fog was observed on 14 June 1974. Although drizzle is observed, fog might not be expected because the marine layer is 150 metres deeper than the empirical 400 metres maximum depth criterion.

Figure 12 graphically shows the echo region of the acoustic sounder and radar near the top of the marine layer during the fog occurrence on 14 June 1974. Both sensors show the same marine layer depth which increases from 460 metres at 1600 PST on 13 June 1974 to 580 metres at 0500 on 14 June 1974. Fog appeared for about 20 minutes near 1800 on 13 June when the marine layer depth was at a minimum during the night. Fog appeared 6 hours after the drizzle commenced and persisted until just before noon. The depth of the layer decreased rapidly after sunrise from 580 metres at

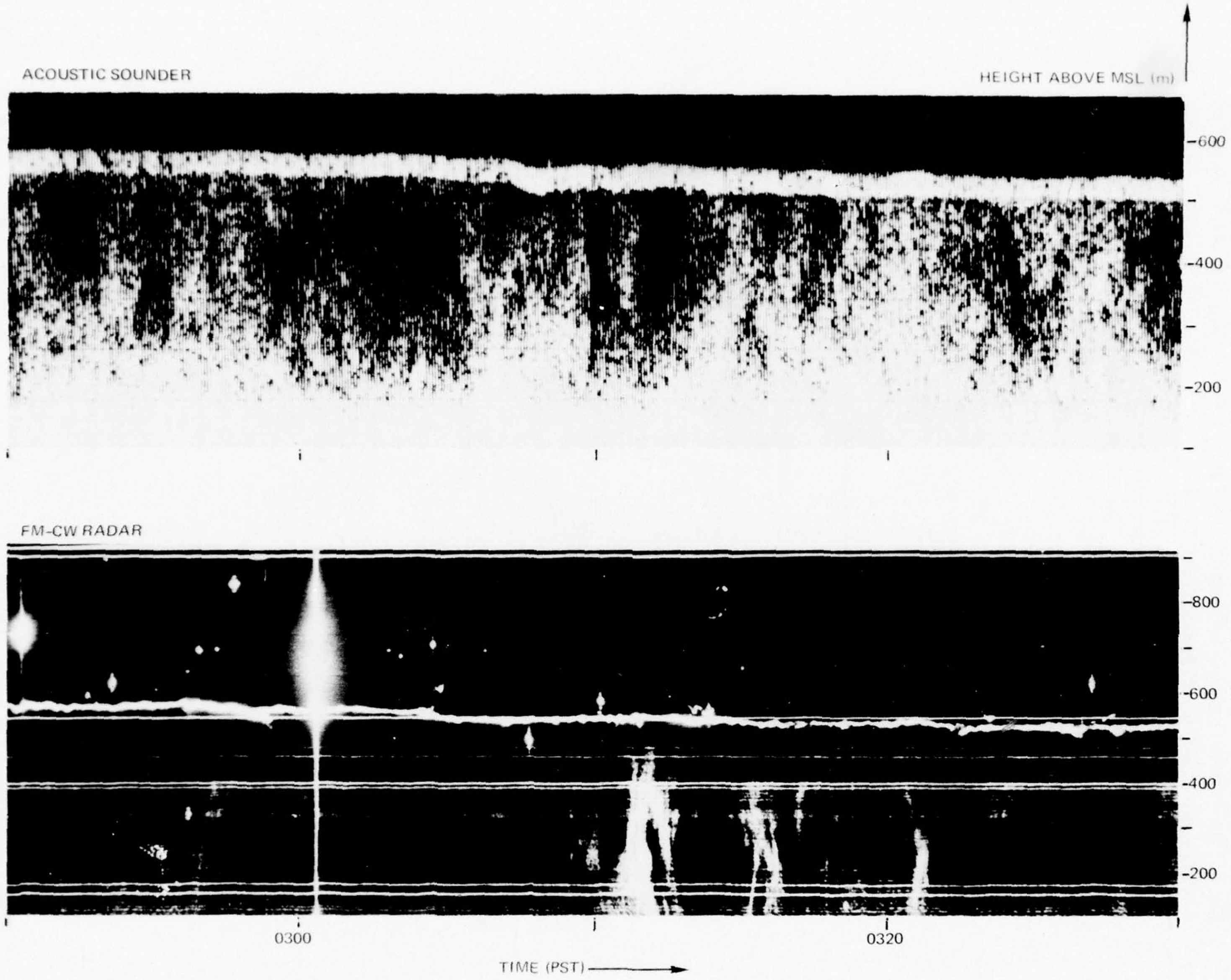

Figure 11. Sensor observations during a fog event on 14 June 1974.

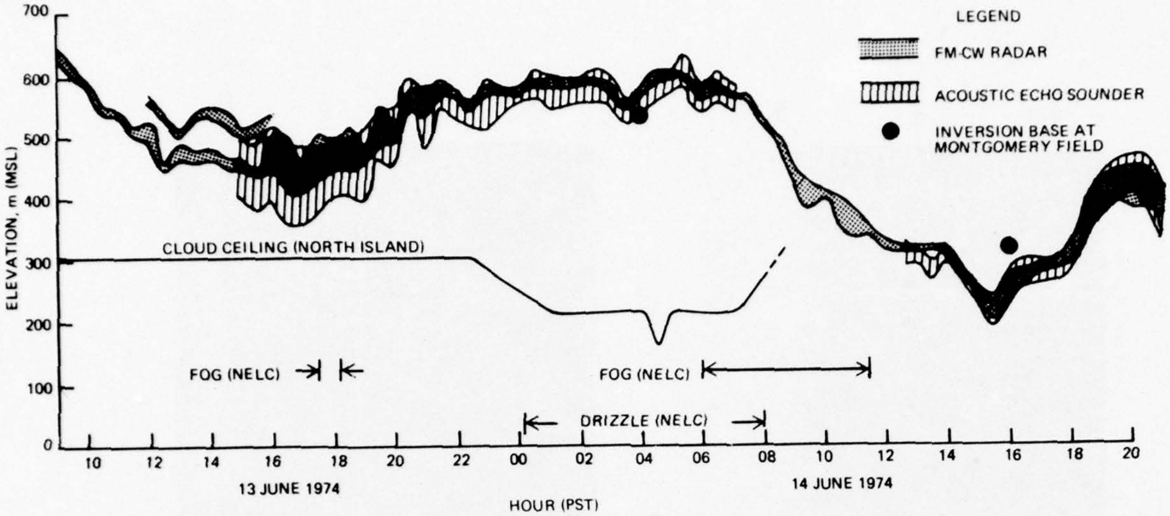

Figure 12. Graphic presentation of significant sensor observations during fog events on 13 and 14 June 1974.

0600 PST to 200 metres at 1530 during the period of fog dissipation. Figure 13 shows the simultaneous acoustic and radar echoes near the time the marine layer depth was at its minimum on 14 June. This decrease is often observed during the morning generation of the sea breeze. Subsidence in the marine layer, which can occur during the decrease in depth, could heat the layer to aid in the dissipation of the fog. Surface heating over land could further aid the dissipation.

The morning dissipation of fog during a decrease in the marine layer depth was observed on 14 Jan 1972 when a lidar (Noonkester, et al, 1974[29]) was monitoring the rise of the fog deck and the FM-CW radar was observing the top of the fog/stratus deck. Figure 14 shows graphically the change in the thickness of the stratus/fog deck during the dissipation of the fog. The combined processes of heating from below and reduction in thickness of the moist layer appear to have accelerated the fog/stratus dissipation.

The height of the inversion base, taken from the radiosonde data at Montgomery Field, coincides with the marine layer depth sensed by the acoustic sounder and the radar at three radiosonde times as shown in figure 12. This implies that the marine layer depth was changing uniformly over the region between the sensors and Montgomery Field (17 km NE). Fog might be expected to be observed simultaneously over this region if the surface elevation differences are properly considered.

Figure 15 shows the visibility at the several locations identified in figure 1 during this fog period. The data reveal considerable variability in the visibility within the mesoscale range (distances < 300 km) even for stations near sea level separated by only a few miles (eg, compare the visibility at NELC with the visibility at North Island). San Clemente Island appears to be completely uninfluenced by stratus fog during this period according to the visibility. The variation in the cloud ceiling shown in figure 16 just prior to the fog occurrence at 0600 on 14 June does not provide any information on the mesoscale behavior of the stratus cloud.

Figure 17 shows the stratus-cloud ceiling and the variability in the visibility during the fog event on 15 June. This event occurred in a thin marine layer (fig 10) apparently

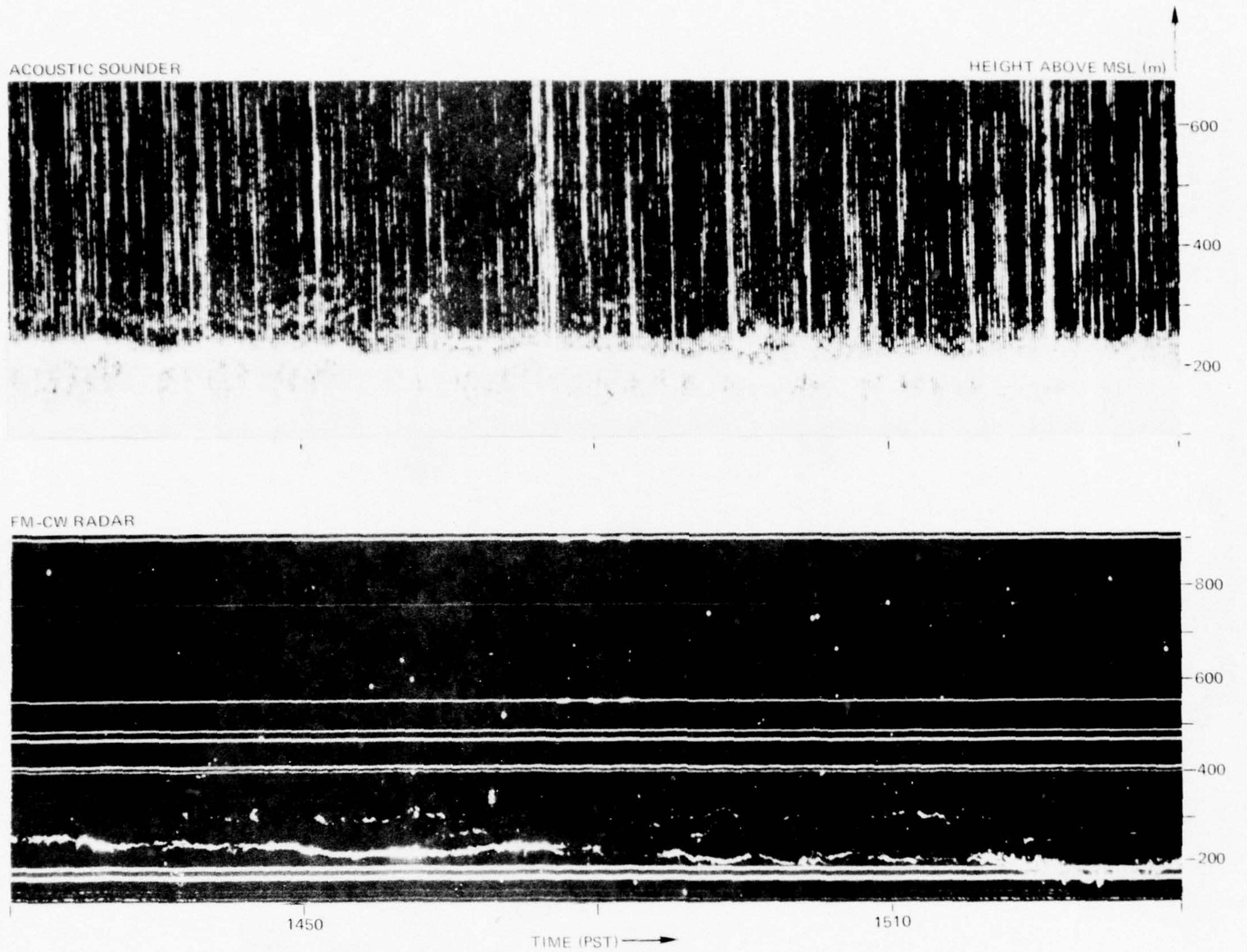

Figure 13. Sensor observations during a fog event on 14 June 1974.

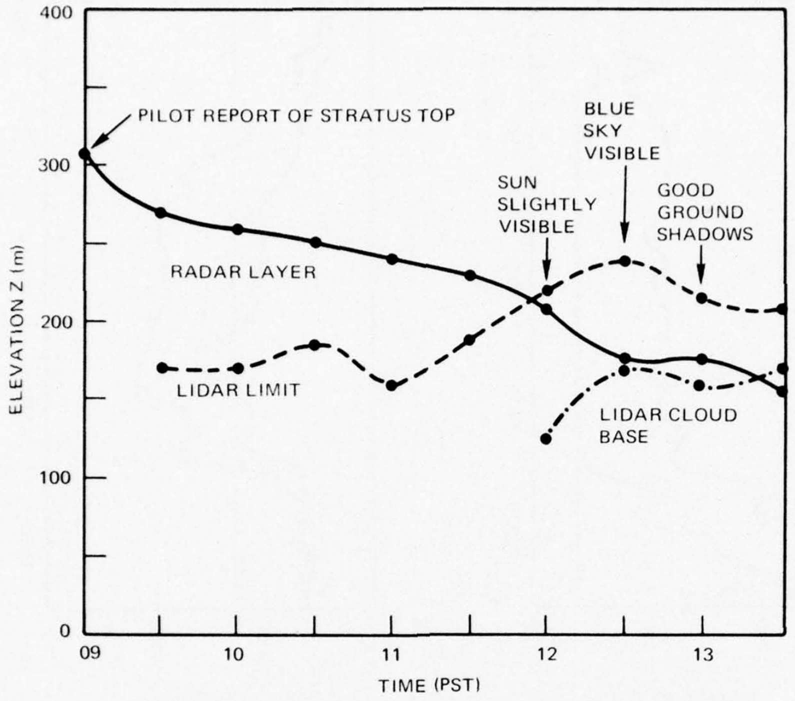

Figure 14. Graphic presentation of significant sensor observation during the dissipation of fog, 14 January 1972.

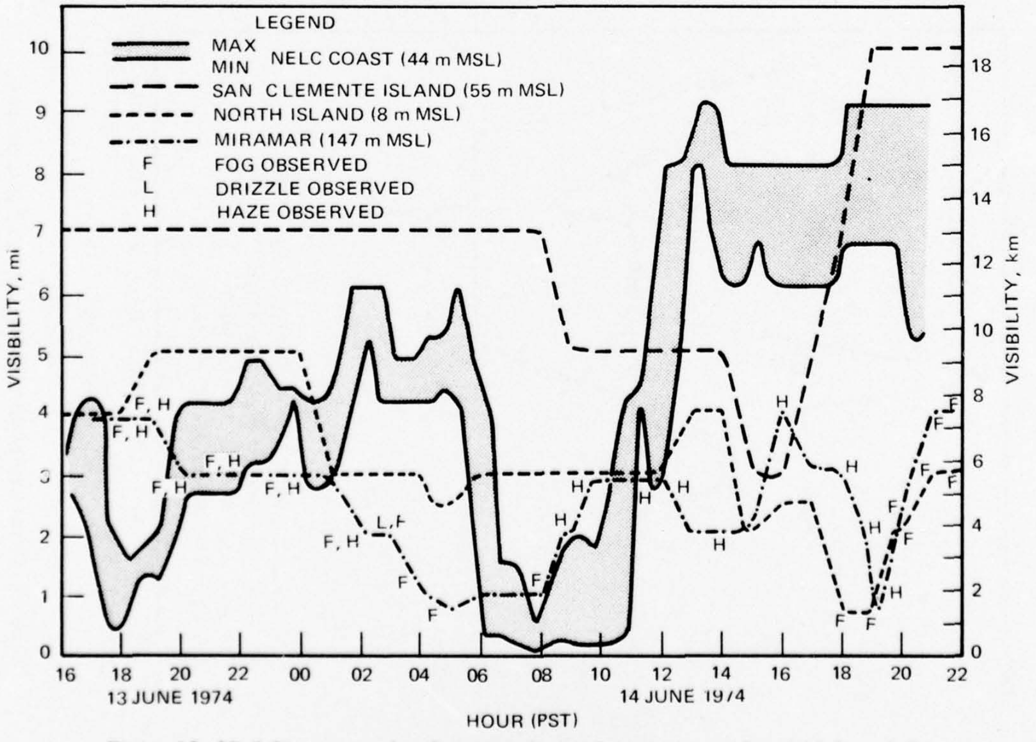

Figure 15. Visibility reported at four sites during fog events on 13 and 14 June 1974.

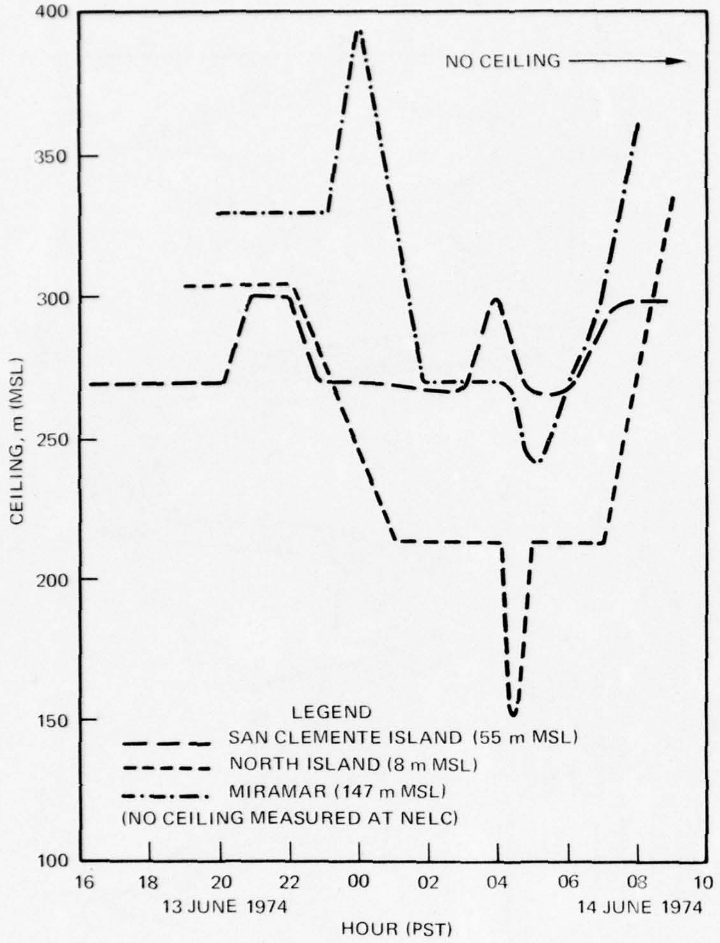

Figure 16. Cloud-base heights (ceiling) reported at three sites during a fog event on 13 – 14 June 1974.

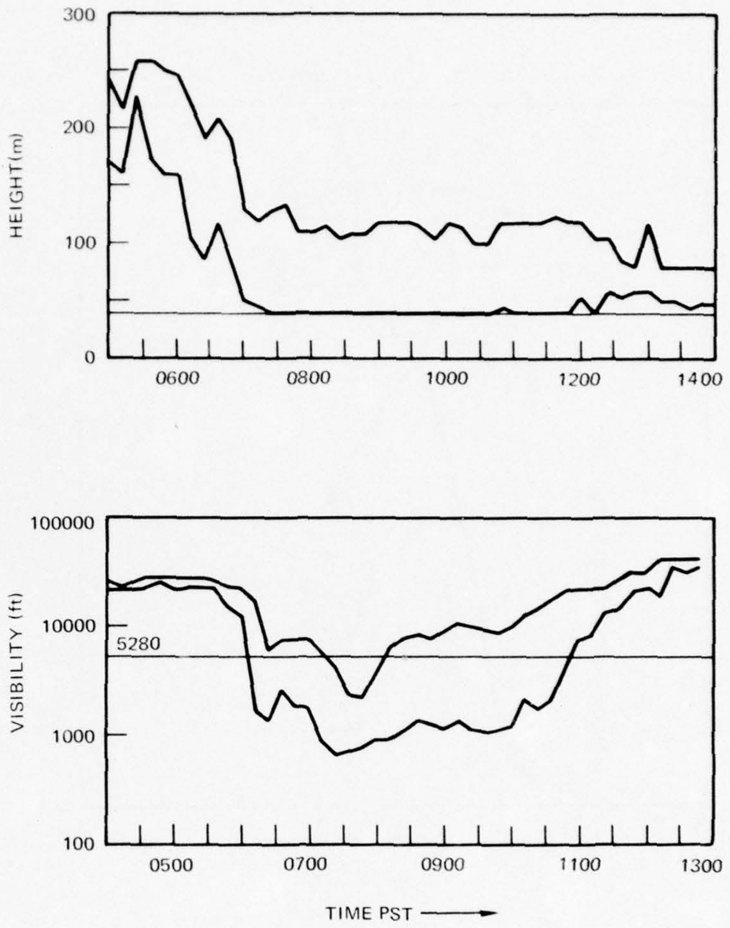

Figure 17. Visibility (maximum and minimum by MRI Fog Visiometer) and cloud ceiling (maximum and minimum by lidar) during a fog event on 15 June 1974.

without drizzle. The acoustic sounder and the radar echoes revealed a marine layer depth less than 300 metres during this period as shown in figure 18. Drizzle could not be detected in the radar echo at any time during this period. This fog event could have been produced by a simple depression of the stratus deck to the ground by a mesoscale action not involving heating (like subsidence) in the marine layer.

Figure 19 shows the trajectory of a large horizontal parcel of air from a region south of San Clemente to the coast between 0000 and 1600 PST on 13 June 1974 (Sklarew, et al, 1975[31]). This trajectory is assumed to represent air parcels arriving at the coast on 14 and 15 June during the fog periods because the synoptic pattern was similar throughout the period. Thus, this fog occurrence can be assumed to occur in marine air and to be composed of marine aerosols. The absence of visibilities below about 1/4 mile (0.4 km) supports this conclusion because fog composed of continental aerosols often creates visibilities below about 1/4 mile (0.4 km).

OBSERVATIONS ON 22 AND 23 JUNE 1974

Fog was observed between 0500 and 0645 PST on 22 June 1974, between 0200 and 1100 PST on 23 June 1974, and for almost 30 minutes about 2300 on 23 June 1974. Although a low-pressure trough was approaching the west coast at the 700 and 500 mb levels, a slight ridge existed at 850 mb which apparently created sufficient subsidence to suppress the marine layer to low levels until 24 June 1974. Figure 20 shows the vertical structure of the temperature and dew point every 12 hours from 1600 PST on 21 June 1974 to 1600 PST on 23 June 1974 according to the Montgomery Field radiosondes. The base of the inversion was below 400 metres on each sounding. Based on the low inversions, fog could be expected on the night of the 22nd and 23rd.

Figure 21 shows the simultaneous acoustic and radar observations about 40 minutes before fog was observed on 22 June 1974. Both sensors revealed the marine layer depth to be below 400 metres and this was in agreement with the Montgomery Field radiosondes. The radar revealed the onset of drizzle which continued until 0600 PST or just before the fog period terminated.

The marine layer depth decreased to 300 metres by 0400 PST on 23 June 1974 (fig 20). Accordingly, fog could have been expected to be more persistent during this period of observation. Figure 22 shows the simultaneous acoustic and radar echoes 2 hours after the fog began. The echoes revealed a steady marine layer thickness of 330 metres. The radar revealed drizzle which began when fog was first observed and which continued until 0930 PST or about 1.5 hours before the time of fog dissipation.

Figures 23 and 24 show the visibility at four sites in the mesoscale region during these two fog periods. The visibility minimum was 0.3 mile (0.5 km) on the morning of the 22nd and 1/5 mile (0.3 km) on the morning of the 23rd. The variation in the visibility at North Island followed a pattern similar to one at NELC but fog occurred only for about 2 hours on 23 June 1974 at North Island. This difference is difficult to understand because of the short distance between the two sites. Miramar had fog both nights

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[31] Sklarew, RC, JC Wilson, and JH Woolf, *Study of San Diego County Ozone Transport*, Xonics, Inc, June 1975

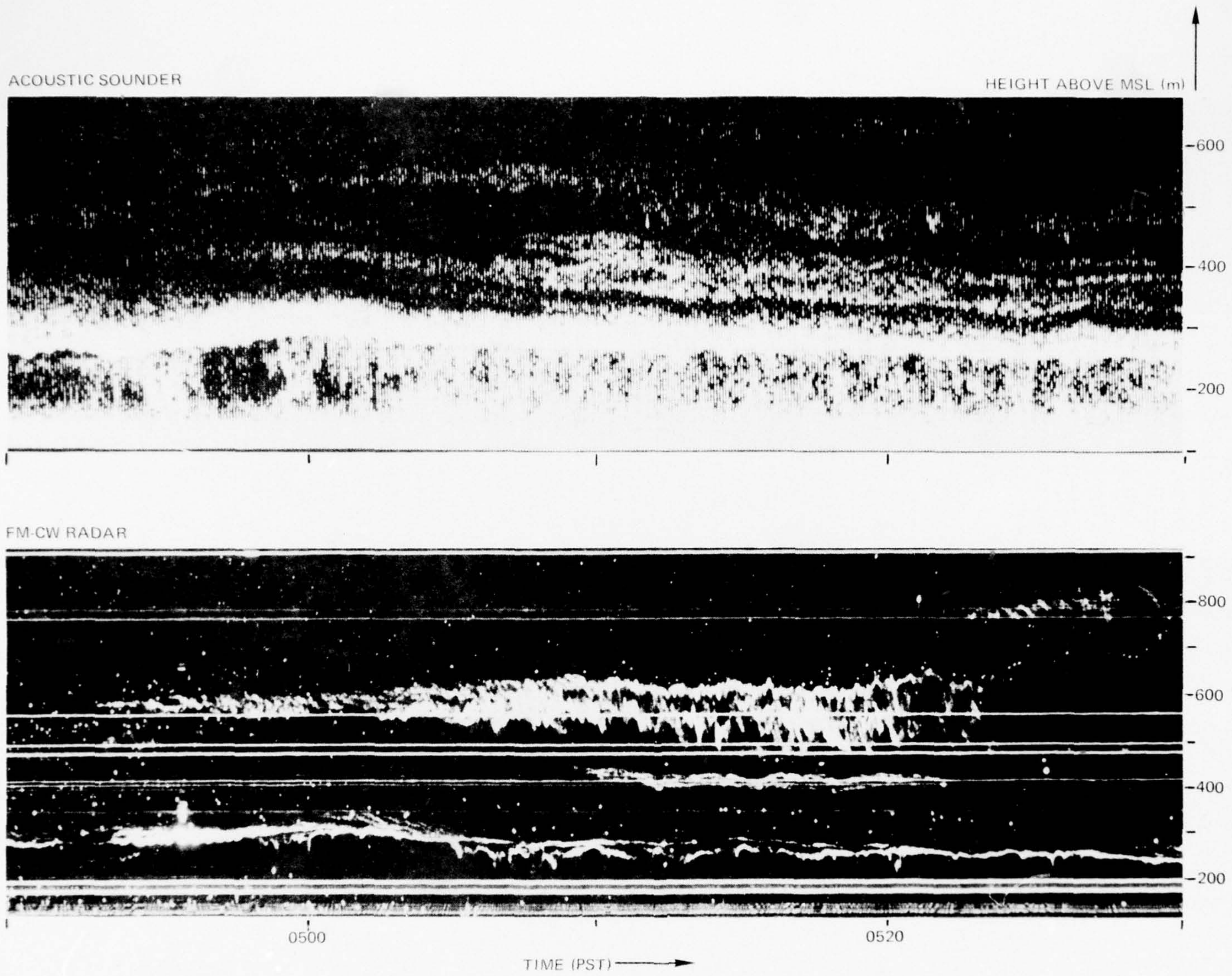

Figure 18. Sensor observations during a fog event on 15 June 1974.

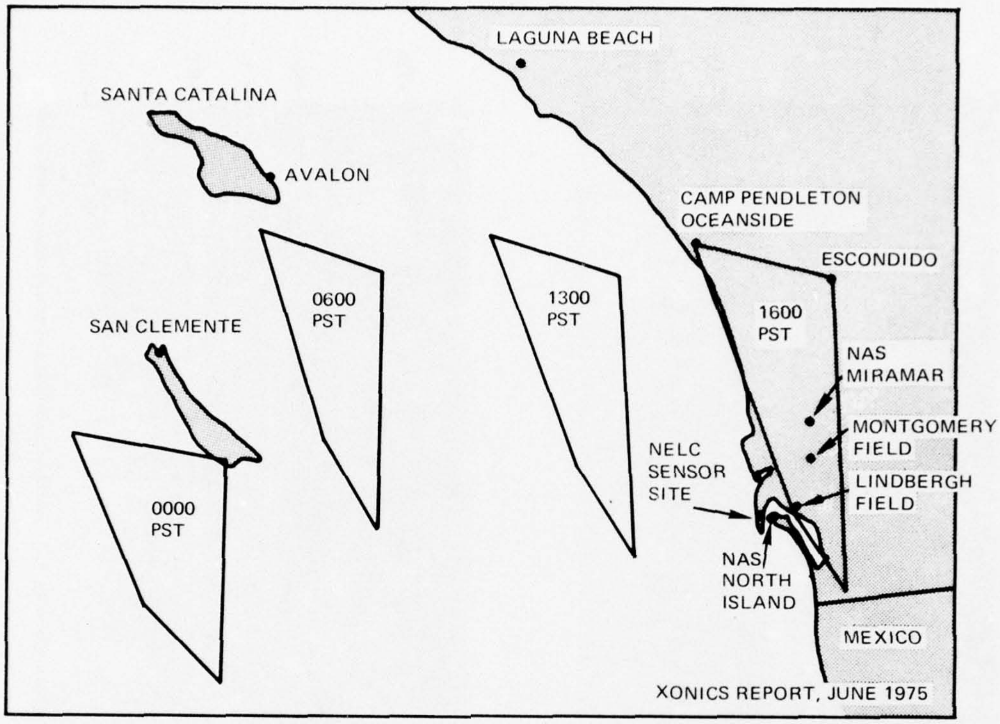

Figure 19. Air-parcel trajectory on 13 June 1974.

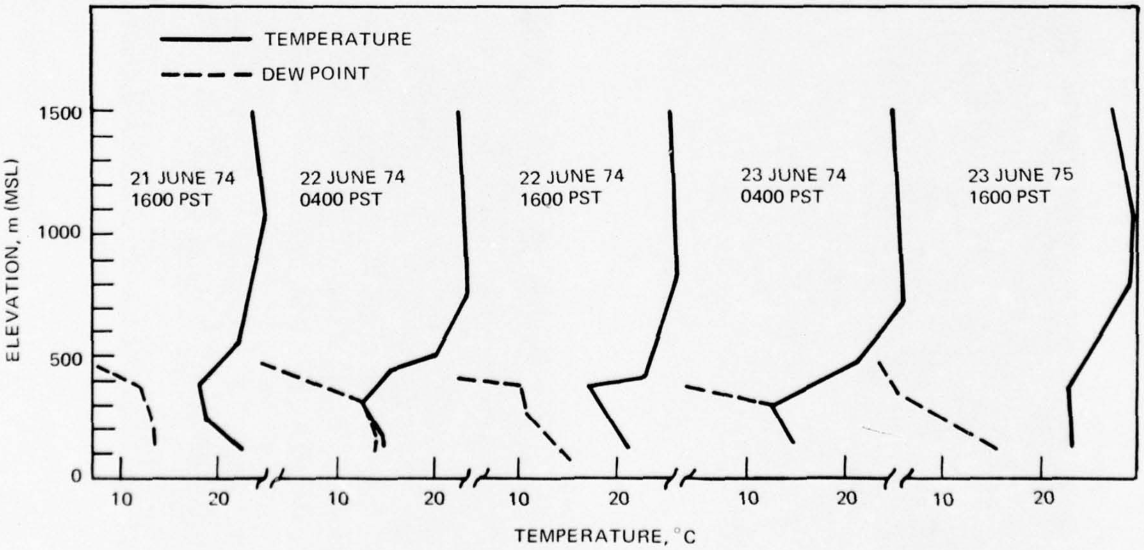

Figure 20. Vertical structure of temperature and dew point as determined by radiosondes taken at Montgomery Field (San Diego) during days having fog.

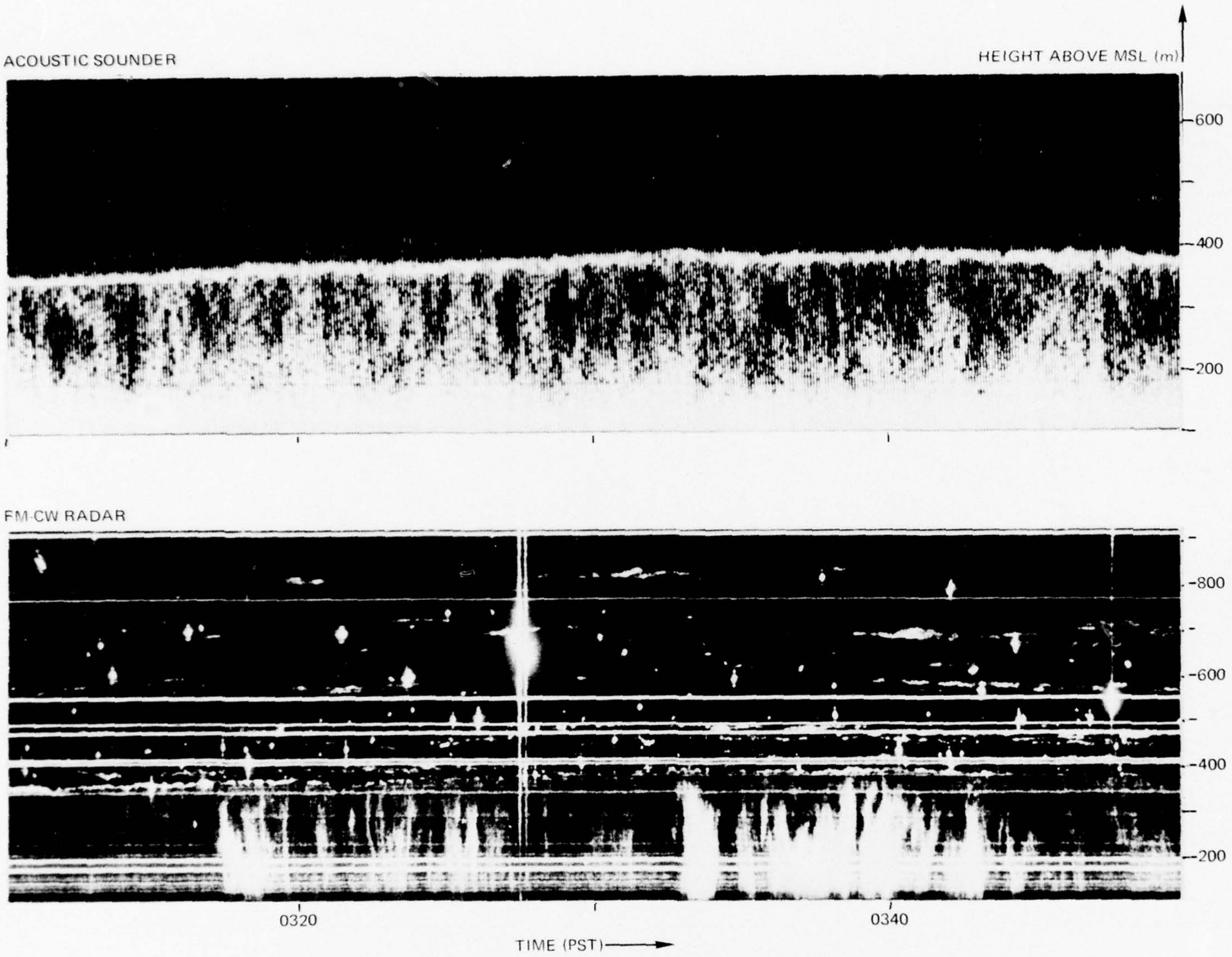

Figure 21. Sensor observation during a fog event on 22 June 1974.

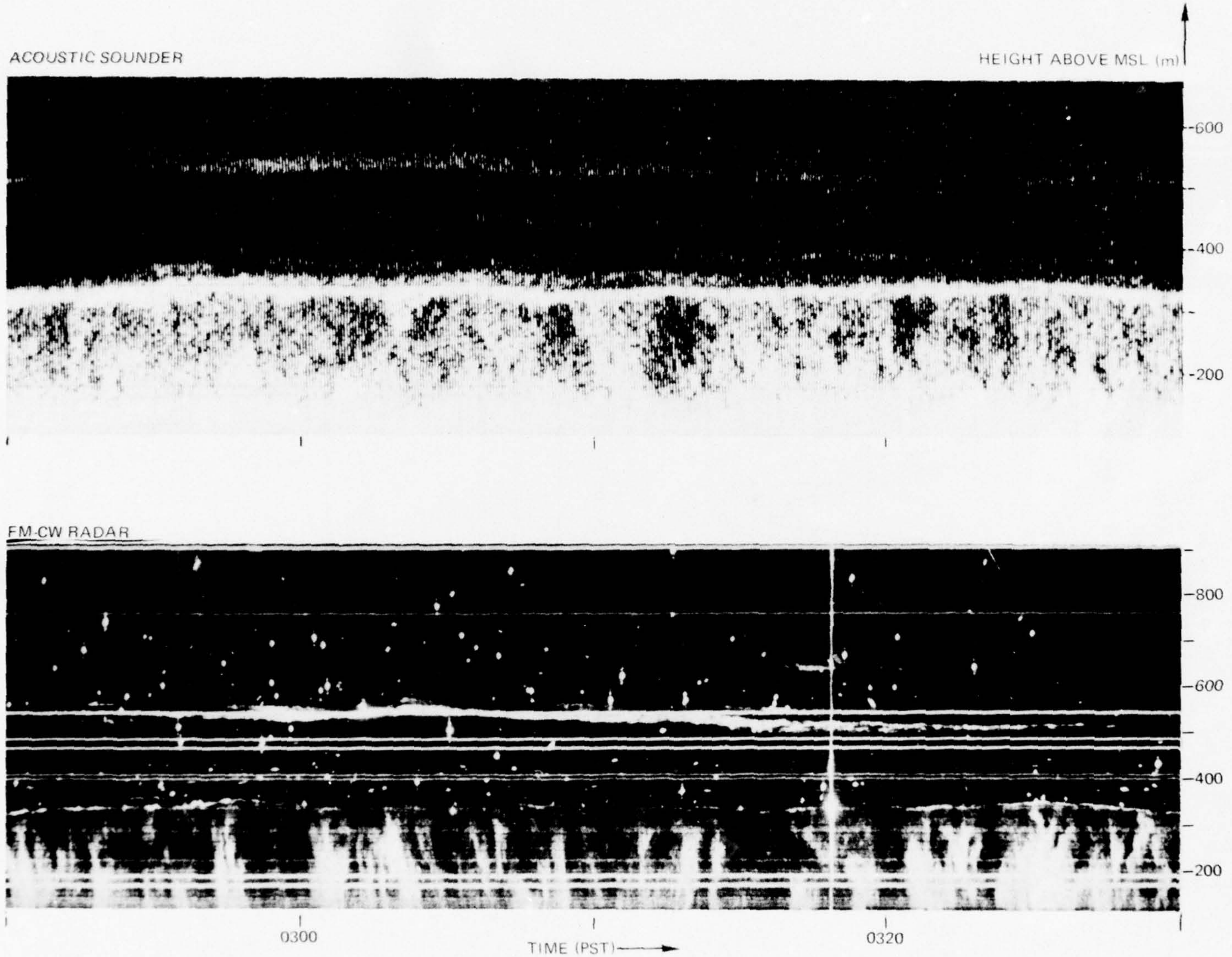

Figure 22. Sensor observations during a fog event on 23 June 1974.

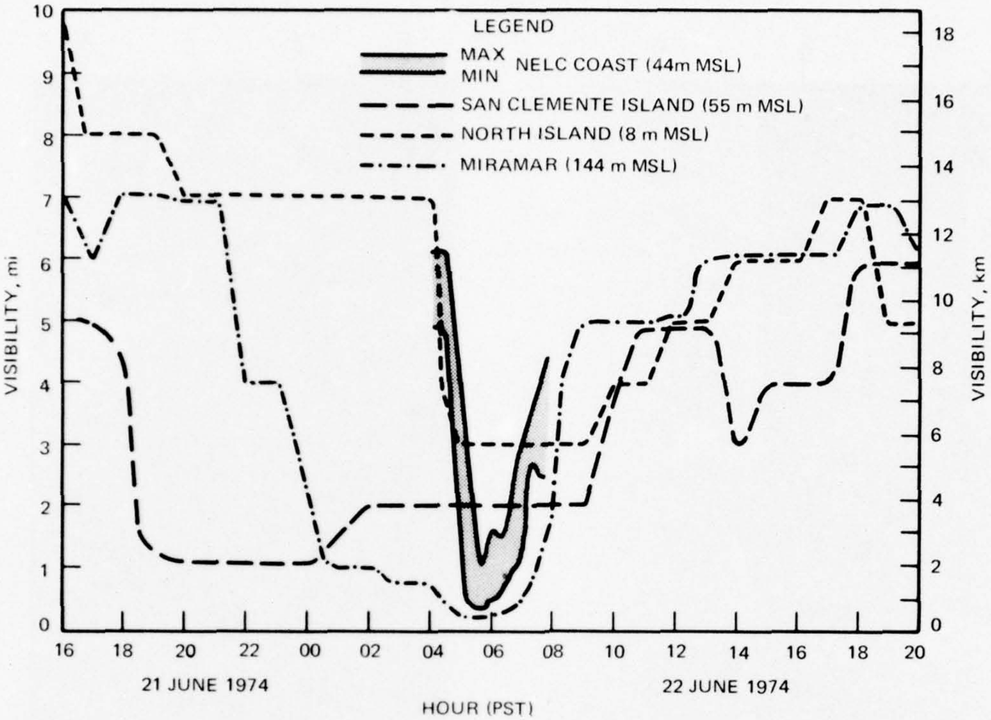

Figure 23. Visibility reported at four sites during a fog event on 21-22 June 1974.

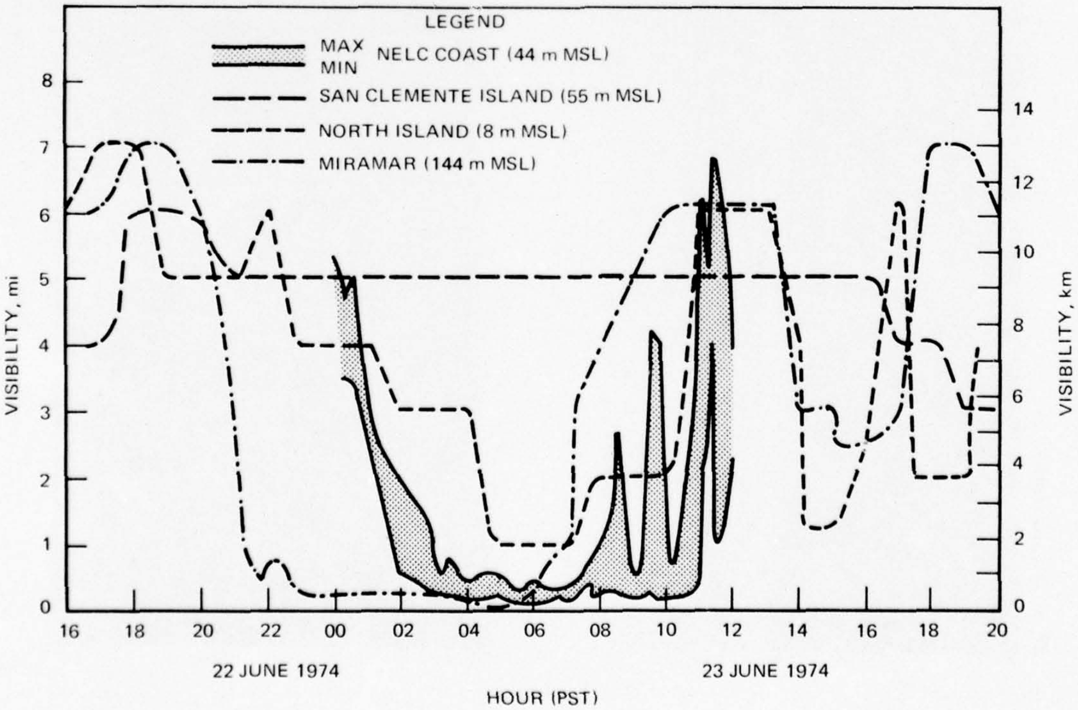

Figure 24. Visibility reported at four sites during a fog event on 22-23 June 1974.

– it began about 5 hours earlier than it did at NELC and terminated just after sunrise. The earlier commencement at Miramar might be expected because the stratus deck could be depressed to the surface there before it is at NELC since NELC has an elevation 100 metres below Miramar. Fog dissipation at Miramar just after sunrise would be expected because of surface heating. The time of fog dissipation at NELC appears to be uninfluenced by sunrise on 23 June 1974.

The pattern of visibility changes at San Clemente Island was completely different on the nights of the 21st and 22nd. Fog occurred between 2000 and 2400 PST on 21 June 1974 and visibilities remained above 5 miles (9.3 km) during the night of the 22nd. Thus, the visibility at San Clemente was greater during the night of the 22nd when persistent fog was observed at NELC and Miramar.

Figures 25 and 26 show the variation in the cloud ceiling during the nights of the 21st and the 22nd. Comparison of the ceilings in figures 25 and 26 with the visibilities in figures 23 and 24 shows that the visibility decreases with the ceiling. This is commensurate with the stratus fog model illustrated in figure 7. Figure 27 shows this clear relationship (ceiling and visibility) for the night of the 22nd at North Island.

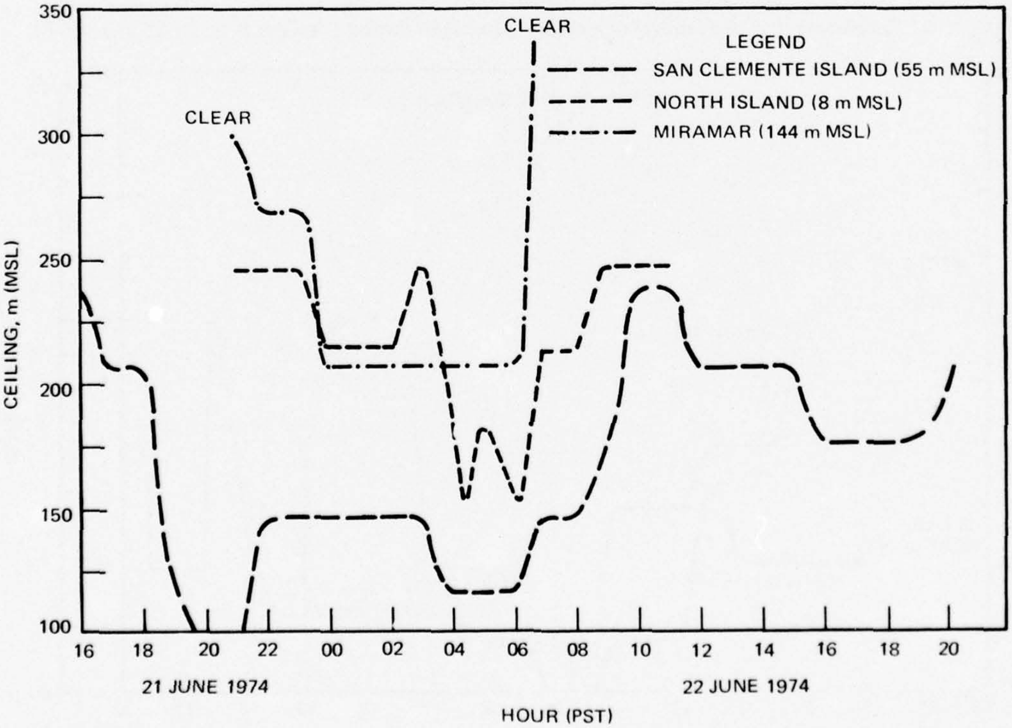

Figure 25. Cloud-base heights (ceiling) reported at three sites during a fog event on 21-22 June 1974.

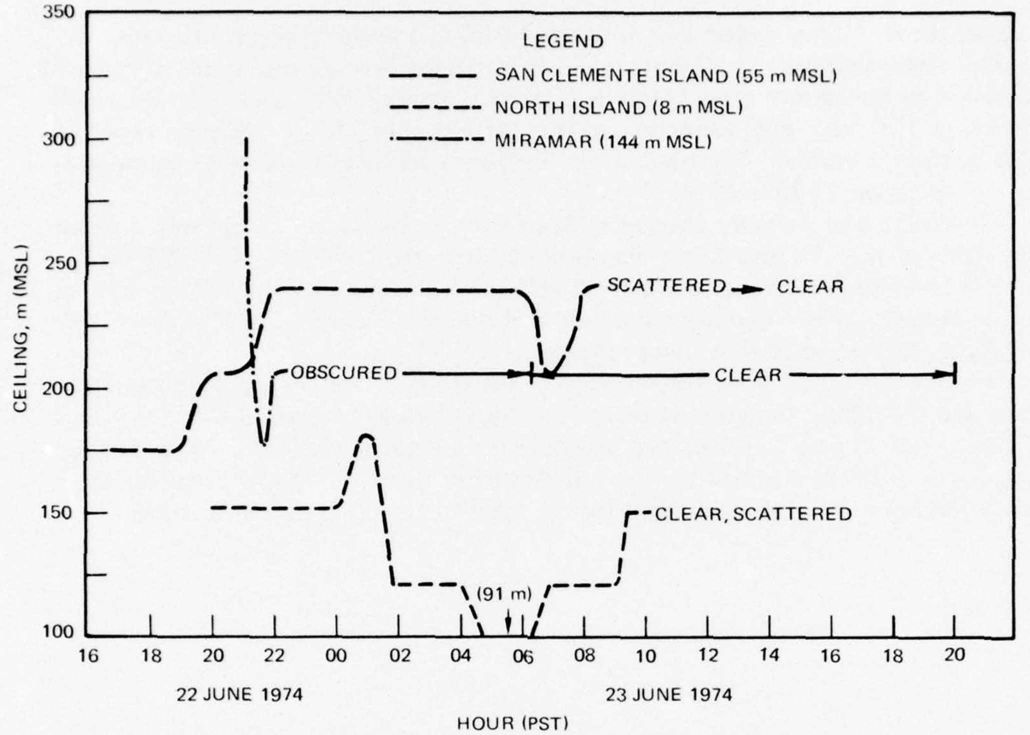

Figure 26. Cloud-base heights (ceiling) reported at three sites during a fog event on 22-23 June 1974.

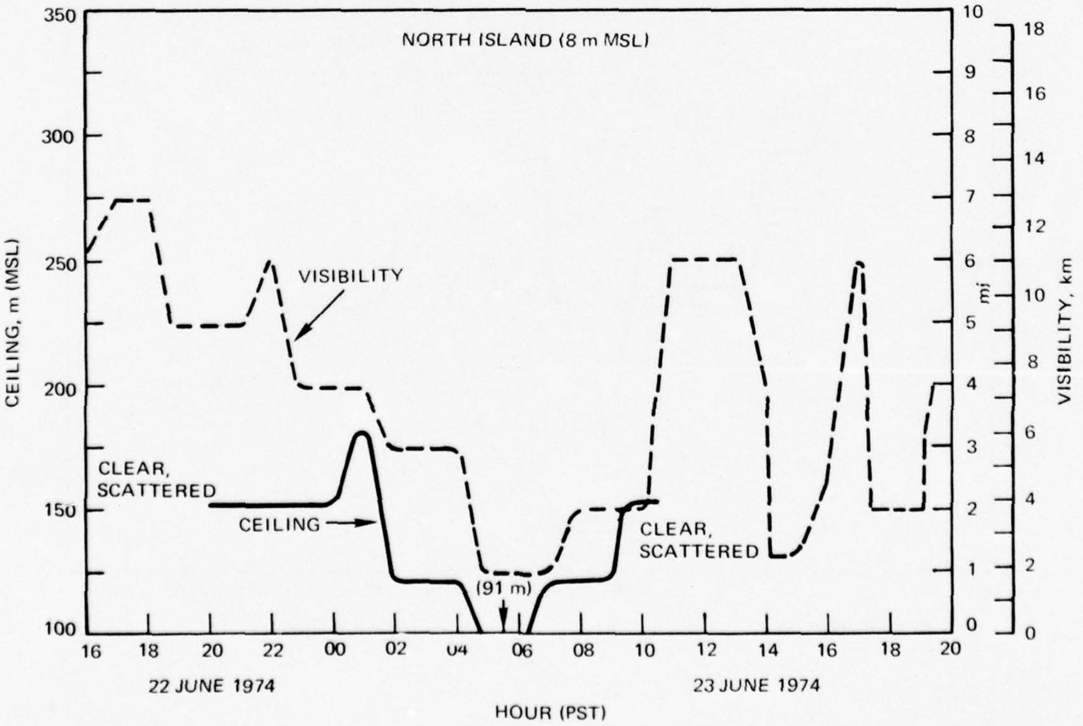

Figure 27. Cloud-base heights (ceiling) and visibility reported at North Island (San Diego) during a fog event on 22-23 June 1974.

OBSERVATIONS ON 15 JULY 1974

A weak high-pressure region present over Southern California at the 850 mb level on 15 July 1974 apparently produced sufficient subsidence to suppress the marine layer to low elevations. The 0400 PST radiosonde at Montgomery Field showed a double temperature inversion base; a weak inversion was present at 420 m and a stronger inversion was present at 510 m.

Figure 28 shows the relationship between the inversion base, the ceiling, and the visibility at NELC. The inversion base (shown by the dashed line on the top of fig 28) is at or below 400 m during this fog episode while the ceiling decreases to the sensor level as the visibility decreases to less than 1 mile (1.6 km). This figure clearly demonstrates the creation of fog by a depression of the stratus base in agreement with the model in figure 7.

OBSERVATIONS ON 19 OCTOBER 1974

A mild Santa Ana condition prevailed in Southern California on 17 October 1974 and a fog bank moved into the NELC site at 1730 PST that day. Fog which occurred on the night of 18 October appeared to be generated by the Santa Ana condition in a continental air mass with low visibilities. By the morning of 19 October, visibility had increased to about 1 mile (1.6 km) and the marine layer was reestablished according to the Montgomery Field radiosonde at 1600 PST. A stratus-cloud weather regime was clearly established by the night of 20 October 1974.

Figure 29 shows the dissipation of fog on the morning of 19 October. The dissipation appeared to result from solar heating over the land and by a lifting of the fog deck as the depth of the marine layer increased about 200 m in a 3-hour period. The fog deck apparently lifted within a region just below the inversion so that it eventually dissipated as a thin stratus cloud along the coast. The primary control of the fog dissipation appeared to be the rapid increase in the depth of the marine layer commencing at 0900 PST.

OBSERVATIONS ON 11 AND 12 MAY 1975

Southern California was dominated by a high-pressure system from the surface up to the 500 mb level on 11 and 12 May 1975. Figure 30 shows the surface-pressure pattern, which is almost a combination of a weak Santa Ana pattern and a summer pattern (compare this figure with the isobaric pattern in fig 8). Subsidence was able to suppress the marine layer to 450 metres at 1600 PST on 11 May and to 300 metres at 0400 PST on 12 May according to the radiosondes taken at Montgomery Field.

Figure 31 shows the onset of fog at NELC at 2000 PST on 11 May and figure 32 shows the termination of fog at 0730 on 12 May. The fog event was continuous throughout this time period. The acoustic echosounder revealed a marine layer depth of 190 metres at 1930 PST on 11 May 1975 which increased to 400 metres by 0600 just before the end of the fog event. The lidar shows a steady decrease in the stratus ceiling during the decrease in visibility (fig 31) and a steady increase in ceiling during the end of the fog event.

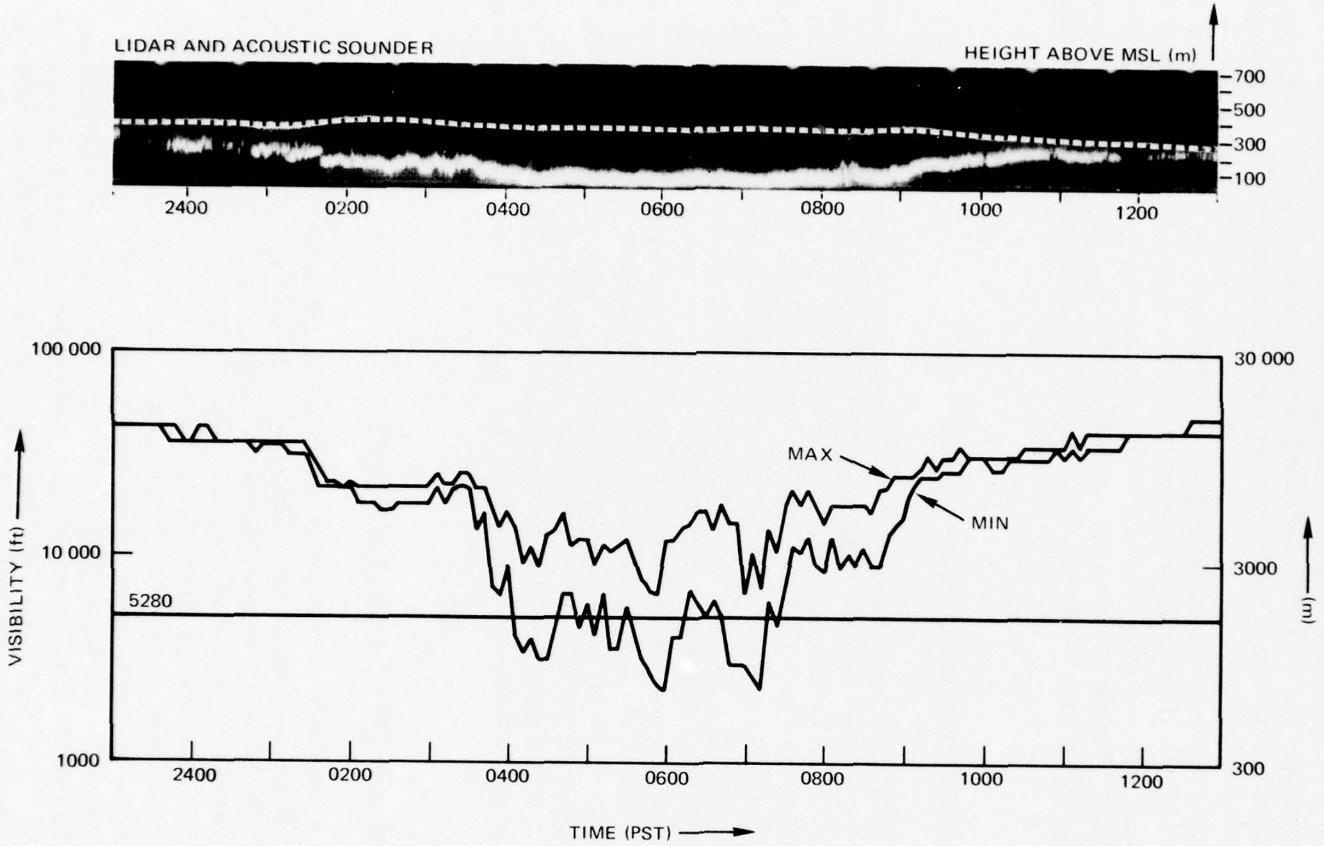

Figure 28. Cloud-base heights (photographic record of lidar observations), cloud-top heights (indicated by dashed line according to acoustic soundings) and visibility (maximum and minimum by MRI Fog Visiometer) during a fog event on 15 July 1974.

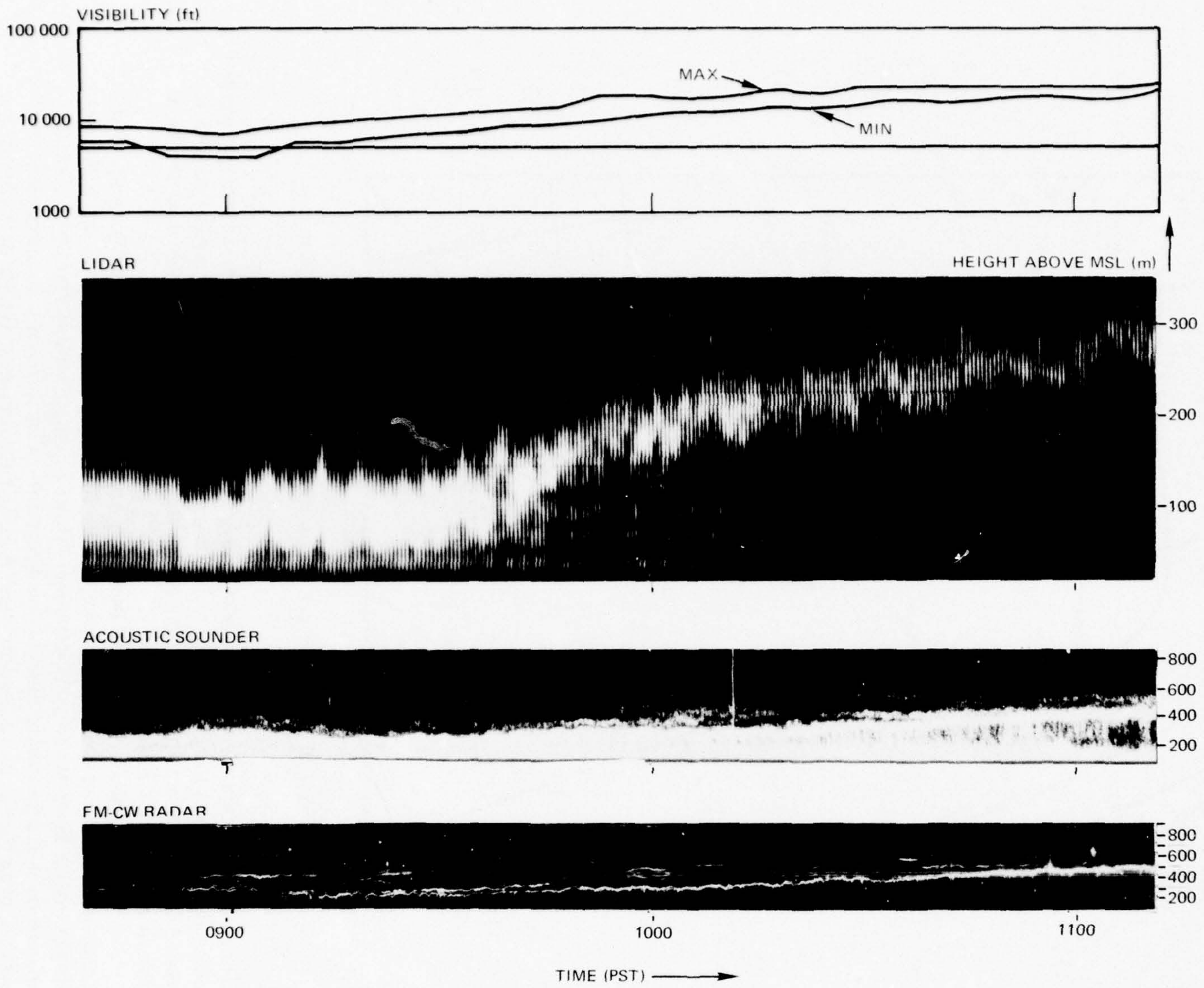

Figure 29. Sensor observations during a fog event on 19 October 1974.

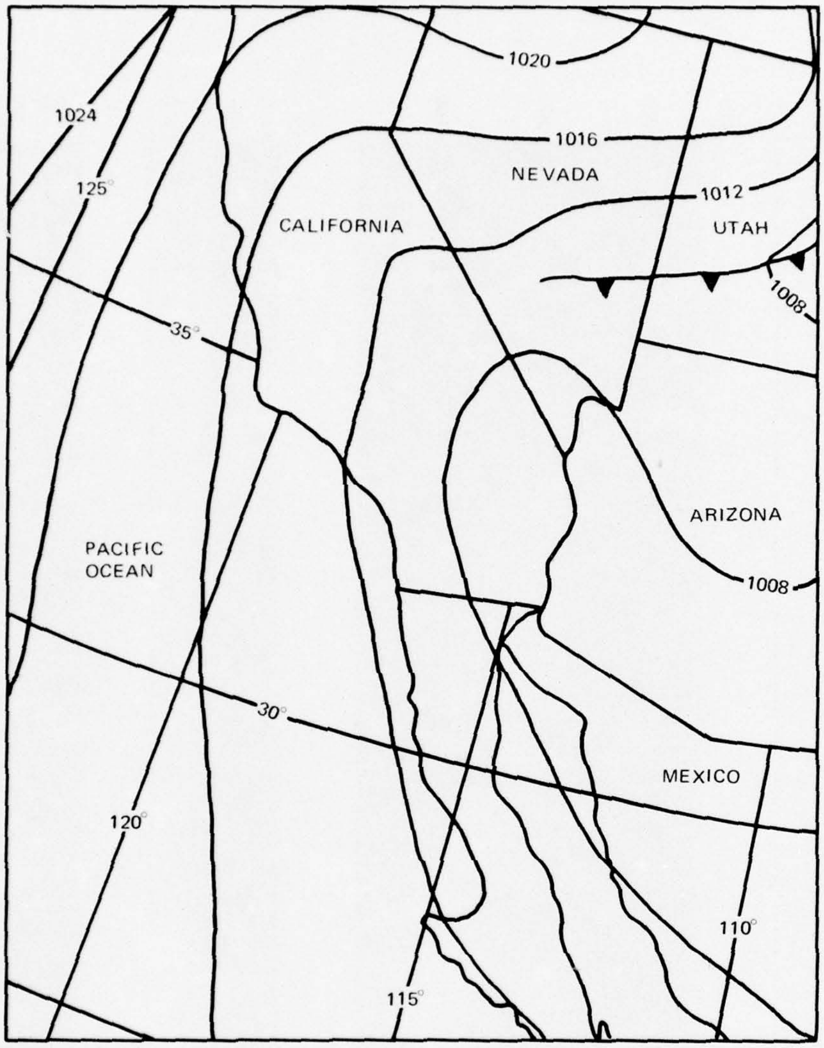

Figure 30. Surface pressure pattern on 11 May 1975 near a fog event.

The radar echo from the top of the marine layer was near the base of the radar height window when the layer was low. However, a careful analysis of the film of the radar record revealed that drizzle was present during the entire fog event; drizzle is shown in the radar record at 0610 PST in figure 32.

Figure 33 shows graphically the major observations during this fog event. The acoustic sounder and the FM-CW radar usually sense a predominate echo from the top of the marine layer at the same elevation. However, these sensors revealed different marine layer depths during most of this fog event. This difference is unexplained but will be given further consideration when a sufficient number of similar data periods are available. Both sensors show a minimum in the marine-layer depth near the time of fog onset which increases later. The depth is less than 400 metres until about 2 hours

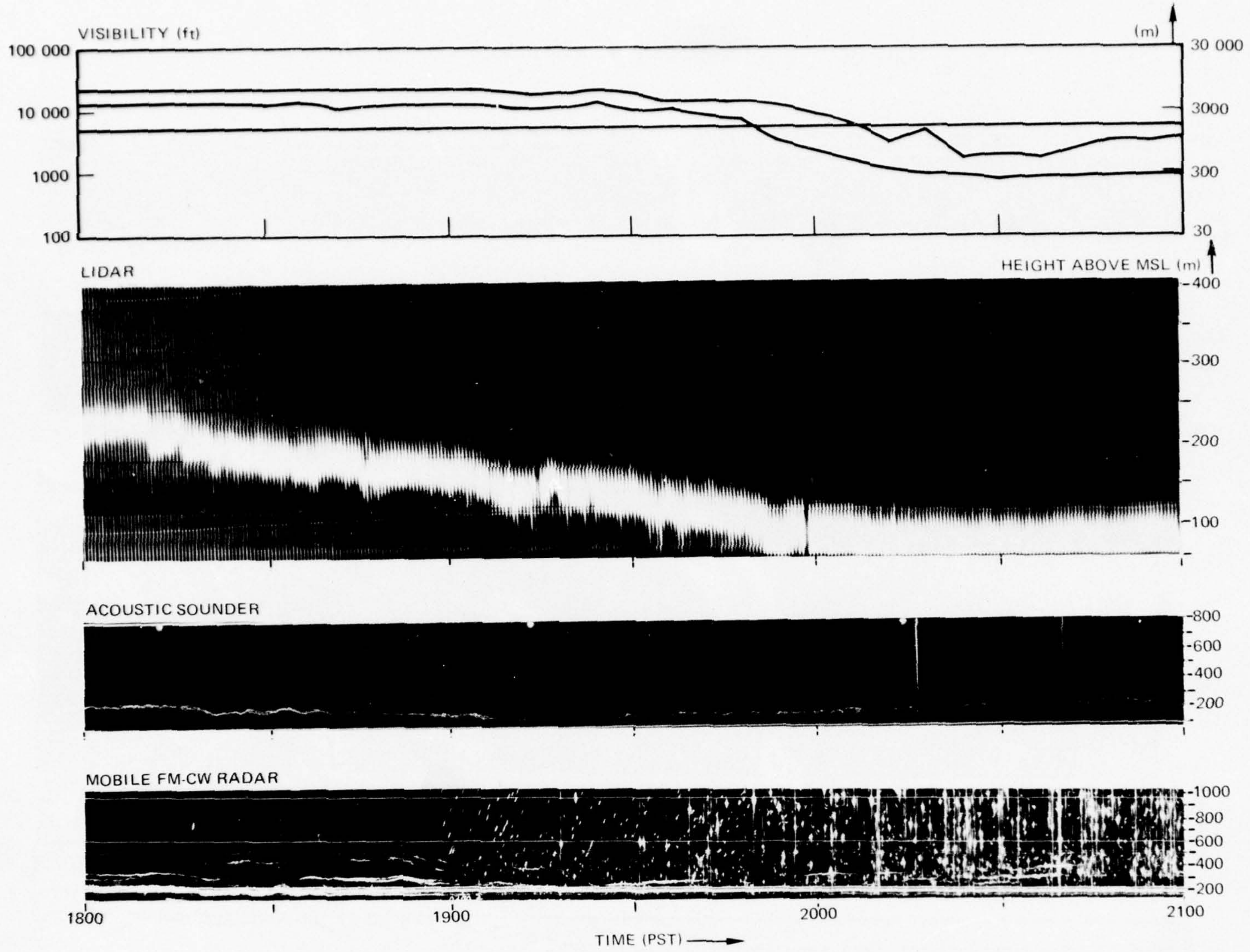

Figure 31. Sensor observations during the onset of fog on 11 May 1975.

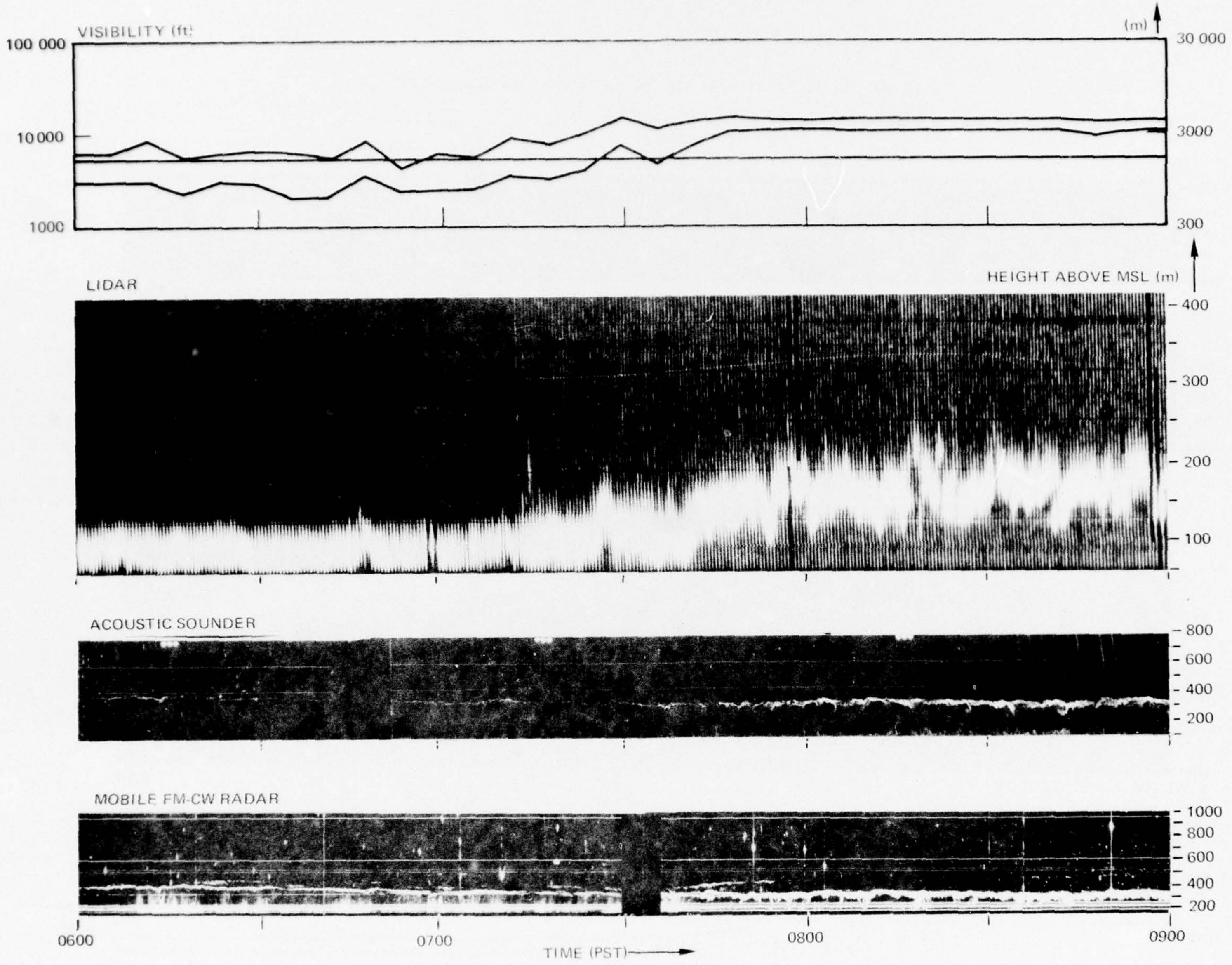

Figure 32. Sensor observations during the dissipation of fog on 12 May 1975.

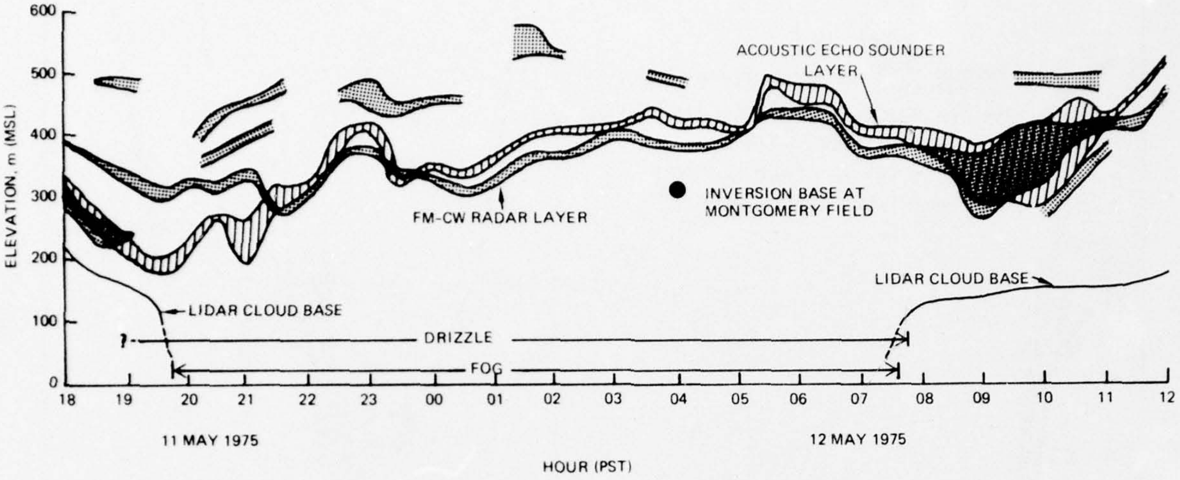

Figure 33. Graphic presentation of significant sensor observations during a fog event on 11-12 May 1975.

before fog dissipation which occurs just after sunrise. Drizzle was observed by the radar throughout the fog event but the onset time of the drizzle could not be determined. These observations support the model given in figure 7.

Figure 34 shows the variability of the visibility in the local mesoscale region during this fog event. (The visibility at NELC is not given throughout the fog event but the average visibility was below 1 mile (1.6 km) during this period.) The visibilities throughout the fog event were approximately the same at NELC, North Island, and Miramar. However, fog was not observed at Imperial Beach (fig 1) which is located about 18 kilometres south of NELC. Fog was not observed at San Clemente Island although the visibility was reduced to 3 miles (4.8 km) near sunrise.

Figure 35 gives the stratus ceiling during this fog period for the same stations identified in figure 34. Although the ceiling was indefinite during part of the fog period at North Island and Miramar, comparison of the data in figures 34 and 35 reveals that the visibility decreased and increased in a manner similar to the ceiling at each station. This supports the stratus fog model illustrated in figure 7.

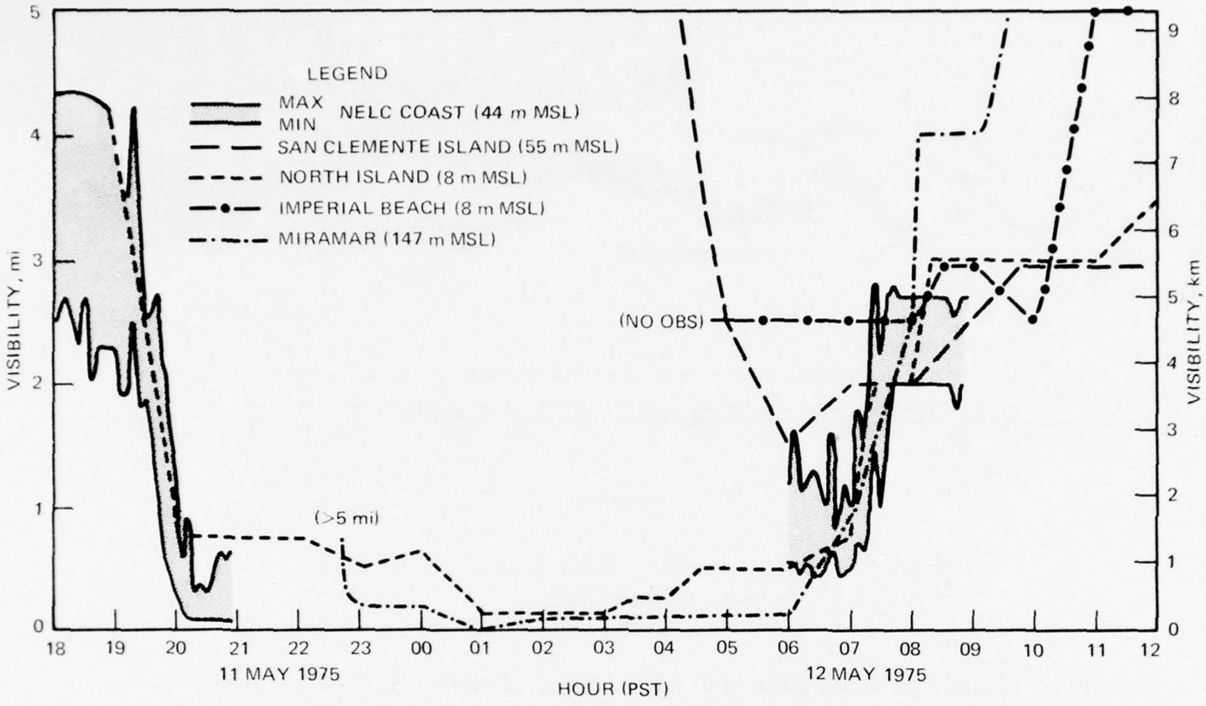

Figure 34. Visibility reported at five sites during a fog event on 11-12 May 1975.

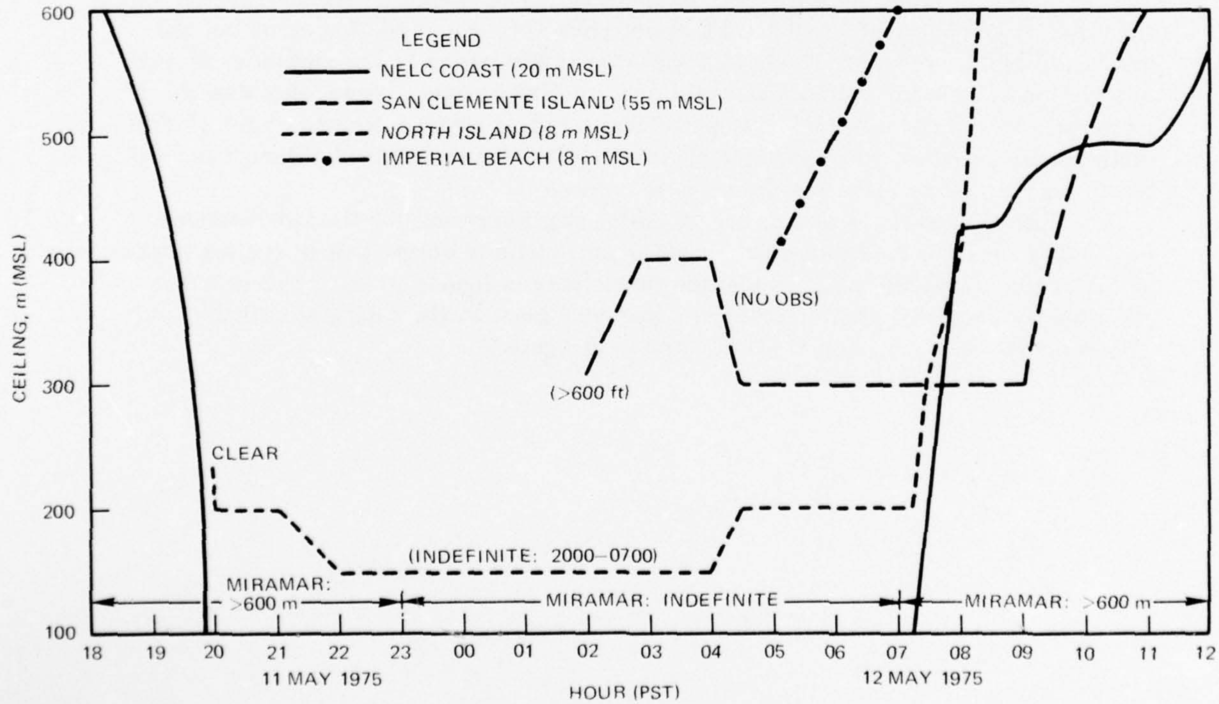

Figure 35. Cloud-base heights (ceiling) reported at four stations during a fog event on 11-12 May 1975.

MARINE LAYER STRUCTURE

Fog associated with stratus clouds is essentially a midcalendar year phenomenon along the California coast. According to the model shown in figure 7, low ceilings and relatively low visibilities would be expected to occur during the stratus season. The supply of moisture from the stratus clouds should maintain low ceilings and high humidities below the cloud base and produce lower surface visibilities particularly at night. The annual variation of low ceiling/visibility conditions along the coast of California was examined using data from San Diego, Pt Mugu, Monterey, and Oakland (fig 36). Figure 37 shows the percentage of days each month that have low ceiling/visibility conditions at these four stations in 1974 for the hours between 0300 and 0500 PST. The maximum percentage of low ceiling/visibility conditions occurs during midyear at all stations, especially at San Diego. The maximum number of cases of low ceiling/visibility conditions occurs later in the year at the more northerly stations rather than at San Diego.

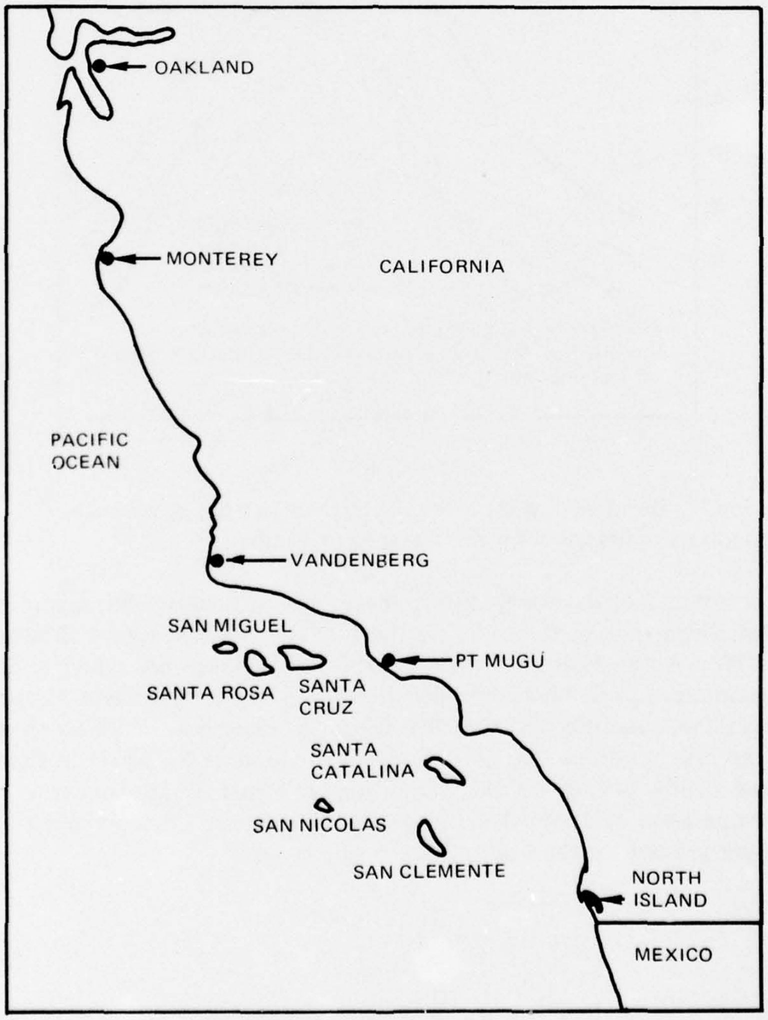

Figure 36. Map showing radiosonde stations considered in an examination of surface-based superadiabatic lapse rates.

Normally the Pacific, subtropical, high-pressure region is fully developed during the summer months. Stratus clouds generally blanket the eastern portion of the high-pressure region extending over California and inland to various distances depending on such factors as the time of day and pressure gradient. The northwesterly air flow associated with the stratus clouds causes the San Diego region to be deeper or farther downwind into the stratus deck as compared to the four other stations considered in figure 37. Being farther downwind, San Diego would be expected to have stratus clouds which have had the stratus-base lowering process (shown in fig 7) in progress a longer time period than stations farther upwind. The larger number of days with low ceiling/visibility conditions in San Diego supports this analysis.

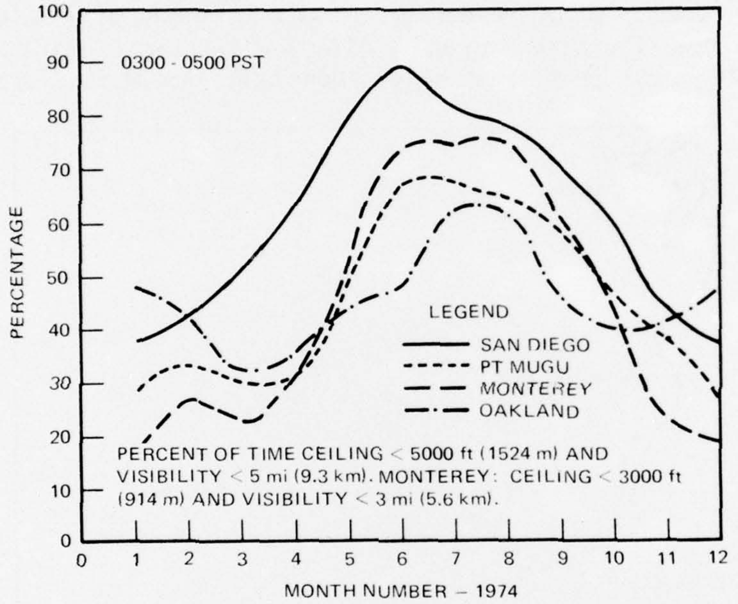

Figure 37. Distribution of the observations at four sites having low ceilings and low visibilities near 0400 PST according to month.

A larger number of days with surface-based superadiabatic (SS) layers would be expected at San Diego than at the more northerly stations if the model shown in figure 7 is applicable. An analysis of the 1974 0400 PST radiosondes taken at San Diego, Pt Mugu, Vandenberg, and Oakland revealed that SS layers are prevalent at all stations during the midcalendar months and that San Diego, as expected, had a much greater number than the other stations (fig 38). The annual trend of SS layers in figure 38 and the annual trend of low ceiling/visibility conditions in figure 37 are similar at all stations. These data provide good evidence that the processes in figure 7 are prevalent when stratus clouds are present on the California coastal region.

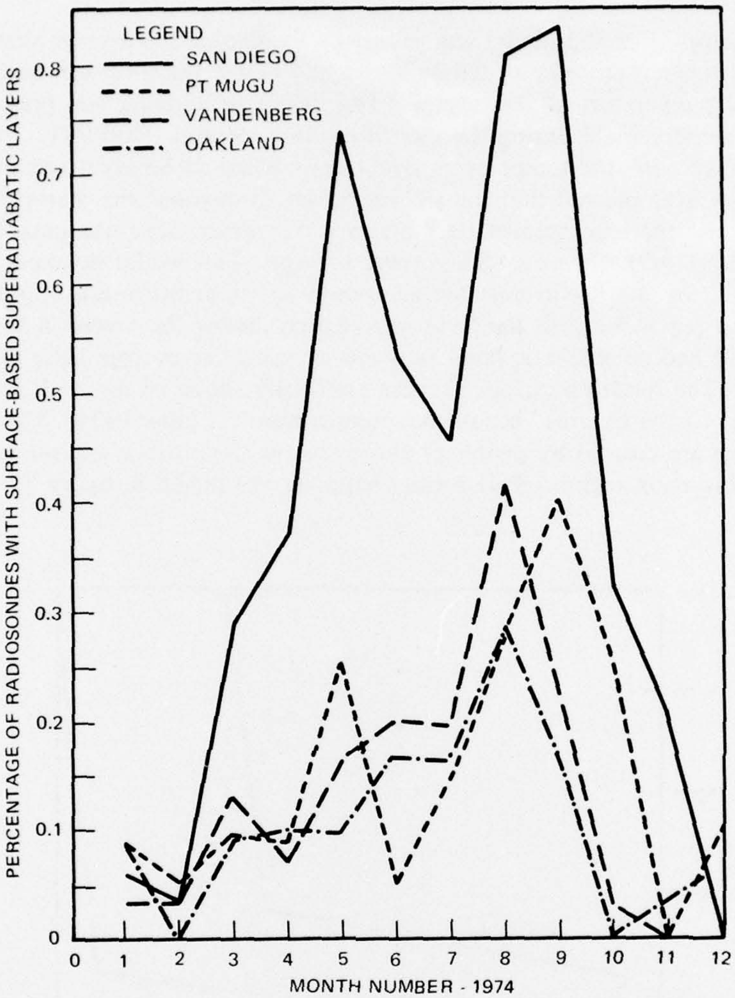

Figure 38. Distribution of the percentage of radiosondes taken at 0400 PST for the year 1974 which have surface-based superadiabatic layers according to month.

An analysis of SS layers occurring at NELC, Montgomery Field, and over the nearby ocean (aircraft data of Edinger and Wurtele, 1971[18]) by Austin and Noonkester (1974)[32] provided some initial data to support the model of figure 7. Data taken on a 100 foot (30.5 m) tower near San Onofre, California, by Meteorology Research Incorporated (private communications, 1976) also reveal SS layers during a large portion of the year. Research on California fog in the 1930s and 1940s revealed the presence of SS layers in fog (see BACKGROUND) and this has recently been confirmed (Calspan, Corporation, 1974, 1975[19,19a]). These results showing the presence of SS layers over the coast at night particularly during the stratus-cloud season appear to be new. This is particularly significant relative to supporting the stratus-base-lowering fog model.

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[32] Naval Electronics Laboratory Center Technical Note 2678, *Statistics on Surface-Based Superadiabatic Layers Over the Ocean Near Southern California*, by LB Austin and VR Noonkester, 26 July 1974

Further support of the model was gained by examining the average vertical potential temperature $\theta(z)$ structure immediately above and below the inversion base and the average potential temperature at the inversion base when an SS layer was present and not present at Montgomery Field during the month of June 1974 at 0400 PST. Figure 39 shows these average potential temperature structures. When an SS layer was present the average profiles of $\theta(z)$ showed that the air was colder throughout the marine layer and inversion region and the layer immediately below the inversion base was unstable compared to the average $\theta(z)$ when no SS layer was present. This would be expected according to the model in figure 7. The average surface potential temperature was approximated by assuming that the region beneath the layer immediately below the inversion base (dashed lines in figure 39) had an adiabatic lapse rate and by using the average lapse rate and depth of the SS layer. The resulting surface θs were essentially the same for both cases and were about equal to the observed sea-surface temperature for June 1974. This suggests that the SS layers are created by processes above the ocean's surface and are processes which cool the inversion region. This further supports the model in figure 7.

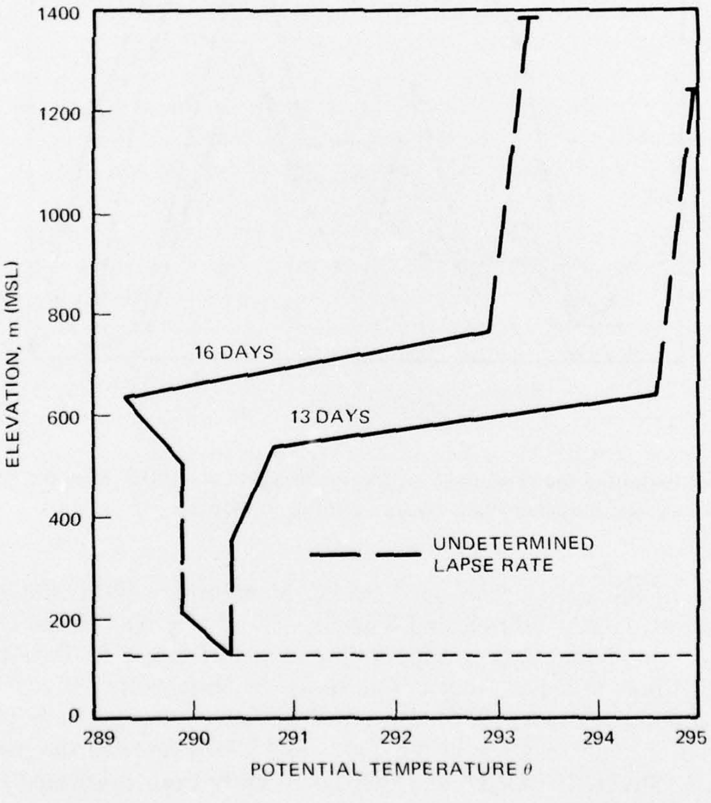

Figure 39. Average vertical structure of the potential temperature when surface-based superadiabatic layers were present and not present at 0400 PST, June 1974, according to radiosondes at Montgomery Field (San Diego).

DISCUSSION AND SUMMARY

The NELC coastal site has proved to be an excellent location from which to conduct studies on marine fog. Not being a field site but rather a permanent facility, observations can be commenced within a few hours of an expected fog event and continue for many hours without burdening the budget or personnel (as sometimes happens) of an off-site location. Even if the number of fog events each year at the NELC site is small, they can be monitored economically and assuredly at this "home-base" site. Many stratus cloud (SC) and Santa Ana (SA) related fog episodes have been observed at the NELC site and a few of the SC ones are presented in this report. A subsequent companion report (Noonkester and Logue, 1976[33]) will present data on representative fog events associated with SA conditions.

As indicated in the BACKGROUND section, SC related fog in the coastal and offshore region of Southern California appears to be somewhat unique. A four-factor objective technique which considers the uniqueness of the fog in Southern California has been developed and is regularly used by the forecasters at the Naval Weather Service Facility at North Island. The success rate of this technique is low (53%) and should be improved. A model has been proposed (fig 7 and Calspan Corporation report, 1974[19]) which is commensurate with the technique, agrees with many past studies, and is supported by recent measurements (Calspan Corporation, 1975[19a]).

The essential ingredient of the model shown in figure 7 is the presence of a stratus cloud deck capped by an inversion with moist cool air below. Without the clouds, radiation cooling could not occur; without the inversion, moisture would be transferred upward and reduce the amount of net upward radiation; without moist air below the cloud layer, saturation could not be extended downward by the radiation-turbulent/drizzle process; and without drizzle, the turbulent transport of moisture and cool air downward might be insufficient to saturate the subcloud layer. These components should be monitored continuously if they are to be evaluated.

The sensors used in this study monitored almost all of the essential factors of the model. The radar and acoustic sounder monitored the height of the inversion base (cloud top); the radar observed drizzle (as little as 0.014 mm/hr at 1 km); and the lidar or ceilometer observed the cloud base. Intermittent radiosondes and surface observations provided information on the moisture below and above the inversion. The visiometer measurements provided a measure of the effectiveness of the stratus-base depression process.

Theoretical estimates and empirical evidence have indicated that the probability of fog increases considerably if the inversion base is below 400 metres; the probability increases as the height of the inversion base decreases below 400 metres. All fog observations made at NELC support this general conclusion. Only a small percentage of the fog cases occur when the inversion is above 400 metres (figs 12 and 33). Generally, it appears that the stratus-lowering process cannot lower the base to the ground during the night unless the cloud top is below 400 metres. The stratus base can be lowered by a continuous decrease in the marine layer depth in response to mesoscale process. The acoustic record in figure 30 from 1800 to 2000 PST indicates this mechanism which can be operating simultaneously with the radiation-stratus-base lowering model. A decrease in the marine layer depth can also aid in the dissipation of the stratus/fog in the morning as indicated in figure 14.

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[33] Naval Electronics Laboratory Center Technical Report 2000, *Fog Related to Santa Ana Conditions in Southern California*, by VR Noonkester and LE Logue (in process)

Drizzle has often been observed at ground level prior to and during fog. The radar has uniquely observed it in and below the stratus clouds as shown in figures 10, 11, 21, and 22. Drizzle has been observed to fall for many hours from a stratus deck of clouds beneath a high inversion without subsequent fog. It is not always observed during fog episodes and particularly not when the fog is beneath an inversion below about 200 metres. The presence of drizzle might be used as one indicator of a stratus base lowering process which, by itself, is insufficient information to specify the likelihood of fog.

Processes upwind (assuming a constant wind direction with elevation) of the point of concern must be considered for predicting the occurrence of fog. The characteristics of the temporal and spatial features of the marine layer along an upwind streamline are needed to make a fog assessment; however, this information is rarely available. The remote sensors are likely to provide measurements which represent the mesoscale region of the atmosphere a large percentage of the time for some purposes (Glevy, 1976[34]), but the extent of horizontal homogeneity for fog producing processes is unknown. The marine layer depth and the occurrence of drizzle may vary considerably upwind of the sensors so that neither factor can be fully evaluated in fog formation when using fixed site measurements. However, the fixed site observations indicate that the inversion base should be less than about 400 metres for fog to be likely and that drizzle is required.

Almost no information is available on the processes of forming drizzle. Radiational cooling at the top of the cloud may be the predominate process, but this is yet to be determined. The radar often shows drizzle falling from regions almost indistinguishable from the echo region representing the cloud top (inversion base). The intensity of the drizzle echo appears to be independent of elevation; this suggests a drizzle source region below which additional drizzle is not being added. These observations imply a drizzle source region near the top of the stratus. This would support a cloud top-cooling mechanism.

Except for echoes caused by drizzle, the radar rarely observes them below the inversion base; this suggests a rather uniform moisture field below the inversion which would be expected in the unstable SS layer near the surface (fig 7). The acoustic sounder often observes diffuse echoes below the inversion base during fog events – this might be created by mixing in the unstable regions and as indicated by the model.

All the data essentially agree with the features of the model shown in figure 7. The remote sensors can monitor the important stratus cloud features related to fog formation and can be used as fog forecasting aids if trends can be extrapolated. However, trend extrapolation has considerable limitations; mesoscale and synoptic scale features usually alter trends significantly for time scales near 2-to-6 hours. Estimates of the mesoscale features which influence the stratus structure upwind are needed. The analysis of the day-to-day trends in, and values of, the four factors used in the objective fog forecasting technique may reveal types of information required to improve the fog forecasts – mesoscale studies are considered essential to this analysis.

Radiational cooling at the top of the stratus deck is the initiating process in the stratus-thickening model. The magnitude of and the factors controlling the radiational cooling have not been measured. Measurements might reveal mesoscale variations dependent on the stratus cloud structure which can be traced upwind from the point of interest.

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[34] Naval Electronics Laboratory Center Technical Note 3153, *An Assessment of Radio Propagation Affected by Horizontal Changes in Refractivity*, by DF Glevy, 3 May 1976

An independent analysis of the temperature structure revealed by radiosondes provided good evidence that the radiation cooling model is a good representation of predominate processes during the presence of extensive stratus cloud decks off the coast of California. The apparent creation of a superadiabatic lapse rate of temperature immediately below the top of the cloud and the subsequent cooling of the entire marine layer (by turbulent transfer of cool air or by drizzle evaporation) to create a surface-based superadiabatic layer indicate that radiational cooling is a highly significant process in the marine layer and is probably the predominate process in creating stratus cloud related fog.

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APPENDIX: NEW CEILOMETER RECORDING TECHNIQUE

A rotating beam ceilometer (AN/GMQ 13C) with a 400 foot (122 m) base leg has been placed at the NELC sensor site and has been operating since September 1975. The output of the ceilometer is displayed on an intensity modulated scope which is filmed by a shutterless movie camera to provide the same type of record made for the FM-CW radar and acoustic echosounder returns. Figure A-1 shows a continuous ceilometer record from a low stratus cloud during a 12-hour period on 22 September 1975. The nonlinearity of the vertical height scale provides considerably more detail during low-ceiling or near-fog conditions. This is in contrast to the lidar which has a linear vertical scale.

The large dynamic range of the filming technique and the automatic gain control of the ceilometer permit considerable detail to be detected in the moist marine layer when clouds are absent or thin. During conditions of minimum signal, the receiver gain is automatically increased to its maximum sensitivity; light scattered from particles is then detected by the receiver. The gain changes at the beginning of each vertical sweep depending on the intensity of the return on the preceding sweep. This provides a rapid response relative to the rotation rate.

Figure A-2 is a ceilometer record showing weak returns from the marine layer before and after the presence of clouds having a base height of 100 metres. When clouds are absent, the weak returns – although not always present in the absence of clouds – provide a measure of the marine layer depths. Figure A-3, obtained by using the film technique above, shows a similar ceilometer record to that in figure A-2 but it also reveals a more detailed variation in the marine layer and cloud structure. A double cloud layer is revealed at 0830 and 0920 GMT and low-level, plume-like echoes are revealed at 0910 GMT. Figure A-4 shows the echoes during a minor fog episode on 16 November 1975. Many details in the fog structure are revealed by this technique. The normal facsimile ceilometer records do not reveal these details.

When recorded by film, the ceilometer provides a superior record of the marine layer or cloud base structure compared to the lidar. The ceilometer will be used in future fog studies at NELC.

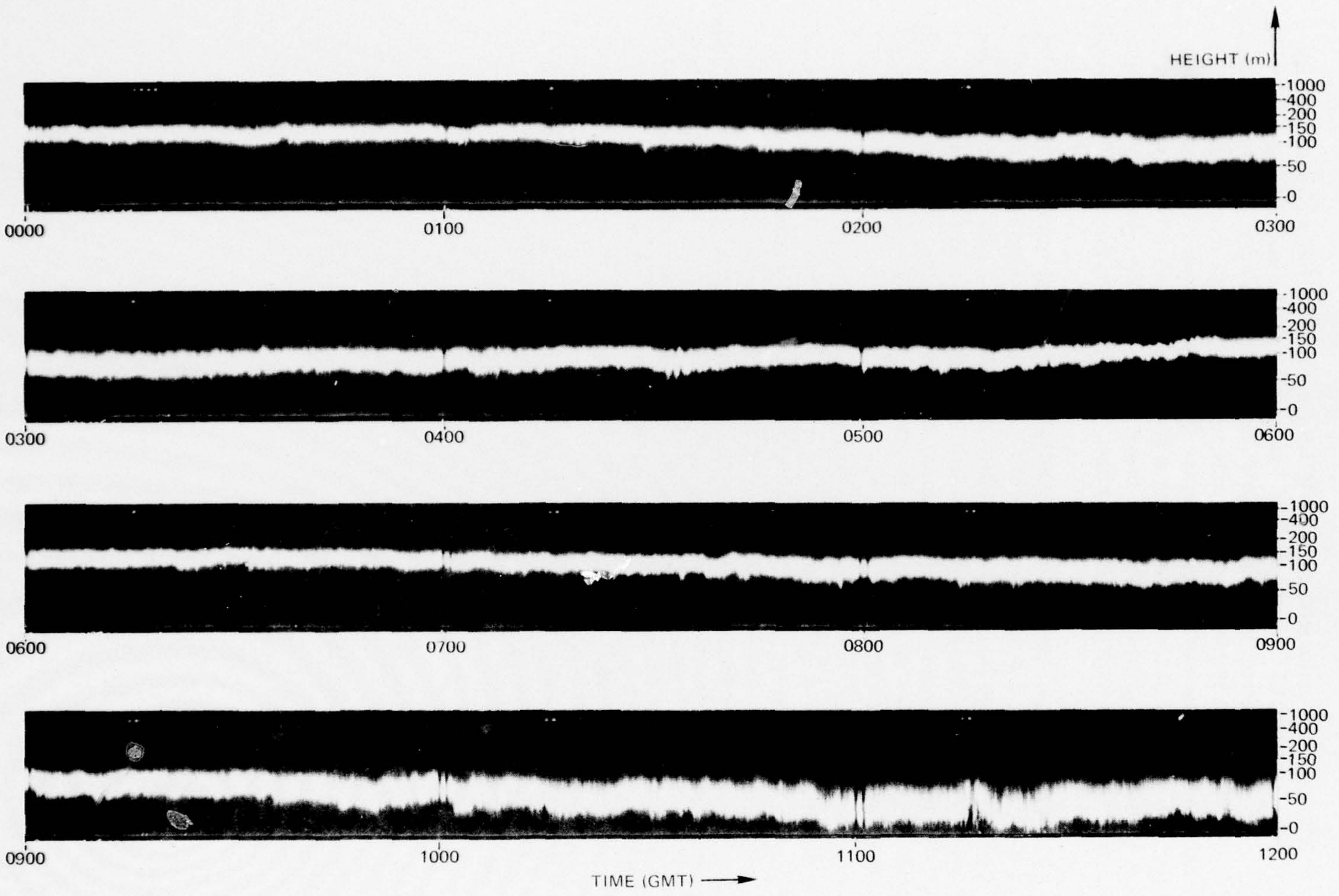

Figure A-1. Ceilometer observations on 22 Sept 1975.

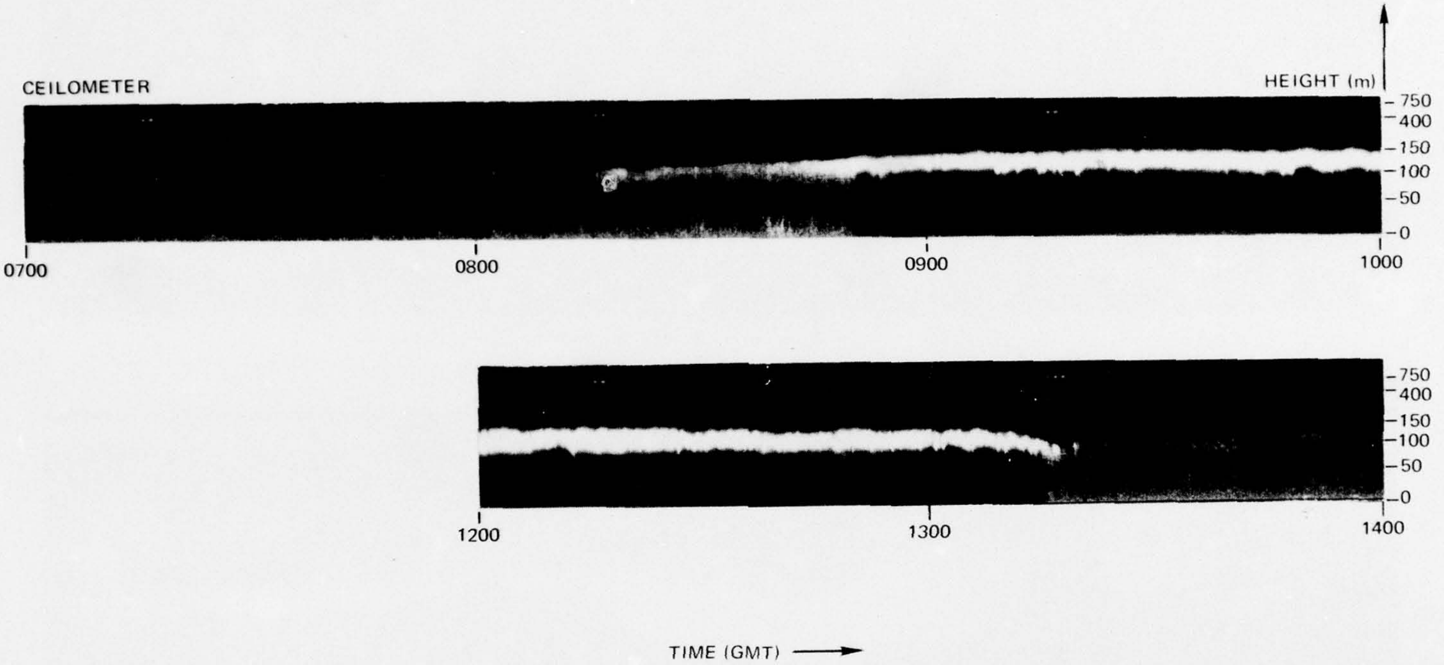

Figure A-2. Ceilometer observations on 19 Sept 1975.

Figure A-3. Ceilometer observations on 20 September 1975.

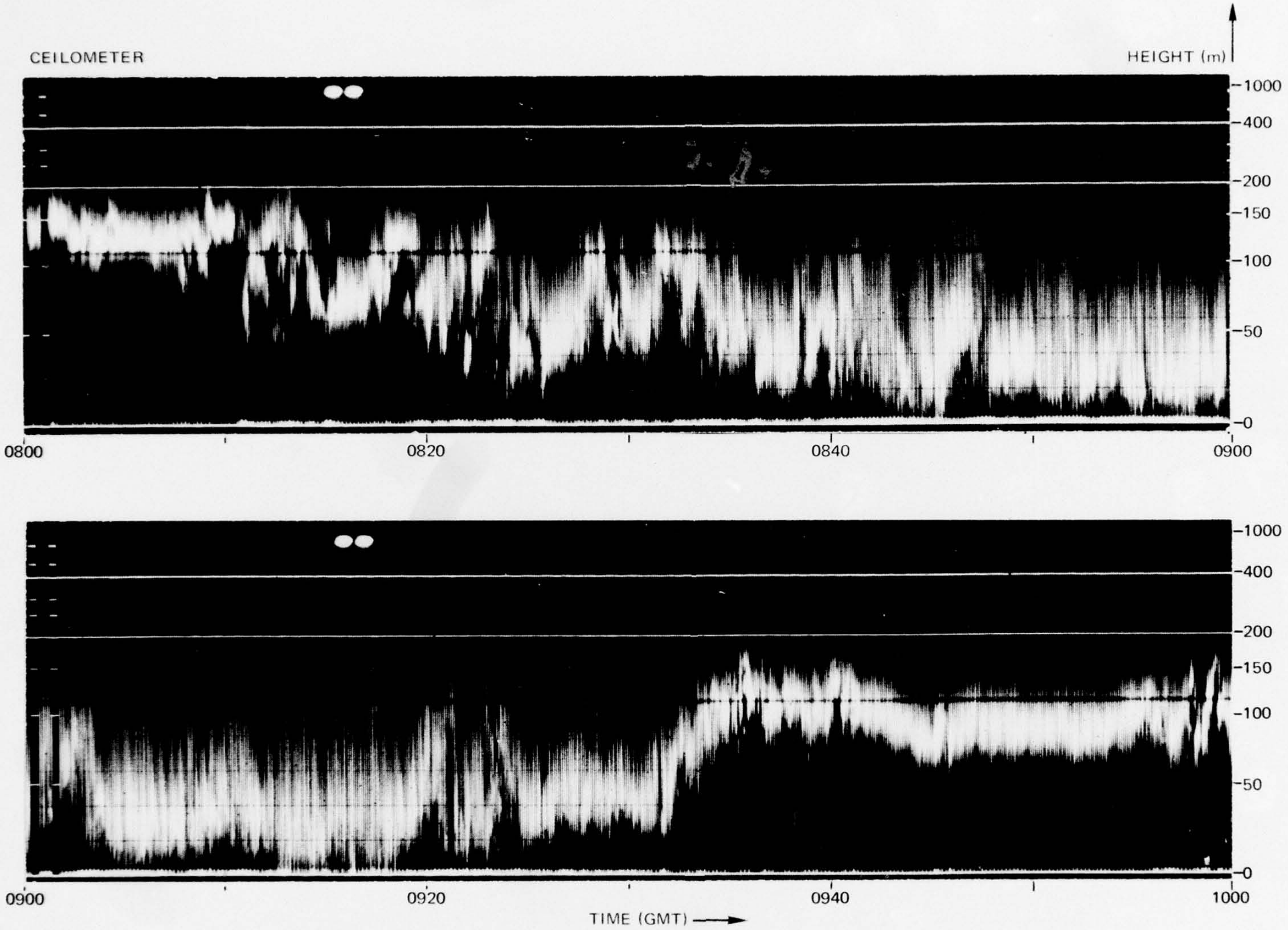

Figure A-4. Ceilometer observations on 16 November 1975.