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Technical Report 172

MARINE FOG INVESTIGATION AT SAN DIEGO DURING CEWCOM –1976

Simultaneous observations made on land at NOSC and by aircraft, ship, and satellite during the Cooperative Experiment in West Coast Oceanography and Meteorology (September and October, 1976) revealed significant relations between low-level vertical structure, surface air flow, sea surface temperature, and area of marine fog patches

VR Noonkester

13 October 1977

Prepared for
Naval Air Systems Command
Washington, D. C. 20782

Research, September 1976 - August 1977

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ADMINISTRATIVE INFORMATION

Work was performed under Air Task A370370C/003A/7R03302001, element 61153N, project WR03302, task WR0330201, by members of the NOSC Electromagnetic Propagation Division (Code 532) for the Naval Air Systems Command. This report covers work performed from September 1976 through August 1977 and was approved for publication on 13 October 1977.

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Under authority of
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Environmental Sciences Department

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(9) Technical rept. Sep 76–Aug 77

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	NOSC Technical Report 172 (TR 172) (14) NOSC/TR-172
2. GOVT ACCESSION NO.	
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle)	(6) MARINE FOG INVESTIGATION AT SAN DIEGO DURING CEWCOM-1976. Simultaneous observations [redacted] on land at NOSC and by aircraft, ship, and satellite during the Cooperative Experiment in West Coast Oceanography and Meteorology (Sept[redacted]/Oct[redacted]76) revealed Significant Relations between Low-Level Vertical Structure, Surface Air Flow Sea Surface Temperature, and Area of Marine Fog Patches.
5. TYPE OF REPORT & PERIOD COVERED	Research, September 1976–August 1977
6. PERFORMING ORG. REPORT NUMBER	
7. AUTHOR(s)	(10) V.R. Noonkester
8. CONTRACT OR GRANT NUMBER(s)	(12) 80p.
9. PERFORMING ORGANIZATION NAME AND ADDRESS	Naval Ocean Systems Center, San Diego, CA 92152 (per bpg)
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS	61153N, (16) WR03302, (17) WR0330201
11. CONTROLLING OFFICE NAME AND ADDRESS	Naval Air Systems Command, Washington, DC 20782
12. REPORT DATE	(11) 13 Oct[redacted]77
13. NUMBER OF PAGES	78
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	
15. SECURITY CLASS. (of this report)	UNCLASSIFIED
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution is unlimited

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

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

The formation and dissipation of Santa Ana marine fog along the coast of Southern California was investigated, using multiple remote sensor data taken on land at NOSC and other data taken by means of aircraft, ship, and satellite. The simultaneous measurements provided excellent, unique data concerning the horizontal distribution of factors controlling the formation and dissipation of marine fog. Santa Ana marine fog appears to form in regions where the sea surface temperature is decreasing in the direction of air flow and where low-level convergence is present after subsidence aloft has attained a maximum. Satellite and aircraft data can provide valuable information on marine fog over the offshore regions. More information on horizontal and temporal variation in air flow and sea surface temperature must be considered to improve fog forecasts related to Santa Ana conditions along the coast of Southern →

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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significant relations between low-level vertical structure, surface air flow, sea surface temperature, and area of marine fog patches.

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California. An unusually detailed sea surface temperature pattern was obtained by aircraft IR data over the ocean near San Diego. Vertical profiles of the horizontal wind measured by acoustic techniques were found to provide valuable information on moisture distribution during one fog event.

OBJECTIVE

Investigate the structure of the lower atmosphere in the mesoscale region by means of remote sensors. In particular, investigate the formation and dissipation of marine fog associated with Santa Ana conditions along the coast of Southern California, using multiple remote sensor data taken on land at NOSC and other data taken by means of aircraft, ship, and satellite during the Cooperative Experiment in West Coast Oceanography and Meteorology (CEWCOM) conducted in September and October, 1976.

RESULTS

The major results of the Santa Ana marine fog investigation at NOSC during CEWCOM-1976 are as follows:

- Simultaneous measurements by sensors on land, ship, aircraft, and satellite provided excellent, unique data concerning the horizontal distribution of factors controlling the formation and dissipation of marine fog.
- Santa Ana marine fog appears to form in regions where the sea surface temperature is decreasing in the direction of air flow and where low-level convergence is present after subsidence aloft has attained a maximum.
- Satellite and aircraft data can provide valuable information on marine fog over the offshore regions.
- More information on the horizontal and temporal variations in air flow and sea surface temperature must be considered to improve fog forecasts along the coast of Southern California.
- An unusually detailed, reliable sea surface temperature pattern was obtained by aircraft IR data over the ocean near San Diego.
- Vertical profiles of the horizontal wind measured by acoustic techniques were found to provide valuable information on moisture distribution during one fog event.

RECOMMENDATIONS

- Low-level atmospheric data taken aboard an aircraft and by satellite should be further exploited in marine fog and atmospheric structure investigations. Aircraft aerosol measurements should be emphasized.
- Conduct other experiments similar to CEWCOM-1976 to investigate atmospheric properties concerning low-level optical and radio propagation and weather, like marine fog, affecting naval operations.
- Add forward and backscatter optical sensors (e.g., FM-CW lidar) to the NOSC Sensor System.

ACKNOWLEDGEMENTS

The author is indebted to DR Jensen, ML Phares, and WK Horner for their efforts in operating the sensors during CEWCOM-76; to AGC LE Logue for his detailed analysis of mesoscale data and fog-forecast indices; and to JT McKee and BE Portwood for their careful processing of the data. Thanks are extended to AGC R Whritner of the Naval Weather Service Facility, North Island, for his detailed analysis of DMSP and sea surface temperature data. Appreciation is extended to CL Campbell, also of the Naval Weather Service Facility, for his sea surface temperature analysis. The author offers appreciation to JH Richter and HG Hughes for their assistance in planning and expediting NOSC's contribution to CEWCOM-1976.

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ILLUSTRATIONS

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INTRODUCTION

Fog over ocean regions poses serious threats to many naval operations and has been critically examined for five years by several agencies sponsored by the Naval Air Systems Command and the Office of Naval Research. The Naval Ocean Systems Center has been investigating marine fog under the NAVAIR program since 1974, using a fixed position, multisensor measurement system on the coast of San Diego (Richter et al, 1976)[1]. The results of these studies at NOSC have been presented by Noonkester and Logue (1976a, 1976b)[2,3] and Noonkester, et al (1976)[4].

One major conclusion of the NOSC studies is that the formation and dissipation of the coastal marine fogs near Southern California are strongly controlled by mesoscale variations in the atmospheric circulation and vertical structure. Mesoscale atmospheric variations and sea surface temperature gradients were concluded to be important in the evolution of marine fog in other coastal regions by other NAVAIR sponsored groups (eg, Mack, et al, 1975)[5].

An experiment entitled Cooperative Experiment in West Coast Oceanography and Meteorology of 1976 (CEWCOM-1976) was conducted off the coast of Southern California south of Point Conception to investigate (in particular) the atmospheric mesoscale variations and sea surface temperature gradients during the evolution of marine fog, using many measurement techniques and platforms. CEWCOM-1976 utilized sensors on a ship, an aircraft, shore (NOSC), and a satellite. Sensors were placed on the Research Vessel ACANIA [operated by the Naval Postgraduate School (NPS) at Monterey, California] to measure many chemical and physical characteristics of the marine boundary layer. The temperature, humidity, and wind were measured at four levels between 4.2 and 17.7 m MSL on a tower mounted on the ship. Sensors also measured aerosol concentrations, particle characteristics, radio refractive index, temperature structure coefficient C_T, and sea surface temperatures. Standard surface weather observations and radiosondes were made. Sensors aboard a single-engine aircraft [operated by the Airborne Research Associates (ARA), Weston, Massachusetts] measured the horizontal and vertical variations of temperature, dewpoint, radio refractive index, C_T, and electric field and conductivity intensities over the ocean. The aircraft measured the sea surface temperature (SST) by means of an IR sensor and made visual observations of atmospheric conditions. Visual and IR pictures of the region were provided by the Defense Meteorological Satellite Project (DMSP) system (received by the Naval Weather Service Facility, North Island, San Diego). A more complete description of the experiment is given in ref 6.

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[1] Richter, JH, DR Jensen, and VR Noonkester, "A Coastal Multi-Sensor Measurement Facility at San Diego," Preprint, Conference on Coastal Meteorology, Virginia Beach, VA, 21-23 Sept 1976, p 35-42.

[2] Naval Electronics Laboratory Center Technical Report 1989, Fog Related to Stratus Clouds in Southern California, by VR Noonkester and LE Logue, 12 August 1976a.

[3] Naval Electronics Laboratory Center Technical Report 2000, Fog Related to Santa Ana Conditions in Southern California, by VR Noonkester and LE Logue, 5 November 1976b.

[4] Noonkester, VR, JH Richter, and DR Jensen, "Marine Fog Investigations in San Diego," Preprint, 17th Conference on Radar Meteorology, Seattle, Washington, 26-29 October 1976, p 282-289.

[5] Mack, EJ, RJ Pilie, and U Katz, Marine Fog Studies Off the California Coast, Calspan Corporation Report No. CJ-5607-M-1 (Contract N00019-75-C-0053), March 1975.

[6] Naval Postgraduate School and Naval Electronics Laboratory Center, A Preliminary Report on Cooperative Experiment in West Coast Oceanography and Meteorology-1976 (CEWCOM-1976), 25 January 1977.

Figure 1 shows the relation between NOSC, the position of the NPS ship R/V ACANIA, and selected flight patterns of the ARA aircraft during CEWCOM-1976 in the region east of the Los Angeles peninsula. Communications between NOSC and the ship and between the ship and the aircraft provided highly coordinated measurements. Sites making radiosondes during CEWCOM-1976 are also shown in fig 1. Cooperative measurements were made between 20 September and 15 October 1976. No fog was observed by the coastal sensors during September. Table 1 shows the data and hours of fog events observed on the ship and on tne coast during October 1976.

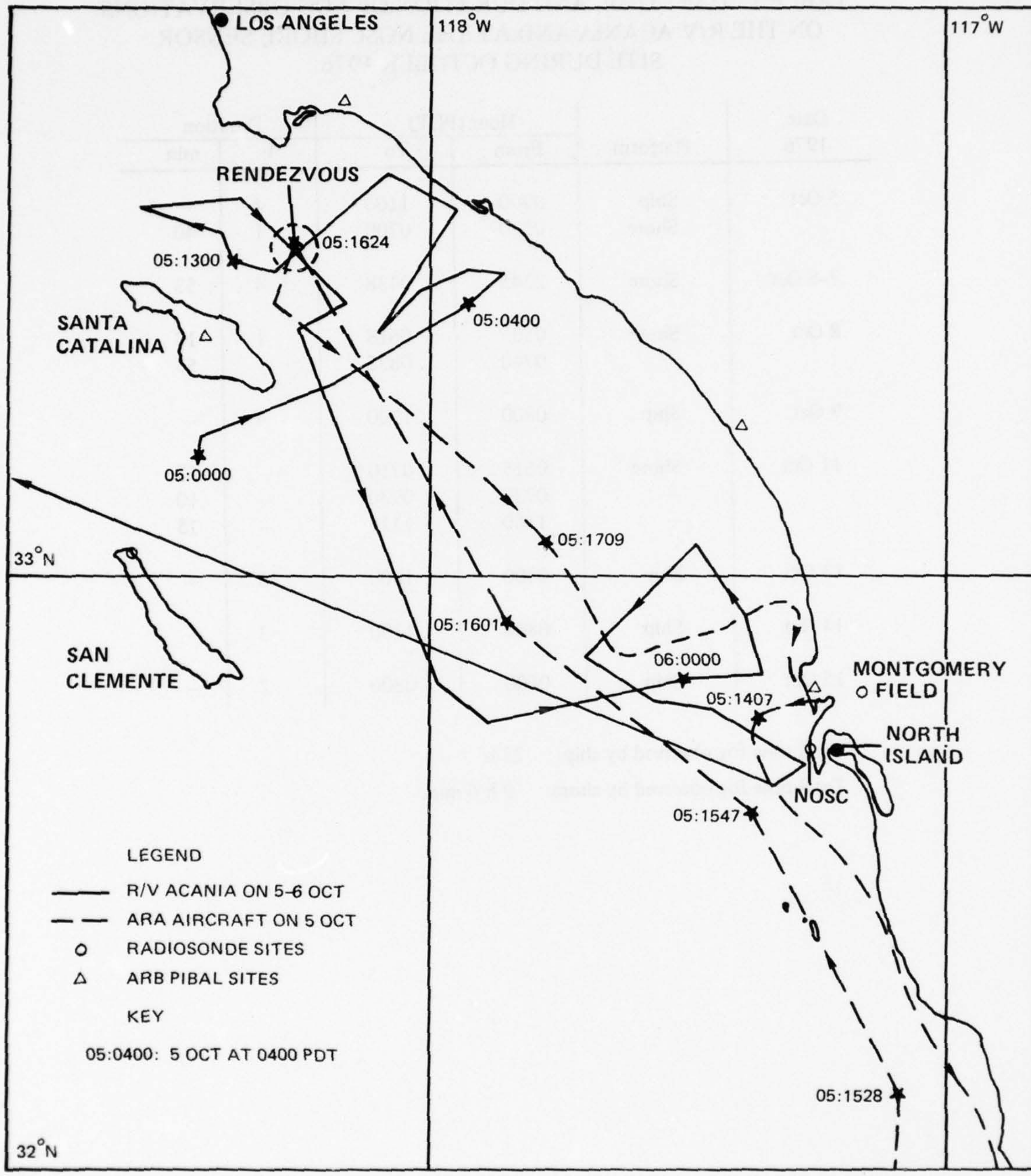

Figure 1. Path of R/V ACANIA and ARA aircraft on 5-6 October 1976.

TABLE 1. DAY, TIME, AND DURATION OF FOG OBSERVATIONS ON THE R/V ACANIA AND AT THE NOSC SHORE SENSOR SITE DURING OCTOBER 1976.

Date, 1976	Platform	Hour (PDT)		Duration	
		From	To	h	min
5 Oct	Ship	0700	1100	4	–
	Shore	0520	0700	1	40
7-8 Oct	Shore	2345	0438	4	53
8 Oct	Shore	0505	0618	1	13
		0740	0835	–	55
9 Oct	Ship	0800	1200	4	–
11 Oct	Shore	0615	0710	–	55
	–	0920	0930	–	10
	–	1100	1115	–	15
13 Oct	Ship	0300	1300	10	–
14 Oct	Ship	0800	1100	3	–
15 Oct	Ship	0600	0800	2	–

Total time fog observed by ship: 23 h

Total time fog observed by shore: 9 h 6 min.

BACKGROUND

NOSC has utilized its coastal multiple sensor system to examine the vertical atmospheric structure during fogs which were transported over the sensor site located on the coast of San Diego (see fig 1). The sensor system has been described by Richter, et al (1976)[1]. Many fog episodes have been monitored by the coastal sensors since 1974. The data analysis revealed[2,3] the following major results:

- Multiple sensors monitor important features of marine fog
- Data substantiate a stratus-cloud fog model, featuring radiation cooling at stratus top and drizzle fallout
- Data indicate a horizontal dependent Santa Ana fog structure concerning small-scale circulation and continental aerosols
- Mesoscale variability is important for all marine fogs.

Based on these results, the principal objectives of NOSC during CEWCOM-1976 were as follows:

- Determine the relationship between the NOSC sensor data and mesoscale features during marine fog events
- Determine the evolution of mesoscale features during fog events
- Relate SST pattern and mesoscale circulation to fog observations.

These objectives were essentially accomplished during CEWCOM-1976.

DATA

A large variety of CEWCOM-1976 data was available at NOSC for analysis because data were obtained by several groups and were made available soon after the termination of the experiment. Table 2 contains a list of data and the source of data considered by NOSC for this report. The data discussed in this report are for fog episodes at NOSC, as given in table 1.

TABLE 2. DATA TYPE AND SOURCE USED BY NOSC IN CEWCOM-1976 DATA ANALYSIS.

Source	Type
NOSC, San Diego	FM-CW radar backscatter echoes
	Acoustic backscatter echoes
	Bistatic acoustic winds
	Ceilometer
	Visiometer
	Surface observations of pressure, temperature, dewpoint, and wind
	Radiosondes with winds
	Weather maps by facsimile
Naval Weather Service Facility, San Diego	Fog forecasts and indices
	Special forecasts
	DMSP* satellite pictures (visual and IR) and analysis
	Sea surface temperature analysis
NPS	Radiosondes from San Clemente Island and the R/V ACANIA; acoustic backscatter on ACANIA
PMTC	Radiosondes from San Nicolas Island and Pt Mugu; GOES** visual pictures; weather forecasts
NOAA	Radiosondes (standard) from Montgomery Field, San Diego
Calspan Corporation	Sea surface temperatures and surface weather observations on R/V ACANIA
California Air Resources Board	Temperature profiles, air trajectories, and pibals
ARA	Temperature and dewpoint profiles, sea surface temperature, and visual observations

*Defense Meteorological Satellite Project
**Geostationary Operational Environmental Satellite.

SANTA ANA FOG FORMATION

Fog along the coast of Southern California has been categorized into two basic types by NOSC, namely fog related to stratus clouds and fog related to Santa Ana conditions[2,3]. The fog episodes observed during CEWCOM-1976 were related to Santa Ana conditions, which is typical for the September–October time period.

In 1948, Leipper[7] developed a model for Santa Ana fog formation along the coast of Southern California from which he specified four objective indices to guide meteorologists in fog forecasting during Santa Ana conditions. These indices were discussed by Noonkester and Logue (1976ab)[2,3] and will be discussed in the later section, Fog Forecasts at North Island.

In his development of the four-factor fog prediction technique, Leipper (1948, 1968)[7,8] stressed the importance of the low-level inversion and its change with time; the SST; and the existing moisture content in the surface layer. He stressed the need to examine the changes in the temperature and humidity structure over the coast, which should provide clues on the mesoscale changes over the ocean. This was based on a two-dimensional (east–west and vertical coordinates) mesoscale model, which contains an interplay between moisture content, vertical distribution of the moisture, radiational cooling at the top of the fog, the capability of the subsiding Santa Ana winds to "push" the marine layer away from the coast, and the offshore cool region of upwelled water. Leipper showed how changes in the atmospheric temperature structure from the surface up to the 700-millibar level (~3 km) provide clues on Santa Ana fog-conducive situations. Leipper indicates that a low inversion and low (relative) surface temperature would generally precede fog. This report will discuss the changes of the spatial structure during each fog event to isolate common evolutionary events, particularly as related to Leipper's[7,8] model.

SEA SURFACE TEMPERATURE PATTERN

The ARA aircraft was equipped with a Barnes PRT-5 infrared sensor to determine sea surface temperature. This sensor was regularly calibrated between flights over the Southern California ocean region between 3 October and 12 October 1976. Comparison of the IR SSTs and bucket temperatures taken by the R/V ACANIA for 30 aircraft flybys at various elevations during clear skies indicated that the IR SSTs were about 0.7°C warmer than the bucket temperatures. The reason for this difference or the accuracy of either temperature has not been established.

Isopleths of SSTs were carefully constructed, using IR SSTs obtained during all ARA flights from 3 October through 12 October. IR SSTs were plotted along the ARA aircraft course each day for all IR SST data read directly from the Barnes PRT-5 meter* except when clouds, fog, or thick haze were noted to be below the aircraft. The composite SST data for these 10 flights are shown in fig 2. The spatial density was considered adequate to construct an SST isopleth pattern and is considered to be unique in the Southern California ocean region.

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

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

*IR SSTs available from the continuous trace on the aircraft data rolls have not been used.

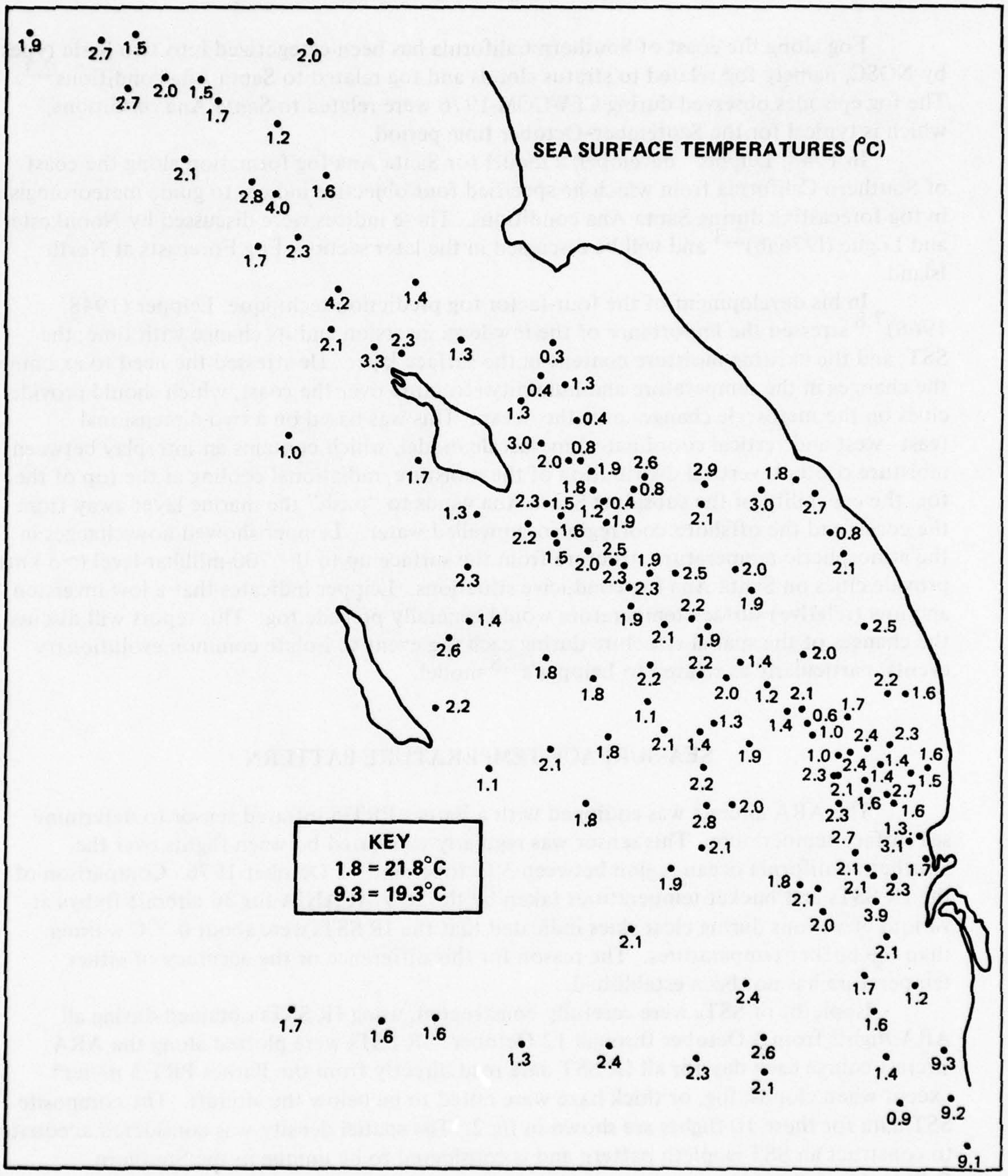

Figure 2. Sea surface temperatures obtained by the Barnes PRT-5 sensor on the ARA aircraft between 3 and 12 October 1976.

Figure 3 shows the isopleths of equal SSTs, using the data shown in fig 2. These isopleths were drawn to within approximately 0.2°C of about 90 percent of the data points. Independent analysis* of the data shown in fig 2 supports the general SST pattern shown in fig 3. Although the temporal persistence of this SST pattern cannot be determined, oceanographers generally assume persistence in such patterns for many (~10–20) days because ocean circulation and temperature patterns normally have a long-term constant. Ocean surface conditions usually respond to atmospheric surface winds and temperatures in such a manner that long-term (many days') averages of atmospheric conditions and ocean currents are reflected on the ocean's surface. Thus the SST isopleth pattern shown in fig 3 is assumed to persist throughout all fog episodes observed during the October CEWCOM-1976 period.

*A final analysis of bucket temperature SST data taken by Calspan Corporation is not available for comparison.

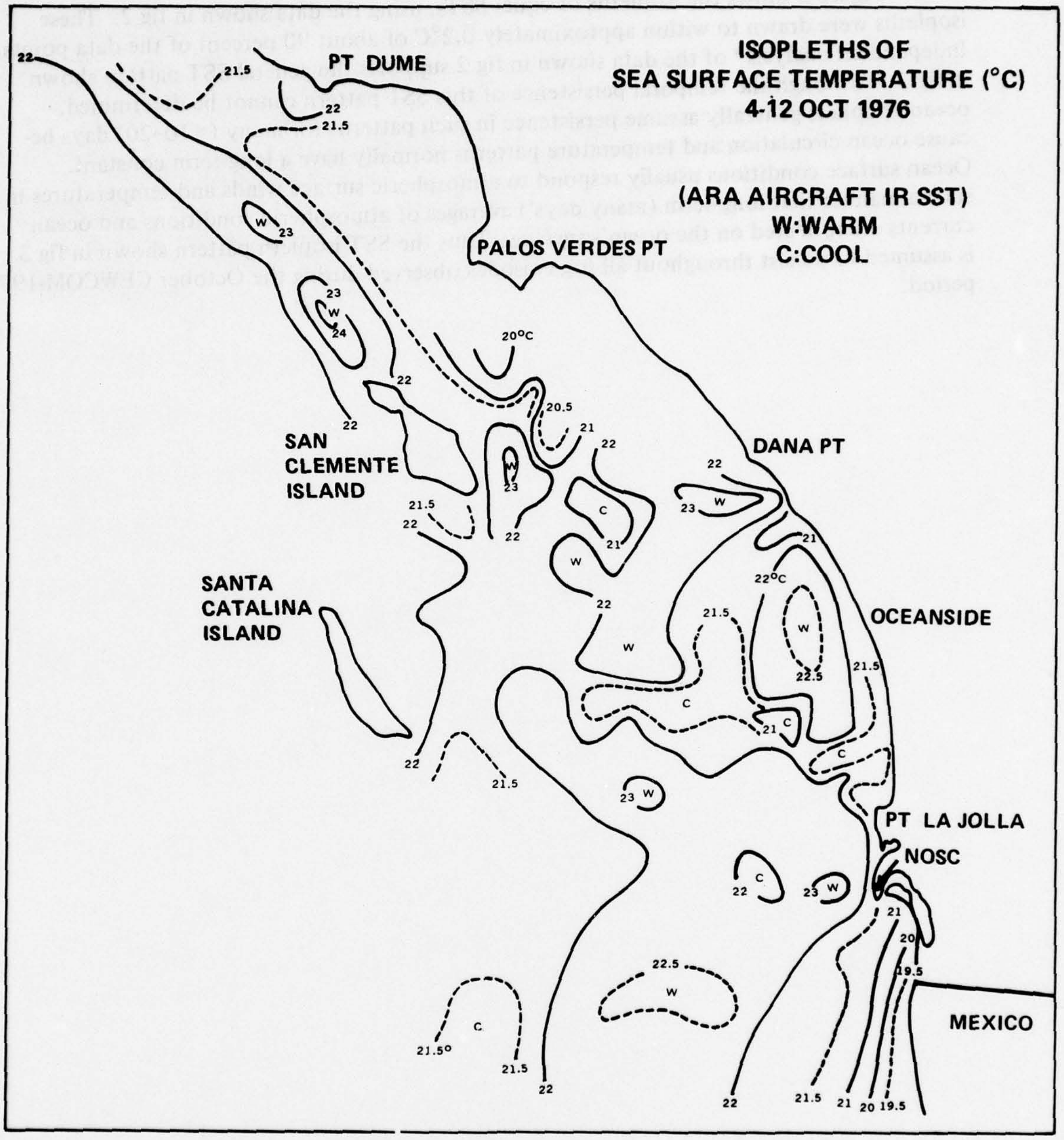

Figure 3. Isopleths of sea surface temperature according to the data in fig 2.

FOG EPISODE ON 7-8 OCTOBER 1976

REMOTE SENSOR OBSERVATIONS

Fog was present at the NOSC sensor site between 2345 PDT on 7 October and 0438 PDT on 8 October, between 0505 and 0618 on 8 October, and between 0740 and 0835 on 8 October. Figures 4 and 5 show the signal return as a function of elevation and time for the acoustic sounder, the FM-CW radar, and the ceilometer, and also show the visibility as a function of time (measured by the MRI visiometer) during this fog episode. In fig 4, the radar echoes show a semicontinuous echo decreasing from near 300 m at 2130 to near 250 m at 0030 (8 October) and intermittent echoes up to 600 m. An enlargement of the radar record near 2200 reveals a train of unstable Kelvin-Helmholtz (K-H) waves commencing near 2152 at 350 m, which merges with the semicontinuous echo at 300 m by 2200. This is followed by vertically extending echoes between 300 and 600 m from 2200 to 2230. Frilly echoes are present near 600 m and 400 m afterwards.

The acoustic echoes in fig 4 are generally continous up to a slightly frilly top, which closely corresponds to the region of semicontinuous radar echoes sloping downward from 300 to 250 m during this time period. The top of the acoustic echo extends above the semicontinuous radar echo by about 30 to 50 m. Slight layering is present in the acoustic echo at 200 m between 2130 and 2200 PDT and near the echo top between 2245 and 2330. No echoes are present above 400 m. Weak acoustic echoes extend vertically near 2215 and correspond in time to the deep vertically extending radar echoes. The near-continuous acoustic echoes up to the acoustic echo top indicate strong mixing along a potential temperature gradient.

The ceilometer record shows the descent of a low cloud base (~150 m) to the ground at 2345 PDT when the surface visibility decreased from about 3.5 km to 0.25 km. The ceilometer echo essentially dissipated near 2215 and returned near 2240; this cloud dissipation period followed the deep radar echoes also persisting for about 25 min.

Figure 5 shows the same type of data for a 3-h period as shown in fig 4 near the end of the fog episodes. The top radar echoes are at the bottom of the radar height window where height calibration lines are present, so that the characteristics of the radar echoes are not determinable. The acoustic echoes are essentially the same as shown in fig 4 and again extend above the top of the radar echoes by about 50–60 m. The ceilometer reveals intermittent low-level clouds, which coincides with the low visibilities measured by the visiometer.

Figure 6 presents a temporal depiction of the vertical profile of the horizontal wind on 7–8 October 1977. Data for this cross section were determined by the bistatic acoustic system, which measured horizontal winds at seven equally spaced elevations between 209 and 589 m every 30 min, using 2-min averages (20 acoustic pulses) (Jensen and Richter, 1976)[9]. The temporal changes in the wind pattern are greater than expected, based on rawindsondes taken every 4 or 5 hours during earlier experiments at the NOSC sensor site, but are commensurate with cross sections determined on the other days during CEWCOM-1976. The time scale of the changes appears to be between 1 and 3 hours, which would suggest that the wind variations are in the lower mesoscale range (1 to 100 km horizontal

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[9] Naval Electronics Laboratory Center Technical Report 1997, Evaluation of A Xonics Echosounder and Wind Sensing System, by DR Jensen and JH Richter, 26 July 1976.

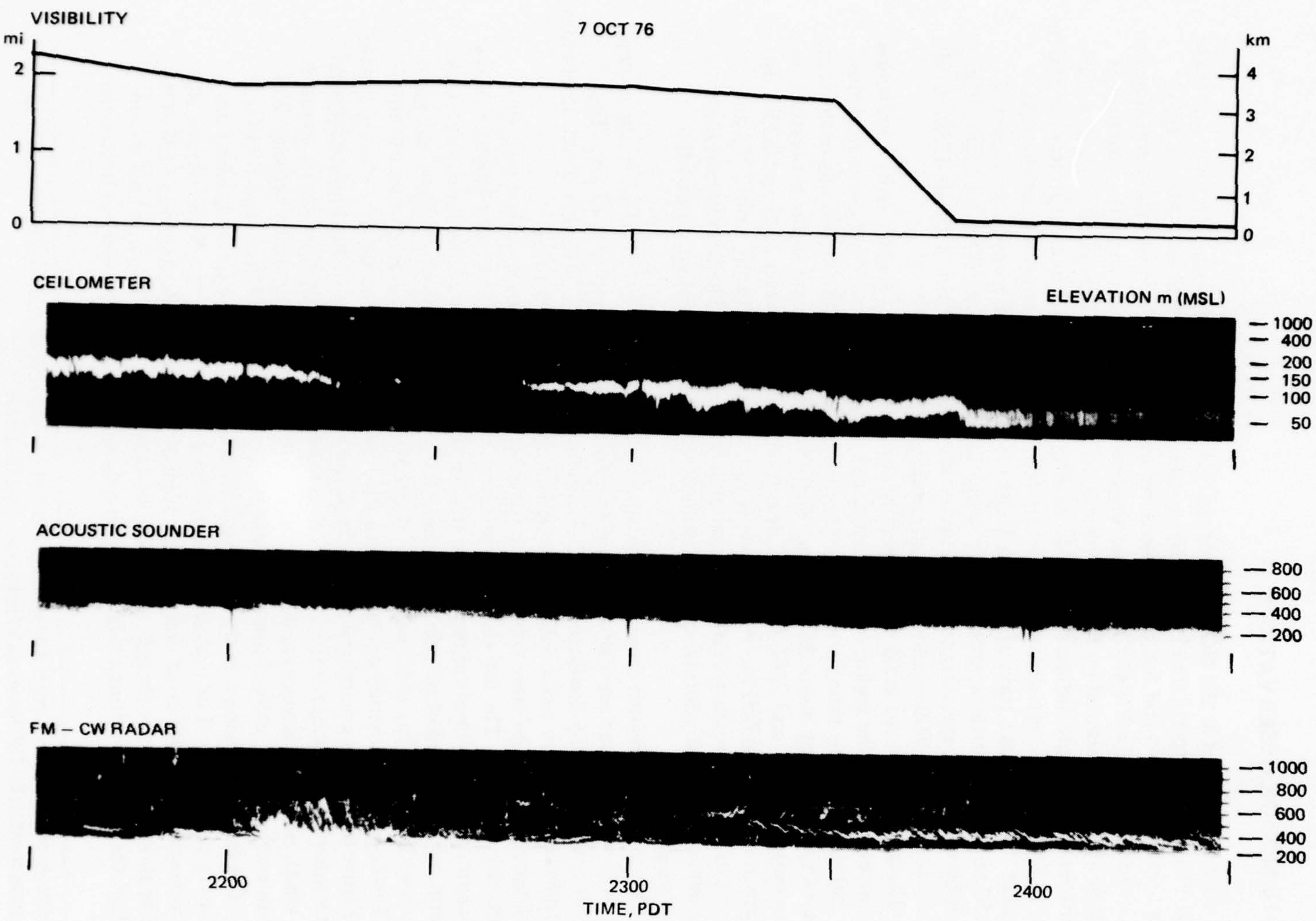

Figure 4. Sensor data taken at the NOSC sensor site, 7 October 1976.

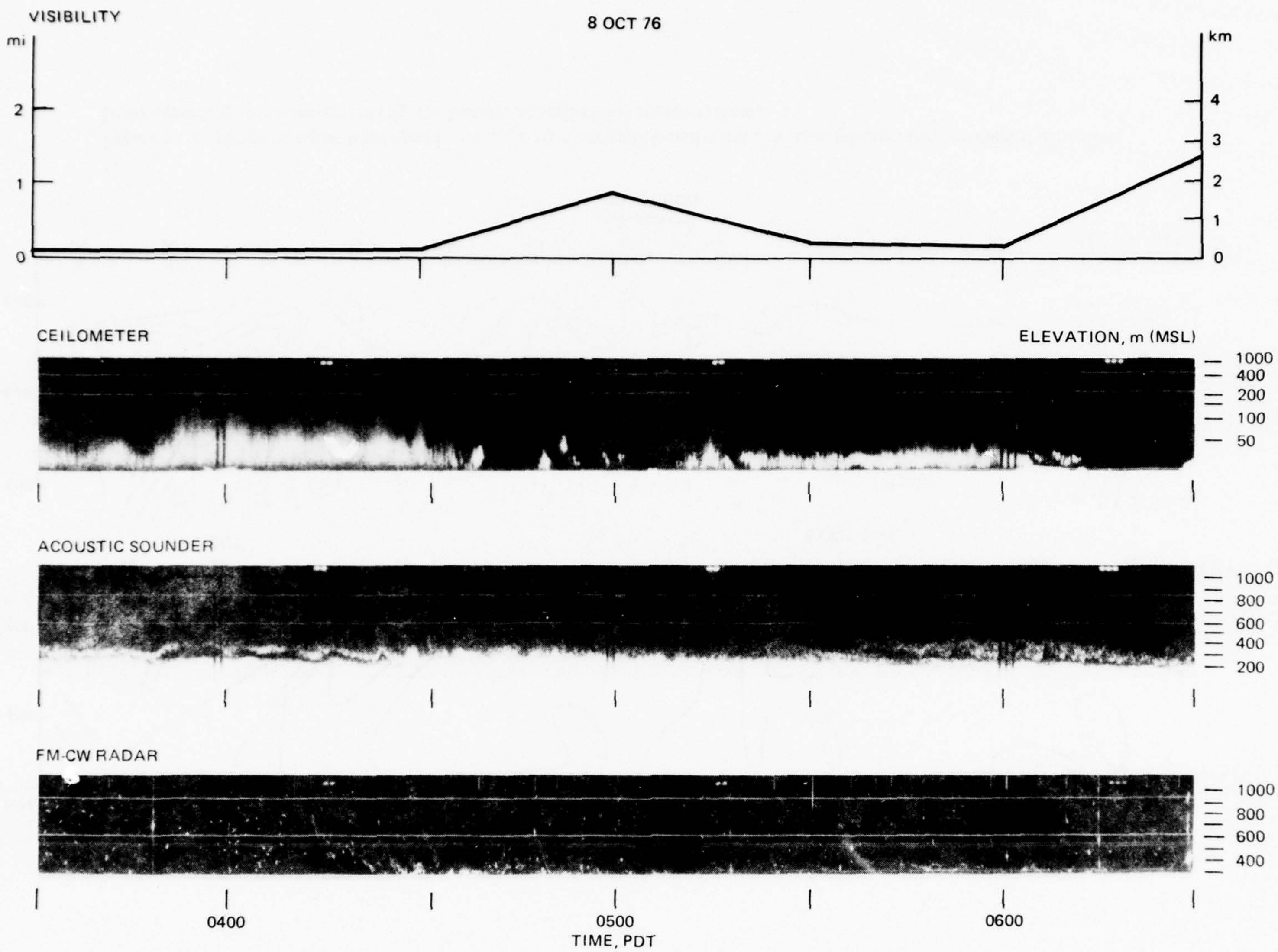

Figure 5. Sensor data taken at the NOSC sensor site, 8 October 1976.

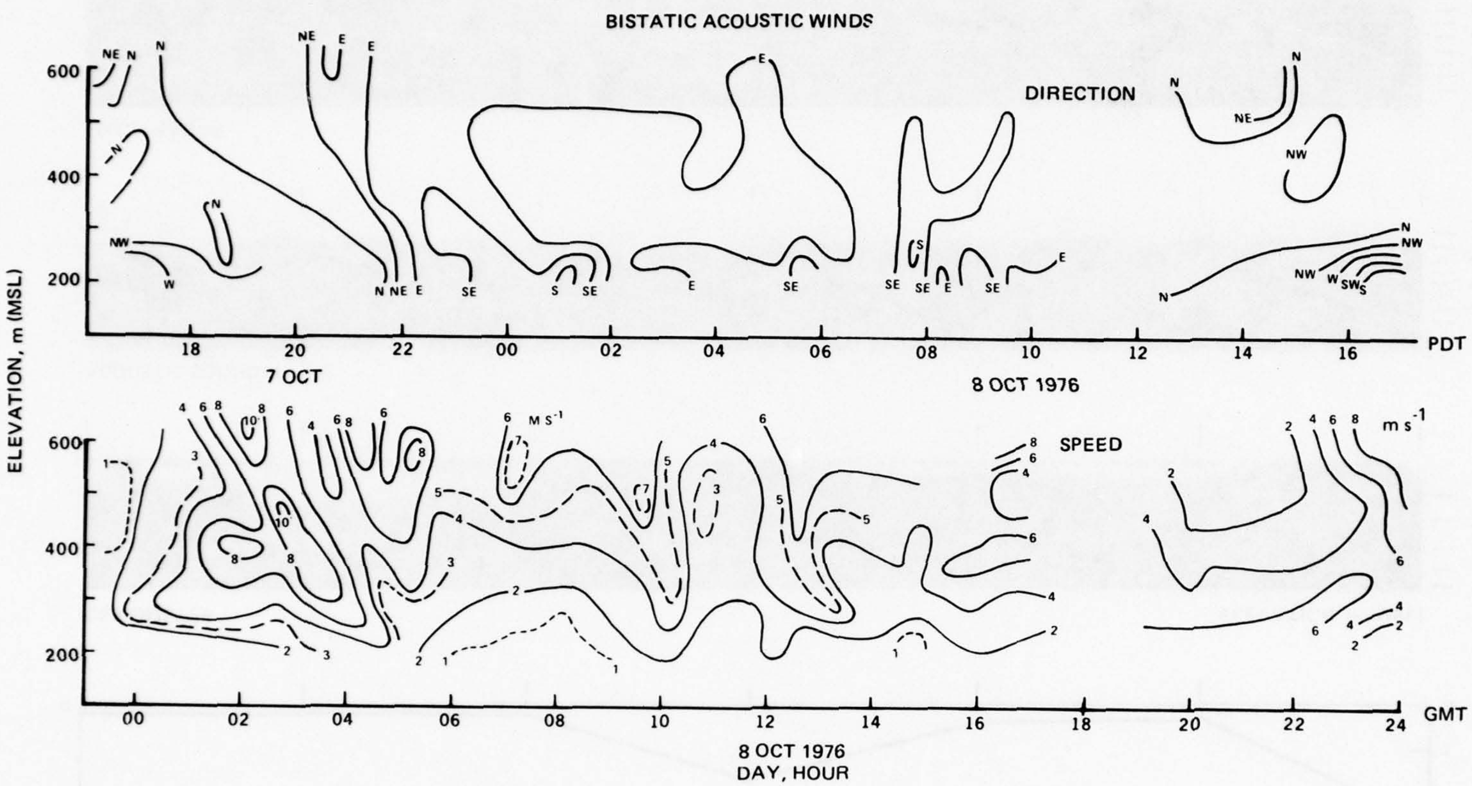

Figure 6. Isopleths of equal wind speed $(m\ s^{-1})$ (bottom) and equal wind direction (degree, meteorological direction) (top) according to measurements by the bistatic acoustic wind sensor system.

scale size). A strong wind shear region moved downward from the top to the bottom of the acoustic wind-sensing height window between 1800 and 2300 PDT on 7 October, just prior to the onset of fog at 2345. Apparently, the mesoscale wind pattern was changing appreciably just before the fog episode. In comparison, the wind pattern was unchanging during the fog episodes between 2345 on 7 October to 0835 on 8 October; this implies a steady mesoscale circulation during the fog period.

The changes in the wind direction between 1800 and 2300 PDT on 7 October show that easterly wind components moved downward into the region of the radar and acoustic echoes below 300 m prior to the fog and then remained steady from the E and SE during the fog. This shift indicates an increase in the south-to-north pressure gradient (geostrophic balance assumed without terrain effects), which could be caused by a mesoscale increase (relative) in pressure north of the San Diego region. If the winds were nongeostrophic (Coriolis forces absent), greater pressures (relative) would be required east of the San Diego region (again, terrain effects assumed absent). The winds were likely to have been responding to pressure changes sufficiently rapid to prevent Coriolis force to be fully involved. Accordingly (ignoring terrain effects), the pressure (relative) would have been increasing to the NE of San Diego during this change. This change is supported by data discussed in the later section, Mesoscale Circulation.

SURFACE MEASUREMENTS AT NOSC

Figure 7 presents the temperature, relative humidity, and wind at two near-surface elevations between 1700 on 7 October and 1700 on 8 October. Figure 7 also contains the relative pressure and visibility at one near-surface elevation during the 24-h time period spanning the fog episode. The temperature records do not show any changes which can be uniquely associated with the change in the visibility. The temperature changes can be associated with the diurnal change. The increase in humidity between 2230 and 0500 would be expected during the fog, but the absence of changes at 21 m would not be expected. The absolute value of the relative humidity at 21 m may be in error, but the relative humidity at 44 m should be accurate to within 5 percent. The wind directions at 21 and 55 m were from the NNW and N during the fog period. The changes in the wind pattern above 200 m revealed by the acoustic system (fig 6) is not evident in the fog layer (21- and 55-m winds), although the gradual decrease in the wind speed from 1700 on 7 October to 0800 on 8 October agrees with the change above 200 m. The increase in the wind speed at 21 and 55 m after 0800 is likely to have been caused by the development of the sea breeze. The relative pressure changes show nothing but the normally diurnal pattern of a double maximum and a double minimum.

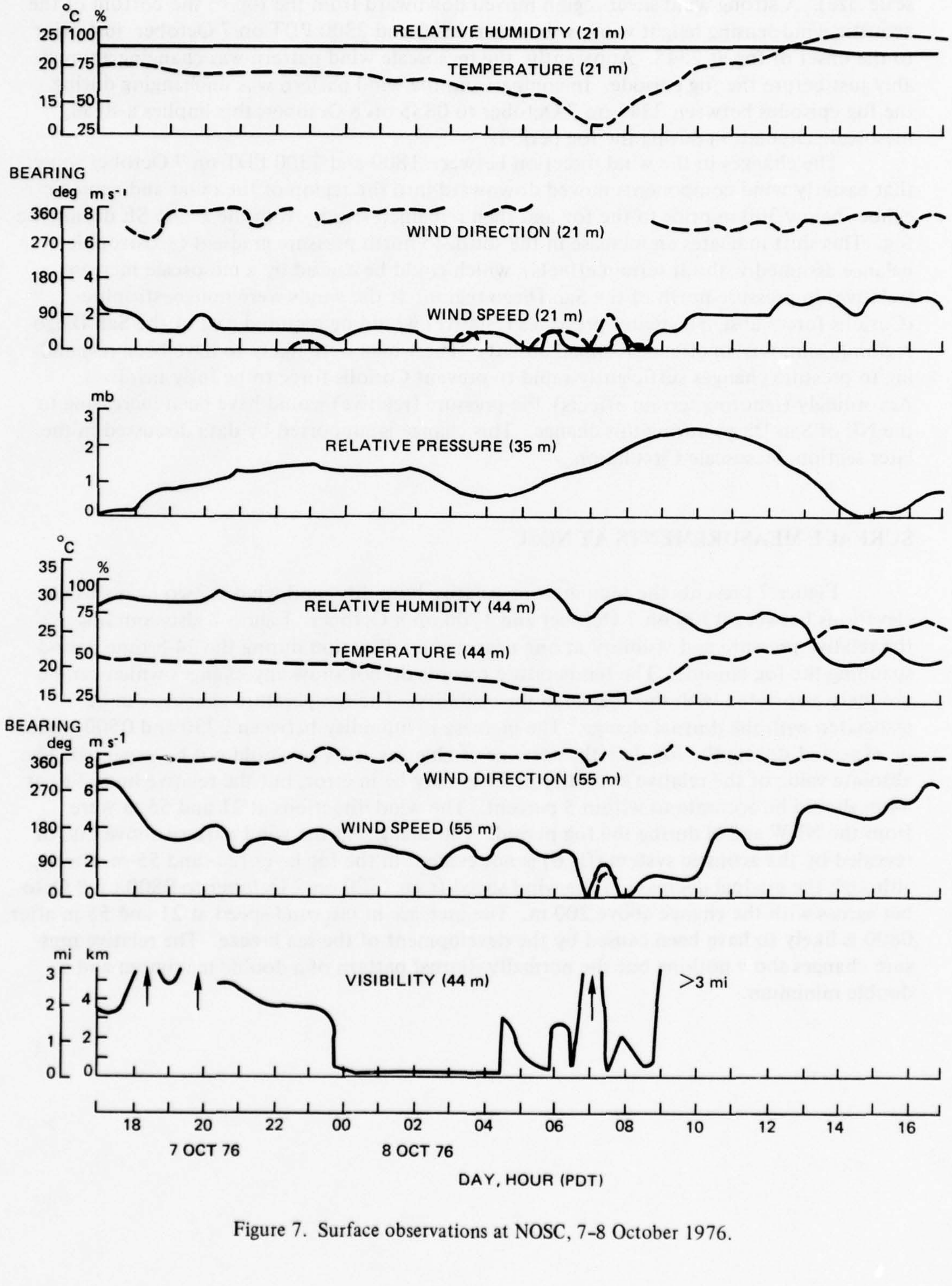

Figure 7. Surface observations at NOSC, 7-8 October 1976.

VERTICAL TEMPERATURE STRUCTURE

Figure 8 presents the vertical profiles of temperature and dewpoint measured by radiosondes at NOSC and Montgomery Field (MYF), the inversion-base height and the 500-m temperature as a function of time during 7–8 October. The inversion-base height shows an almost linear decrease from 0500 PDT to 1700 PDT on 7 October. This descent is rapid. Temporal extrapolation of the base height shows that the base would be at sea level near midnight on 7 October at the time fog commenced at NOSC. The temperature profiles on 8 October show a surface-based inversion in support of the extrapolation. The vertical dewpoint profiles show a slightly moist layer below the inversion and very dry air above. Near-saturated air was measured by radiosondes at NOSC in the fog at 0900 on 8 October.

Figure 9 shows the vertical temperature structure at NOSC, San Clemente Island, and San Nicolas Island near 1400 PDT on 7 October and near 0900 on 8 October. The vertical temperature structure and its changes were similar over a large offshore area, according to these radiosondes.

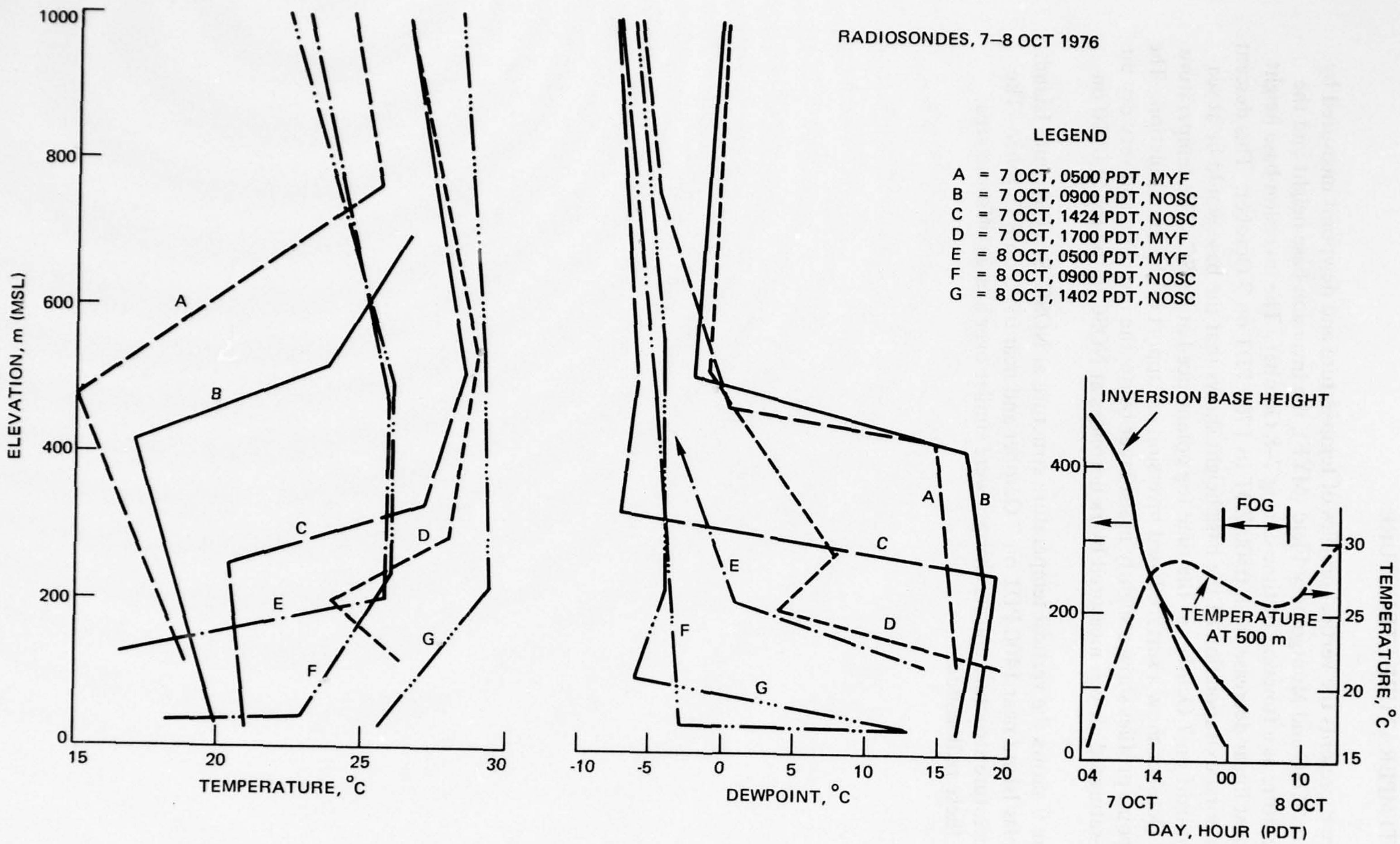

Figure 8. Vertical temperature and dewpoint structure near the time of a fog episode in San Diego, 7–8 October 1976.

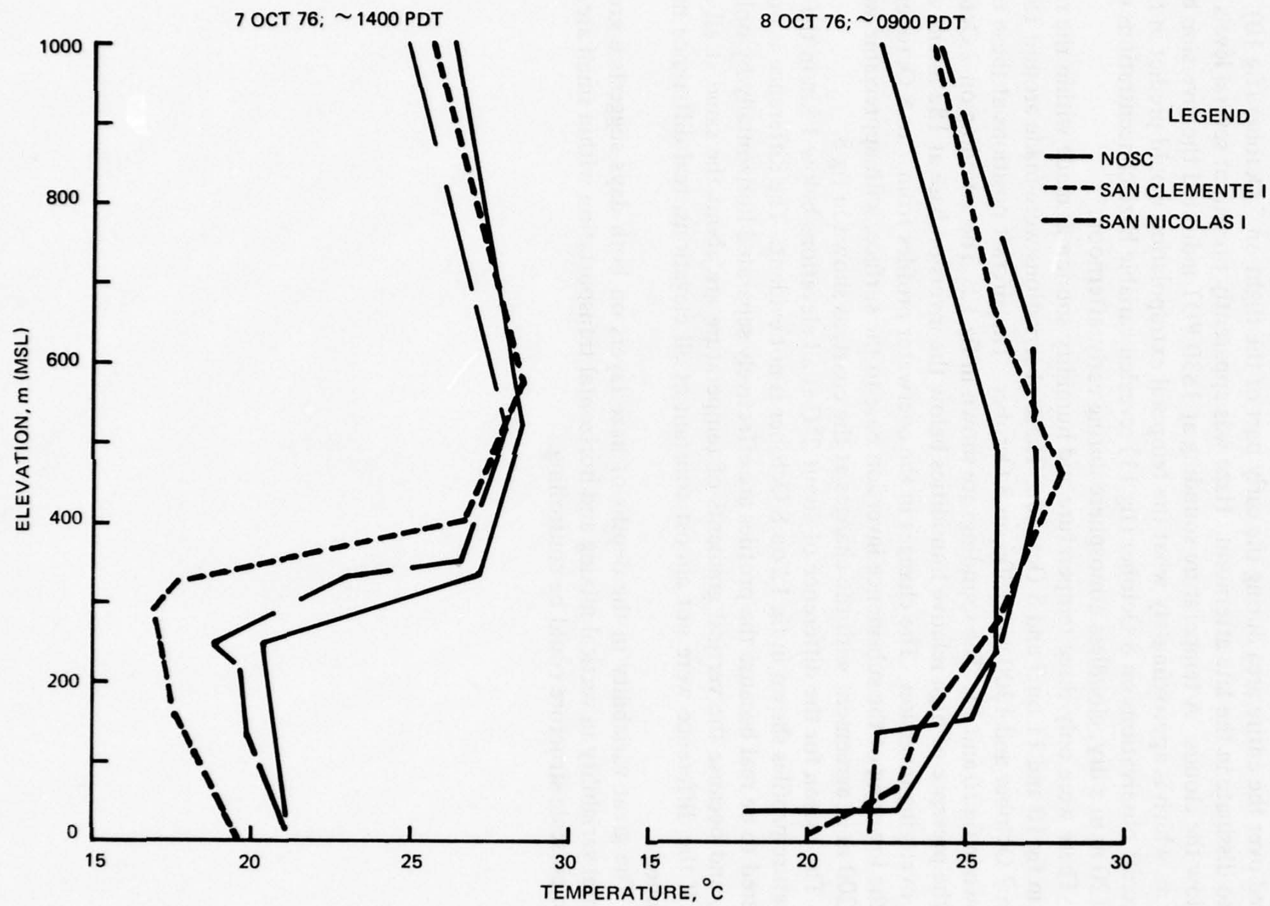

Figure 9. Vertical temperature structure near the time of a fog episode in San Diego, 7-8 October 1976.

AIRCRAFT OBSERVATIONS

Figures 10 and 11 show the flight paths of the ARA aircraft and give observations along the indicated paths on 7 and 8 October. The observations suggest that stratus clouds prevailed over the entire area during the early part of the flight on 7 October (fig 10), but began to dissipate in the late afternoon. Haze was apparently present at several levels above and below the clouds. A temperature sounding at 1830 PDT indicated the inversion base was at 182 m, which is approximately what the temporal extrapolation would predict in fig 8. The aircraft observations on 8 October (fig 11) revealed variable haze concentrations up to about 120 m in a dry, cloudless atmosphere during early afternoon.

There were only three temperature and humidity soundings made within the region shown in fig 10 and 11 on 7 and 8 October. These observations were made around 1830 PDT on 7 October and 1300 and 1306 on 8 October. The aircraft positions at these times are shown in fig 10 and 11. The soundings are shown in fig 12. The sounding on 7 October shows the presence of high relative humidities below the inversion base at 182 m and a dry, strong, overlying inversion. The changes in the overwater profiles from 7 to 8 October reveal the lowering of the subsidence inversion base to the surface, with appreciable warming below 200 m in agreement with the changes at the coast, as shown in fig 8.

The reason for the difference of about 2°C at all elevations below 1 km in the ARA temperature profiles shown in fig 12 on 8 October is not evident. The difference is not considered to be real because the profiles are effectively separated horizontally by only 28 km, and because the vertical gradients of temperature are about the same at all elevations. If the difference were not almost constant at all elevations, real difference might be assumed.

The great variability in the depths of haze layers on both days suggests a great horizontal variability in vertical mixing and horizontal transportation within small areas where mesoscale structure could be controlling.

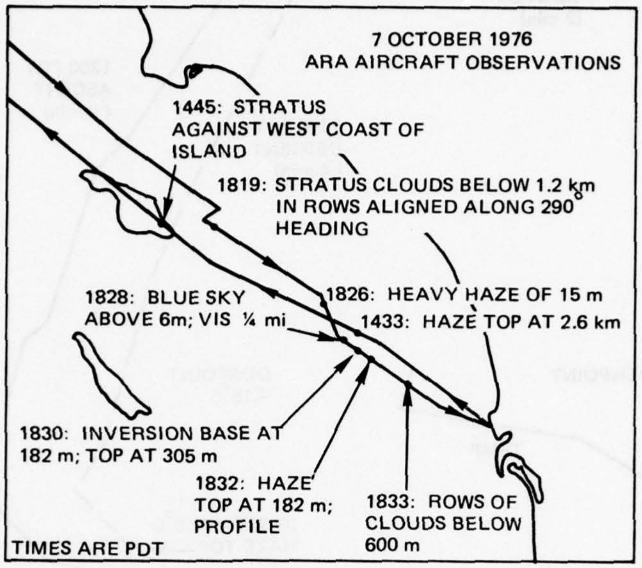

Figure 10. Path and observations of the ARA aircraft, 7 October 1976.

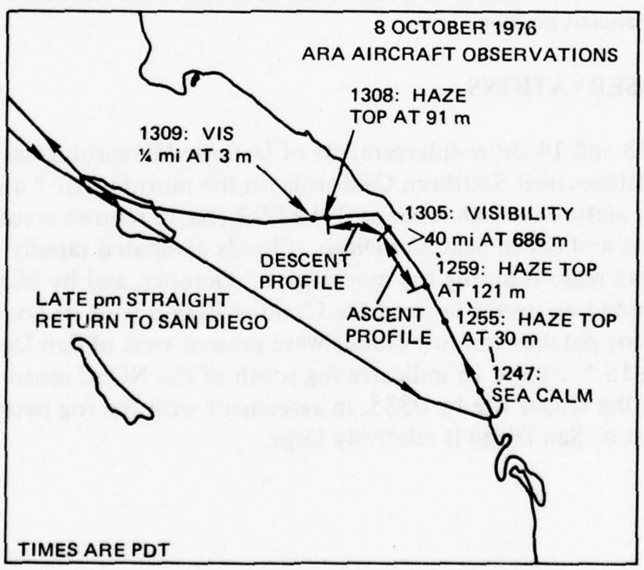

Figure 11. Path and observations of the ARA aircraft, 8 October 1976.

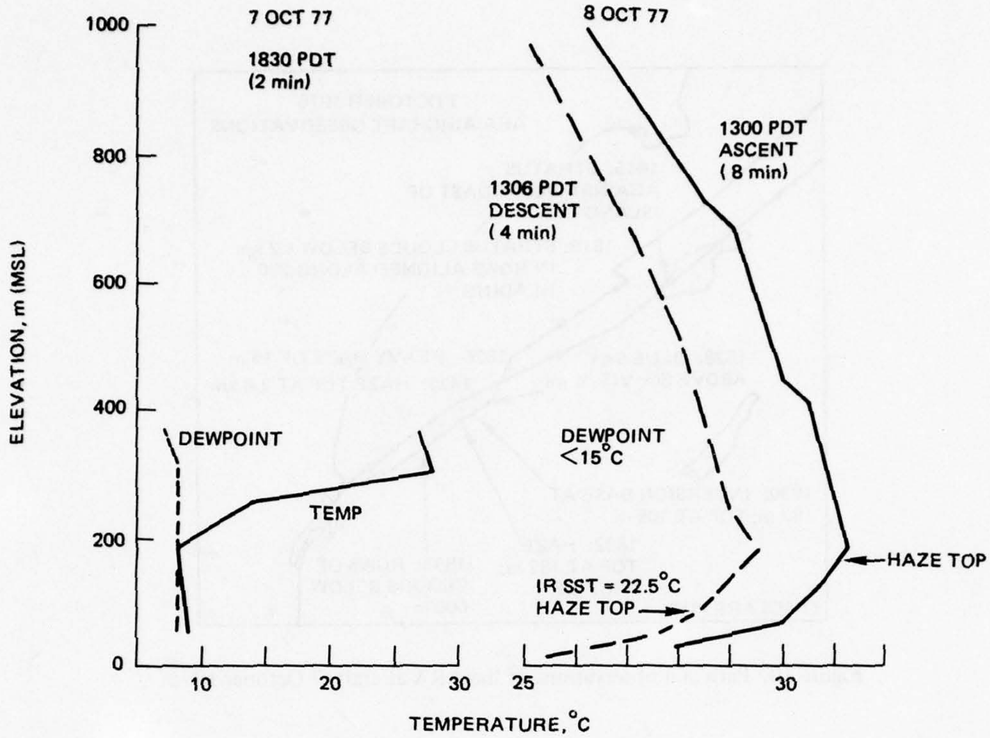

Figure 12. Vertical profile of temperature and dewpoint by the ARA aircraft. See fig 10 and 11 for aircraft position.

SATELLITE OBSERVATIONS

Figures 13 and 14 show enlargements of Defense Meteorological Satellite Project (DMSP) visual pictures near Southern California on the mornings of 7 and 8 October 1976. The DMSP visual picture on 7 October at 0910 PDT (fig 13) shows considerable clouds over the coastal regions and ocean near San Diego. Clouds dissipated rapidly along the coast and adjacent ocean regions during the morning of 7 October, and by 0852 on 8 October the clearing extended westward beyond the Channel Islands west of Los Angeles, as seen in fig 14. Some fog patches and low clouds were present west of San Diego, as shown graphically in fig 15.* Figure 15 indicates fog south of the NOSC sensor site at 0852. Fog had dissipated at the sensor site by 0835, in agreement with the fog pattern shown in fig 15. The fog deck west of San Diego is relatively large.

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*This depiction follows an analysis by AGC R Whritner of the Naval Weather Service Facility at North Island, San Diego. See acknowledgements.

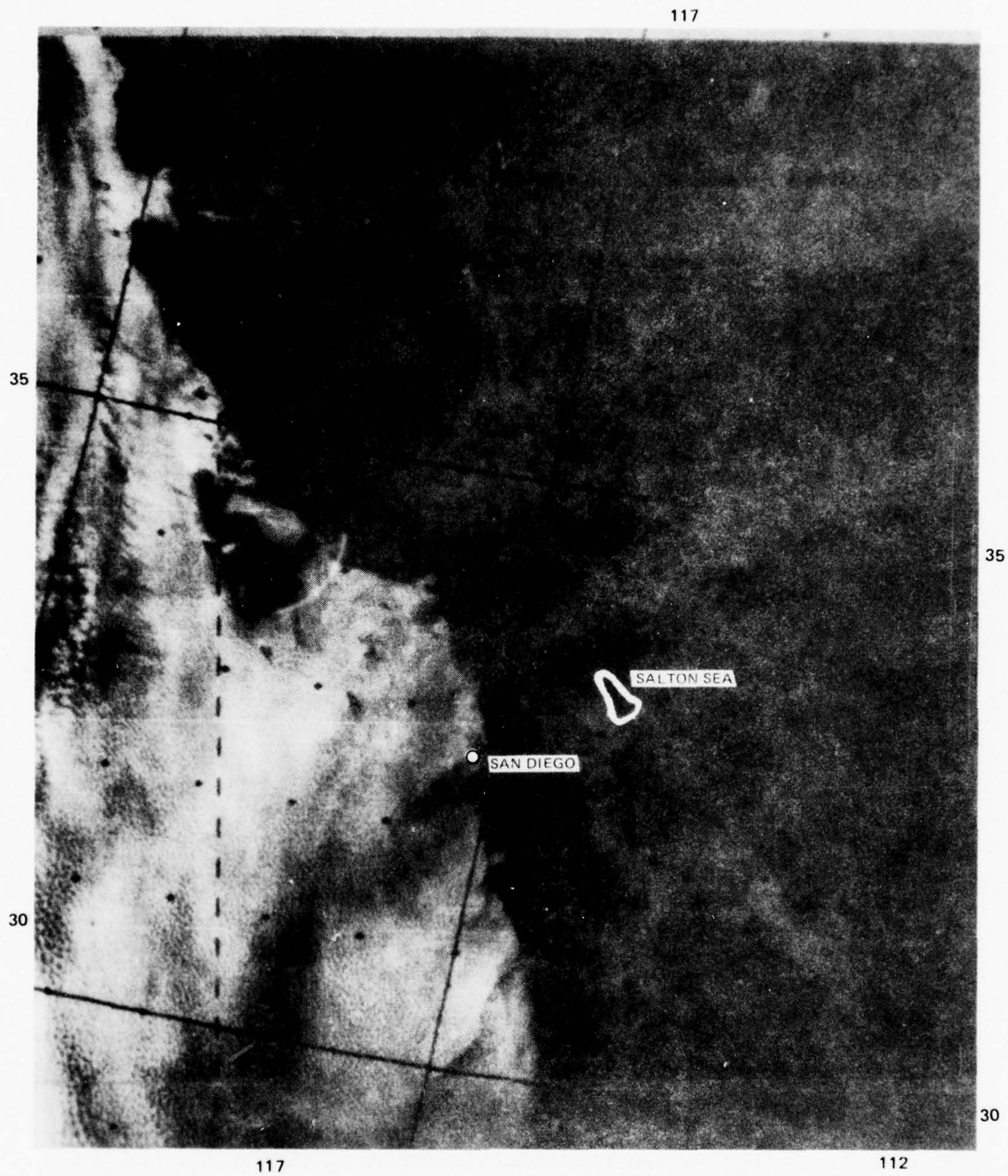

Figure 13. Enlargement of DMSP image at 0910 PDT on 7 October 1976.

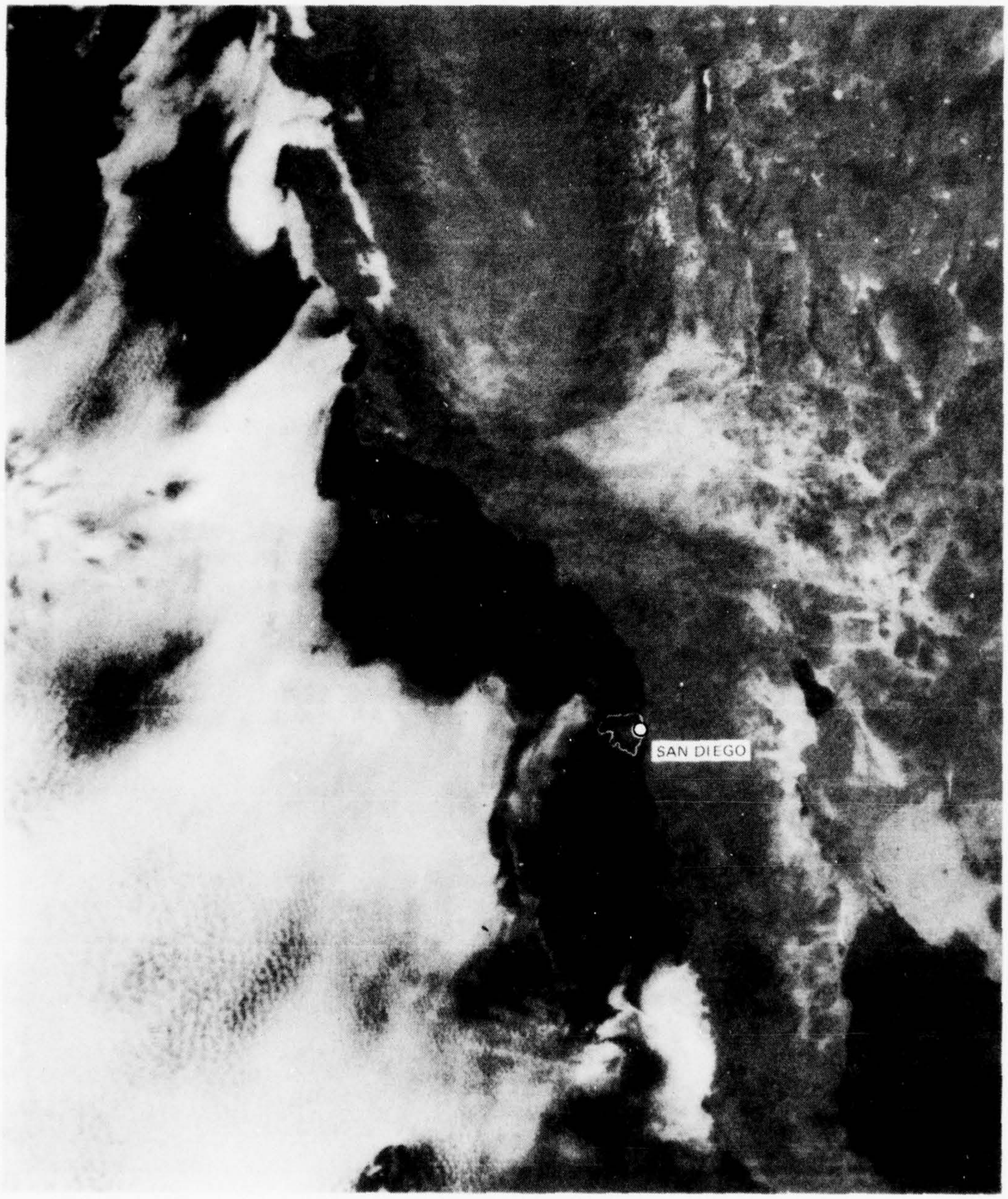

Figure 14. Enlargement of DMSP image at 0852 PDT on 8 October 1976.
(Fog area outlined in white for reader's convenience.)

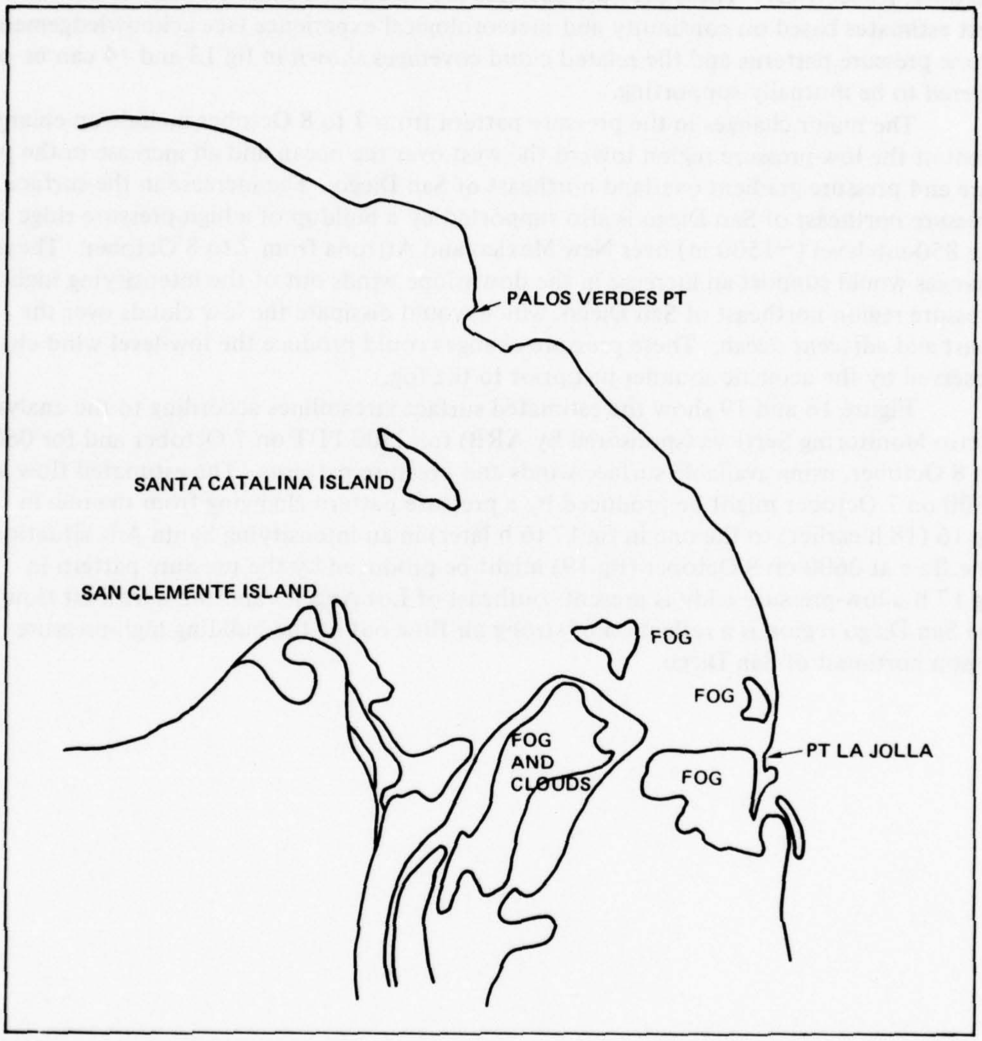

Figure 15. Outline of major cloud, fog, and land forms according to fig 14.

MESOSCALE CIRCULATION

Figures 16 and 17 show the sea-level pressure pattern at 0500 PDT on 7 and 8 October, respectively. These pressure patterns are based on a small amount of data and are best estimates based on continuity and meteorological experience (see acknowledgements). These pressure patterns and the related cloud coverages shown in fig 13 and 14 can be considered to be mutually supporting.

The major changes in the pressure pattern from 7 to 8 October include an enlargement of the low-pressure region toward the west over the ocean and an increase in the pressure and pressure gradient overland northeast of San Diego. The increase in the surface pressure northeast of San Diego is also supported by a buildup of a high-pressure ridge at the 850-mb level (~1500 m) over New Mexico and Arizona from 7 to 8 October. These changes would support an increase in the downslope winds out of the intensifying high-pressure region northeast of San Diego, which would dissipate the low clouds over the coast and adjacent ocean. These pressure changes could produce the low-level wind changes observed by the acoustic sounder just prior to the fog.

Figure 18 and 19 show the estimated surface streamlines according to the analysis of Metro Monitoring Services (sponsored by ARB) for 2300 PDT on 7 October and for 0600 on 8 October, using available surface winds and pressure patterns. The estimated flow at 2300 on 7 October might be produced by a pressure pattern changing from the one in fig 16 (18 h earlier) to the one in fig 17 (6 h later) in an intensifying Santa Ana situation. The flow at 0600 on 8 October (fig 19) might be produced by the pressure pattern in fig 17 if a low-pressure eddy is present southeast of Los Angeles and the northeast flow in the San Diego region is a reflection of strong air flow out of the building high-pressure region northeast of San Diego.

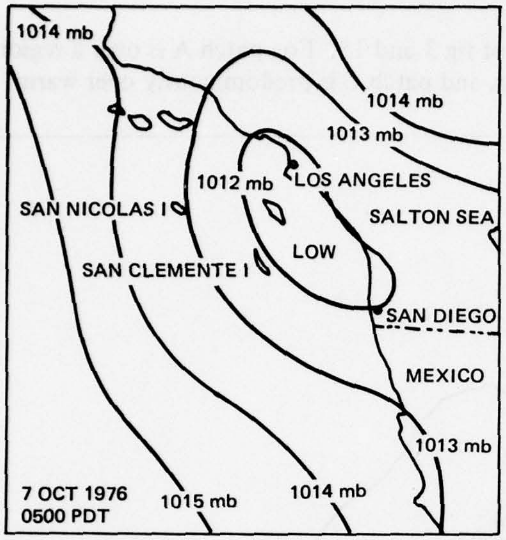

Figure 16. Surface, synoptic pressure pattern, 7 October 1976.

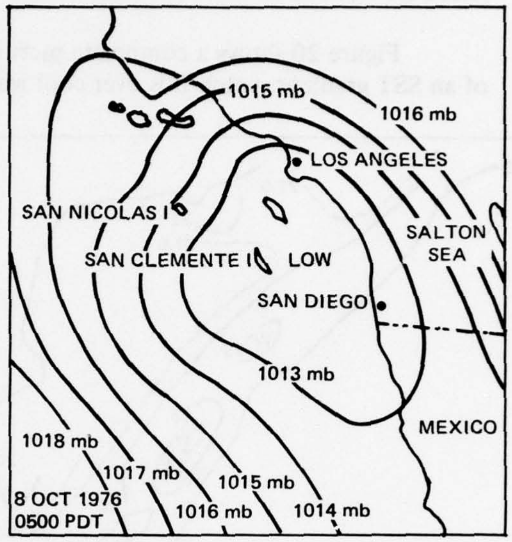

Figure 17. Surface, synoptic pressure pattern, 8 October 1976.

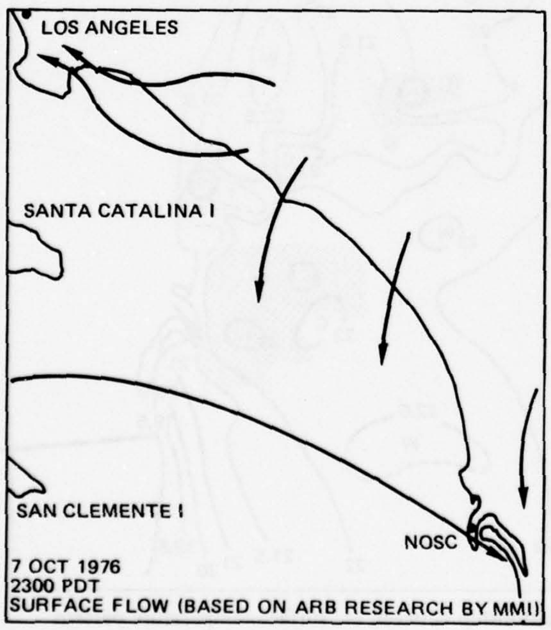

Figure 18. Estimated streamlines, 7 October 1976.

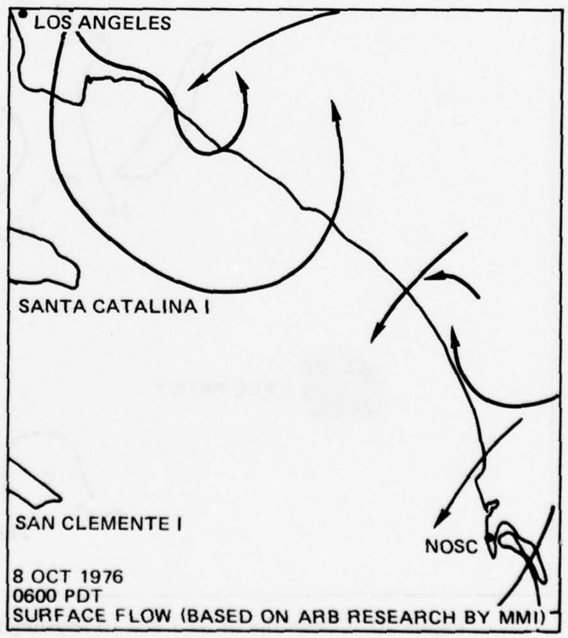

Figure 19. Estimated streamlines, 8 October 1976.

AIR FLOW, SEA SURFACE TEMPERATURE, AND FOG

Figure 20 shows a composite picture of fig 3 and 15. Fog patch A is over a region of an SST gradient, patch B is over cool water, and patch C is predominantly over warm

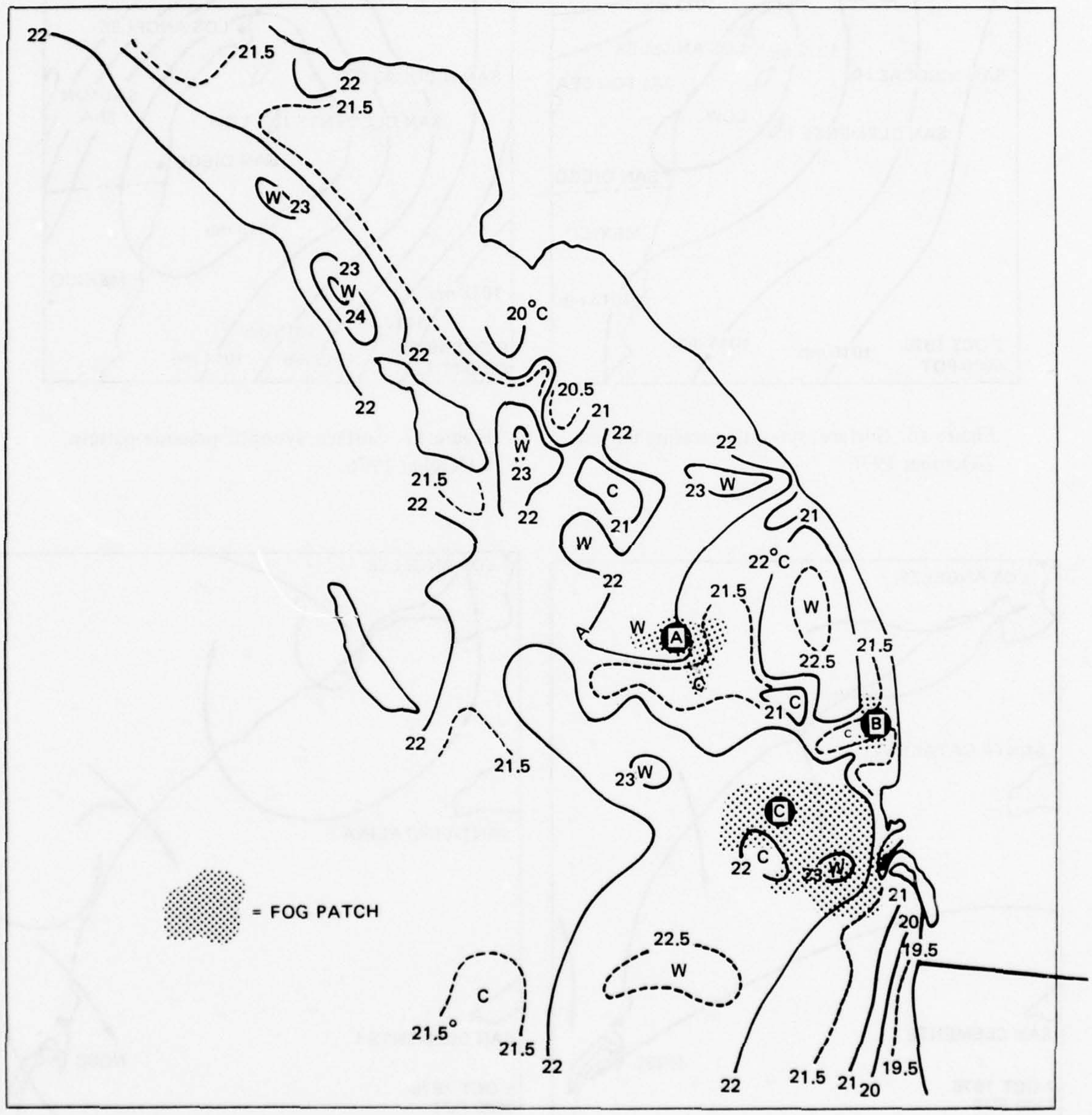

Figure 20. Composite of fig 3 and 15 showing relationship between sea surface temperature pattern and fog patches.

water. The motion of these patches relative to the surface air flow and the SST gradients must be known if the location of the patches relative to the SST patterns is to be determined. Surface air trajectories over the coastal waters cannot be constructed with high reliability because wind data over the water were not available. Figure 21 gives possible surface air trajectories up to the fog patches, which are assumed to have little motion relative to the

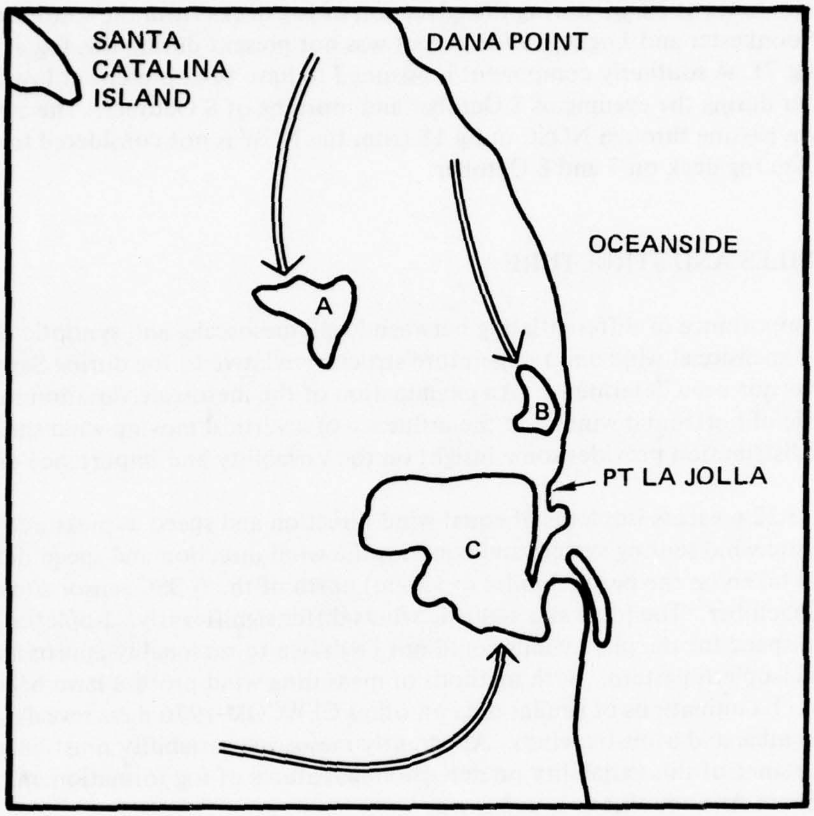

Figure 21. Estimated air parcel trajectories moving into regions of fog.

SST pattern. The air trajectories shown in fig 21 approximate the trajectories given in fig 18 for fog patches A and B. The air moving into fog patches A and B crosses a large region of warm water where moisture could have been added to the air. If the surface air had been cooler than the water, surface heating could create low-level convective mixing to transport moisture upward to the top of the mixing layer. When this moist air cooled at the surface as it passed over cooler water just north of fog patches A and B, fog could have been formed. Radiation cooling at the top of the fog could have propagated the fog vertically upward through the moist layer to the top of the mixed layer. After forming, continued radiational cooling at the top of the fog and mixing in the fog layer could have maintained the fog deck in a manner discussed by Noonkester and Logue (1976a, 1976b)[2,3] and Calspan Corporation (1974)[10]. The air would have been moving through these fog patches.

[10]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 N00019-74-C-0049, July 1974.

If fog patch C formed by a similar process, the most likely region of surface cooling would be the extensive cool water along the coast of Baja California. Thus the air trajectory shown in fig 21 for fog patch C would be a likely one. A southerly wind has been observed many times at NOSC during the advection of fog decks from the south on previous occasions (Noonkester and Logue, 1976b)[3], but was not present during this fog event at NOSC (see fig 7). A southerly component is assumed to have been present at low levels over the water during the evening of 7 October and morning of 8 October. The air trajectory shown passing through NOSC in fig 18 from the NNW is not considered to be representative of the fog deck on 7 and 8 October.

WIND PROFILES AND STRUCTURE

The importance of differentiating between local, mesoscale, and synoptic changes in the three-dimensional wind and temperature structure relative to fog during Santa Ana conditions has not been determined. An examination of the mesoscale variation in the vertical profile of horizontal winds and the influence of a vertical moving wind shear region on moisture distribution provides some insight on the variability and importance of wind profiles.

Figure 22 presents isopleths of equal wind direction and speed as measured by the bistatic acoustic wind sensing system and contains the wind direction and speed determined by MMI pibal taken on the beach 7 miles (~13 km) north of the NOSC sensor site during the day on 8 October. The pibal and acoustic winds differ significantly. Isopleths of wind direction and speed for the pibal winds could not be drawn to reasonably approximate the acoustic wind isopleth pattern. Both methods of measuring wind profiles have been shown to be reliable. Examinations of similar data on other CEWCOM-1976 days reveals similar differences in pibal and acoustic winds. Apparently mesoscale variability must be appreciable, but the importance of this variability on determining features of fog formation and dissipation during Santa Ana conditions is unknown.

The reliability and significance of measuring details in the vertical profiles of horizontal winds using remote sensors are demonstrated in fig 23. Figure 23 shows the FM-CW radar echoes during a 45-min period just prior to fog formation on 7 October (see fig 4). The radar echoes are duplicated at the top and bottom of the figure. Isopleths of wind direction are shown at the top of the figure over the radar echoes, and isopleths of equal wind speed are shown at the bottom over the radar echoes. Acoustic winds were measured at 2200 and 2230 PDT (see fig 6 for the isopleths during a 24-h period spanning the fog period). The isopleths of wind speed at the bottom (drawn for intervals of 1 m s^{-1}) show little variation during this period. However, the isopleths of wind direction (drawn for intervals of 15 degrees for meteorological wind directions) show a shear region near 325 m at 2150 PDT which moves down to about 250 m by 2220. A careful examination of the negative sloping radar echoes (starting near 350 m at 2153) between the 105- and 120-degree isopleth from 2153 to 2200 reveals that the echoes are breaking Kelvin-Helmholtz (K-H) waves. The K-H waves require a positive vertical gradient in potential temperature in a region of wind shear. Apparently, the shear in wind direction just above the 105-degree isopleth is producing the K-H waves. This shear region moved downward steadily several hours (see fig 6) prior to moving into the moist region below 300 m (see fig 4). Deep

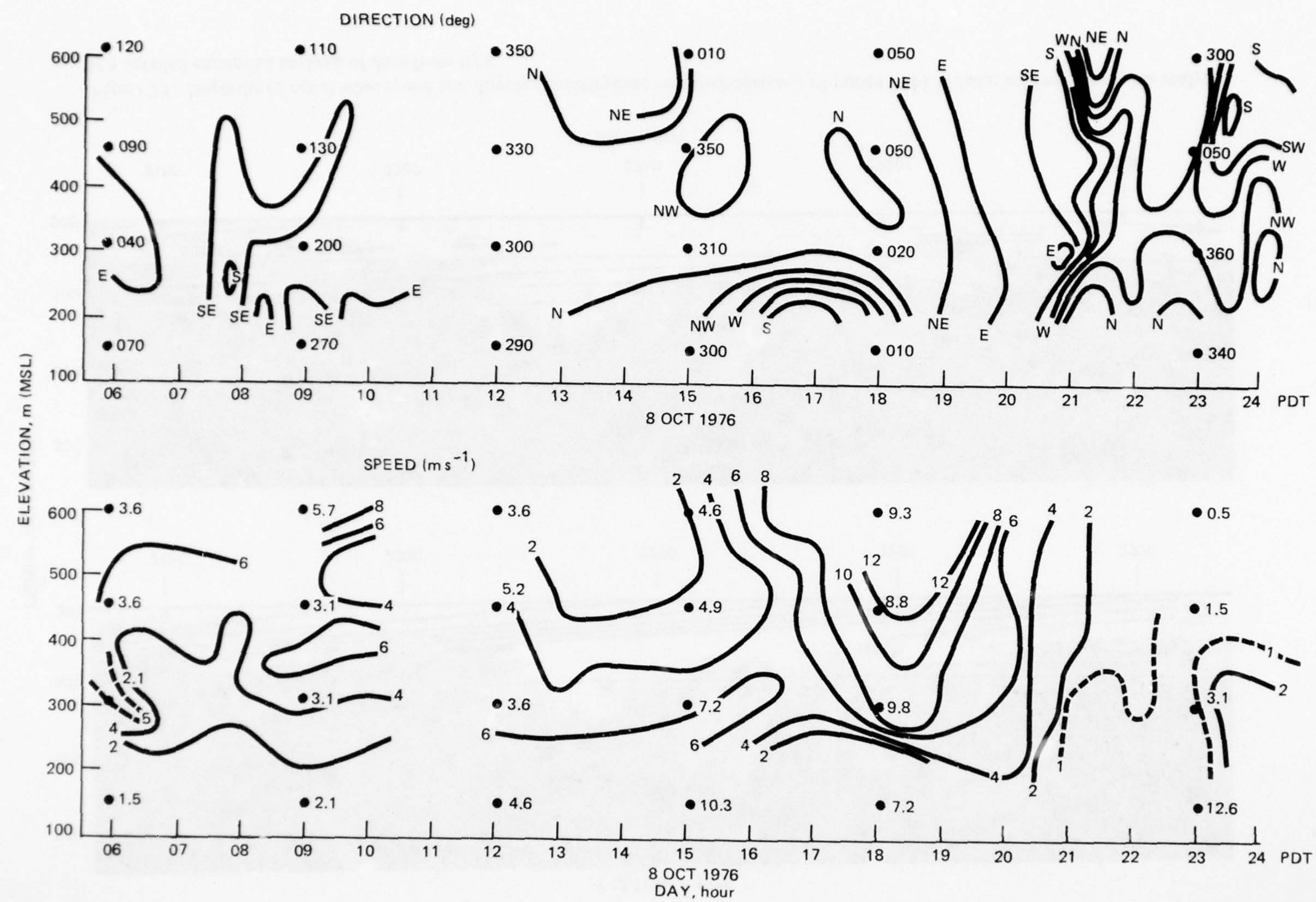

Figure 22. Isopleths of equal wind speed (m s^{-1}, bottom) and direction (degrees, top) according to the bistatic acoustic wind sensor. The vertical profile data are from pibal winds taken 13 km north of the NOSC sensor site.

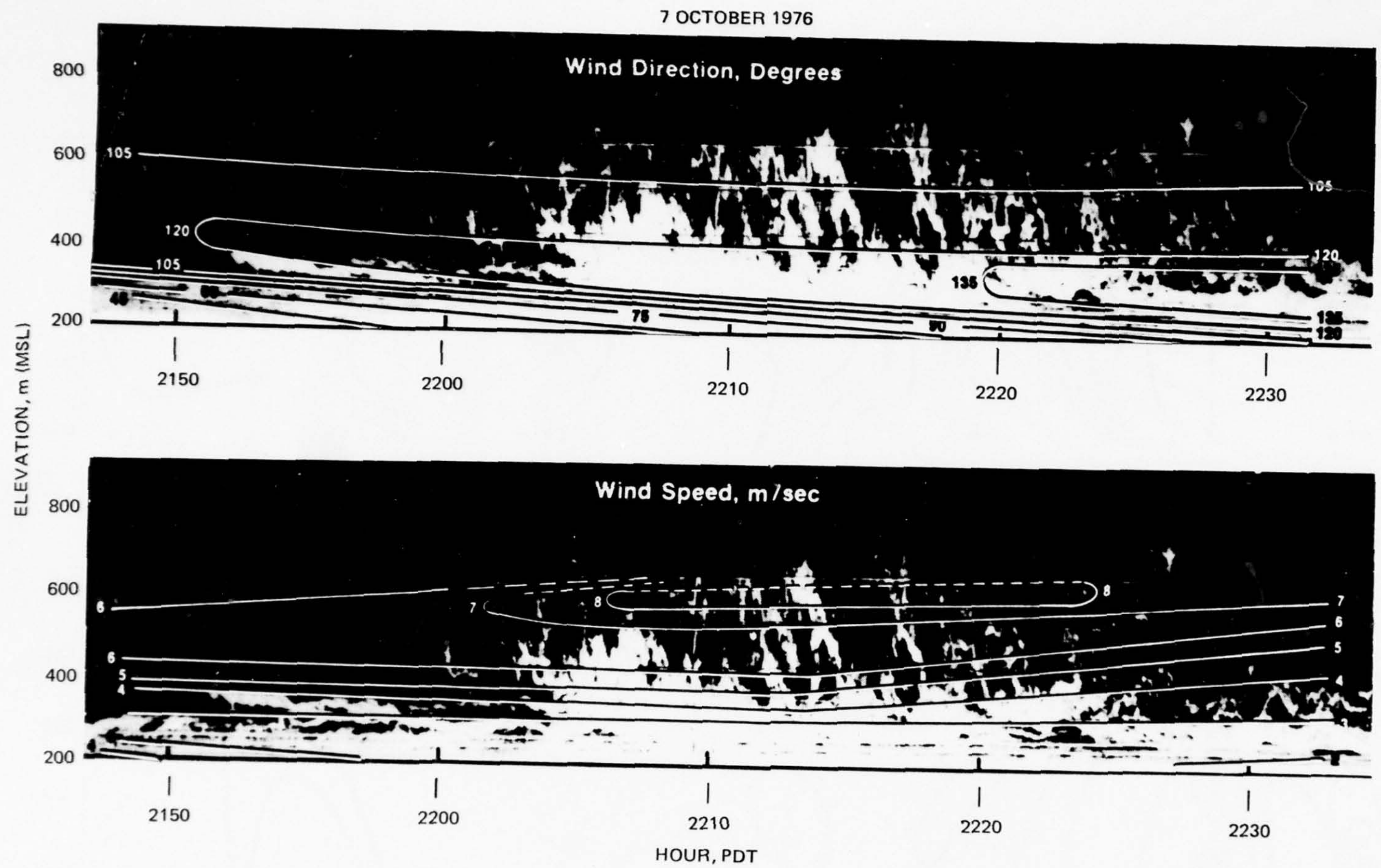

Figure 23. Isopleths of equal wind speed and direction overlayered on simultaneously obtained FM-CW radar echoes. The wind analysis is a detailed expanded analysis of data from fig 6.

convective-like echoes (Noonkester, 1976)[11] appeared between 300 and 700 m immediately after the directional-shear region moved into the moist layer near 300 m at 2203 and continued until 2230. According to the vertical temperature profiles (profiles d and e, fig 8) 5 hours before and 7 hours after the appearance of the deep convective-like echoes shown in fig 8, the convective echoes were moving upward in a nearby dry isothermal region. Such a deep upward penetration through a slightly stable region is unexpected because surface-based free convective activity would not be expected to penetrate as deeply upward into a stable region out of a surface-based superadiabatic region. The energetic convective activity between 2203 and 2230 in fig 23 must have been driven by considerable wind-shear energy not accurately measured by the acoustic wind sensing system.

The ceilometer record in fig 4 shows the dissipation of the cloud at 2215 PDT or 12 min after the appearance of the convective-like achoes. The cloud did not reappear until 2240, or 10 min after the termination of the convective echo. The duration of the "hole in the cloud" and the convective echoes was about 25 min although the "cloud hole" was temporally delayed about 10 min after the emergence of the convective echoes. Apparently, the convective mixing transported moisture upward out of the moist region below 300 m and dry air downward from above into the moist region to reduce the humidity sufficiently to dissipate the low cloud. This relationship between moisture and wind shear near a cloud capped by a stable region has apparently not been demonstrated before. The capability of wind shear to deplete moisture in a moist layer in a highly efficient manner suggests the need to perform more detailed measurements and to reexamine theory on entrainment at the top of a mixing layer because moisture containment in the mixed layer is important for many meteorological, optical, and aircraft operational problems.

FOG EPISODE ON 5 OCTOBER 1976

REMOTE SENSOR OBSERVATIONS

Fog was observed at the NOSC sensor site on 5 October between about 0520 and 0700 PDT (visibility less than about 1.5 mile). Figure 24 shows the signal returns as a function of elevation and time for the FM-CW radar, the acoustic sounder, and the ceilometer, and shows the visibility measured by the MRI visiometer. The acoustic sounder returns show an echo region below 200 m with intermittent layered echoes above. Accordingly, the temperature inversion base would be expected to be near 200 m. The continuous acoustic echo below the inversion base indicates the presence of turbulent mixing of potential temperature in an unstable region. The height window of the radar, being above 200 m, prohibits the radar from sensing the unstable region below 200 m. The radar reveals layered echoes above 200 m commensurate with the layered acoustic echoes. Unstable K-H waves were detected by the radar beginning at 0715 near 330 m; the height resolution of the acoustic sounder prevented the sounder from providing details of these K-H waves, although it sensed a thick layer at that elevation.

The ceilometer revealed an intermittent cloud base near 200 m, which corresponds closely to the major acoustic echo top or the expected base of the temperature inversion.

[11] Noonkester, VR, "The Evolution of the Clear Air Convective Layer Revealed by Surface-Based Remote Sensors", Journal of Applied Meteorology, v 15, p 594-606, 1976.

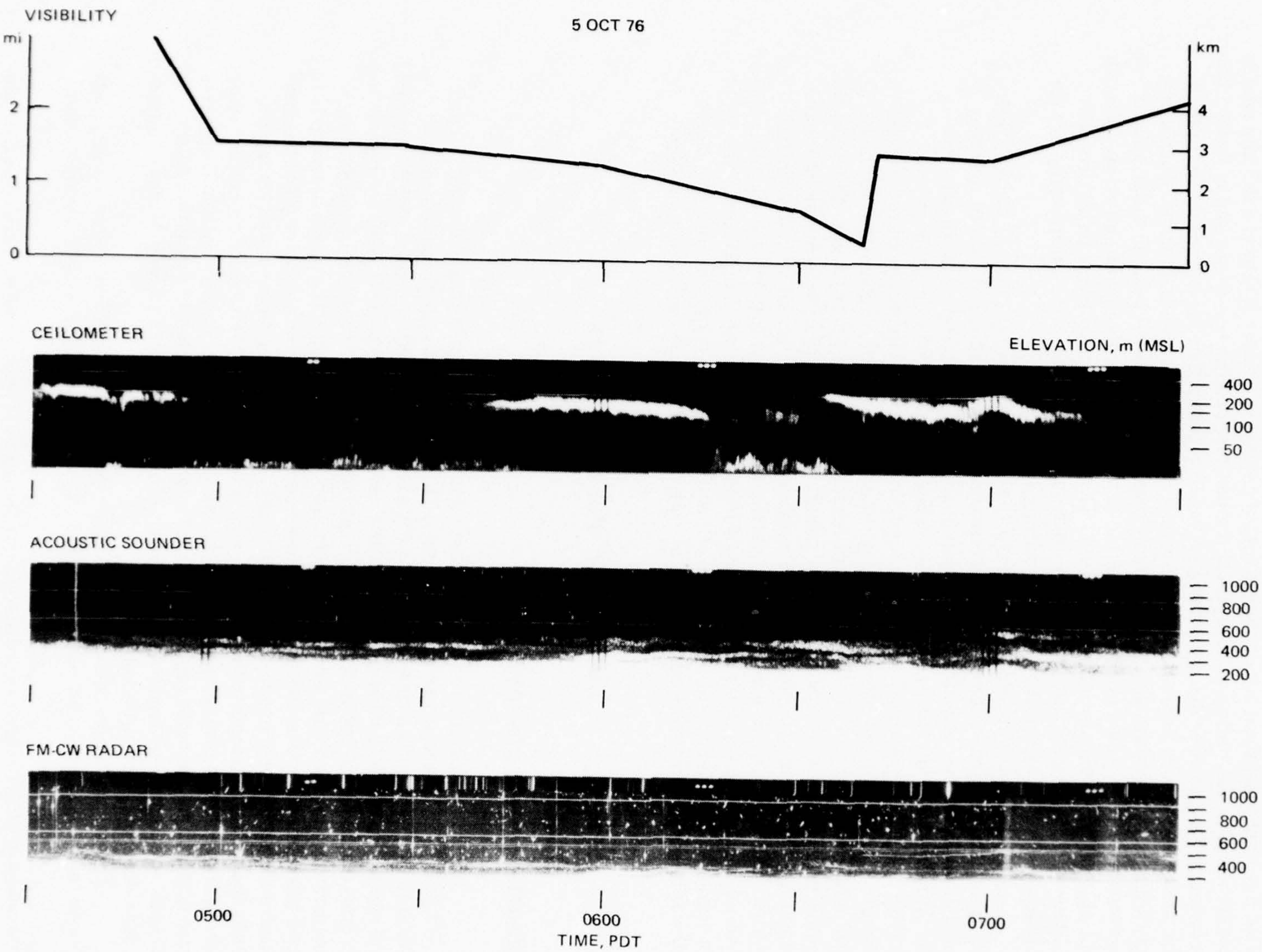

Figure 24. Sensor data taken at NOSC, 5 October 1976: visibility, ceilometer, acoustic sounder, FM-CW radar.

The cloud top would be expected to be at the temperature inversion base at 200 m. These measurements indicate that the intermittent cloud was thin, probably less than 40 m thick. Ceilometer echoes near 50 m indicate the presence of fog, giving the low visibility shown at the top of the figure. The fog was not "dense" except for a few minutes near 0640 PDT. These ceilometer echoes show that the fog was not formed by a descent of the cloud base to the surface, as often observed. Weak ceilometer echoes near 200 m above the low echoes near 50 m indicate that clouds were essentially absent at the time of the fog. These step changes between cloud echoes at 200 m and fog echoes at 50 m suggest that low-level mixing may have caused fog to be "lifted" to the inversion base in patches so that the fog observed may have been dissipating.

Figure 25 presents the acoustic wind structure according to observations taken every 30 min on 4 and 5 October from 1600 PDT on 4 October to 1200 on 5 October. (Some observations were missing above 450 m before 0200 on 5 October.) The wind pattern changed slowly during the 19-hour period. No significant mesoscale changes or wind shear regions are indicated.

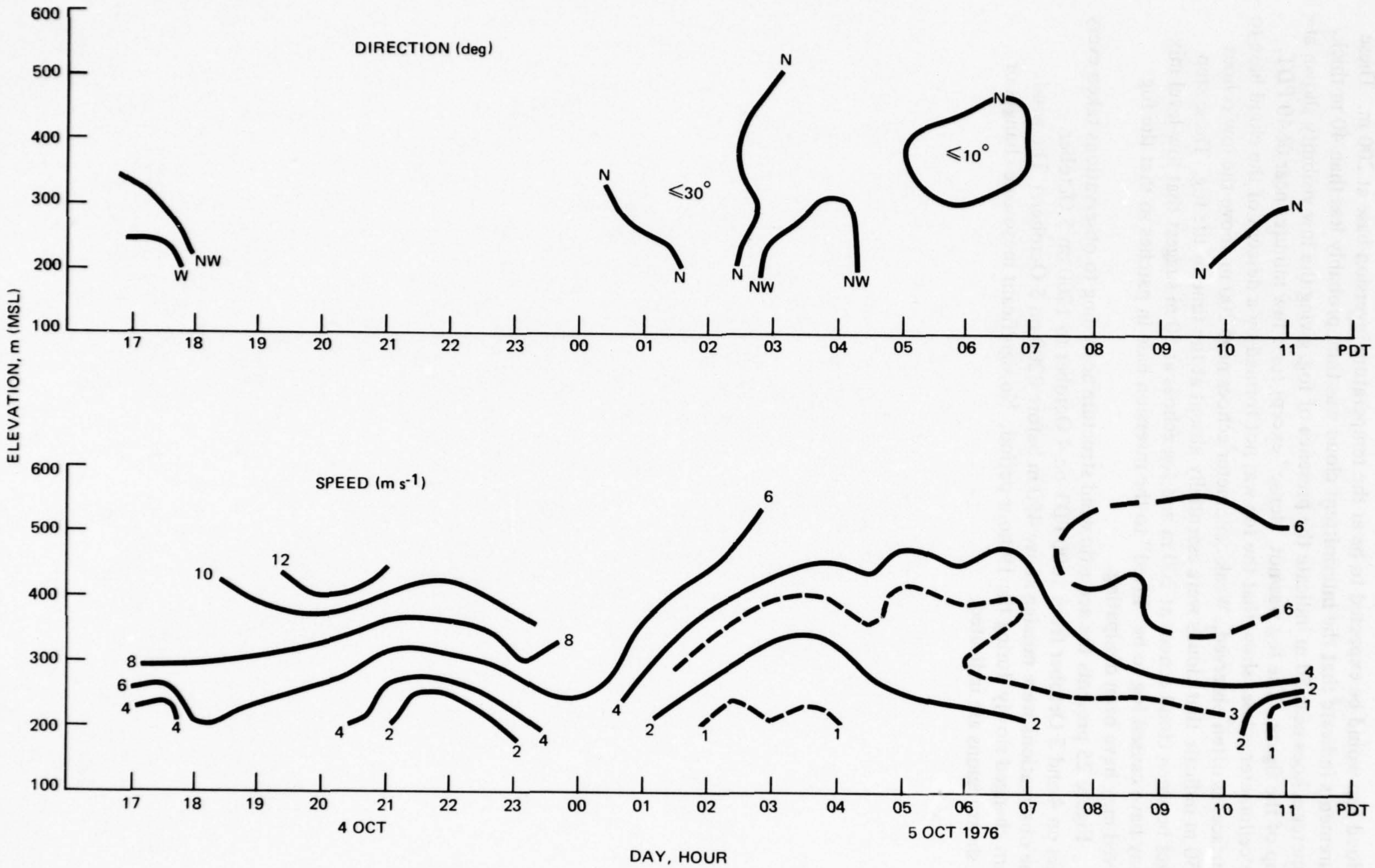

Figure 25. Sensor data taken at NOSC, 5 October 1976: direction, speed.

SURFACE MEASUREMENTS AT NOSC

Surface observations at the NOSC sensor site are given in fig 26. The temperature and humidity records show almost no variation except what might be associated with normal diurnal variations. The wind was generally from the north; the wind speed diminished during the night prior to the fog episode and increased considerably after 1000 PDT as the sea breeze developed. The pressure changes were near the normal diurnal changes.

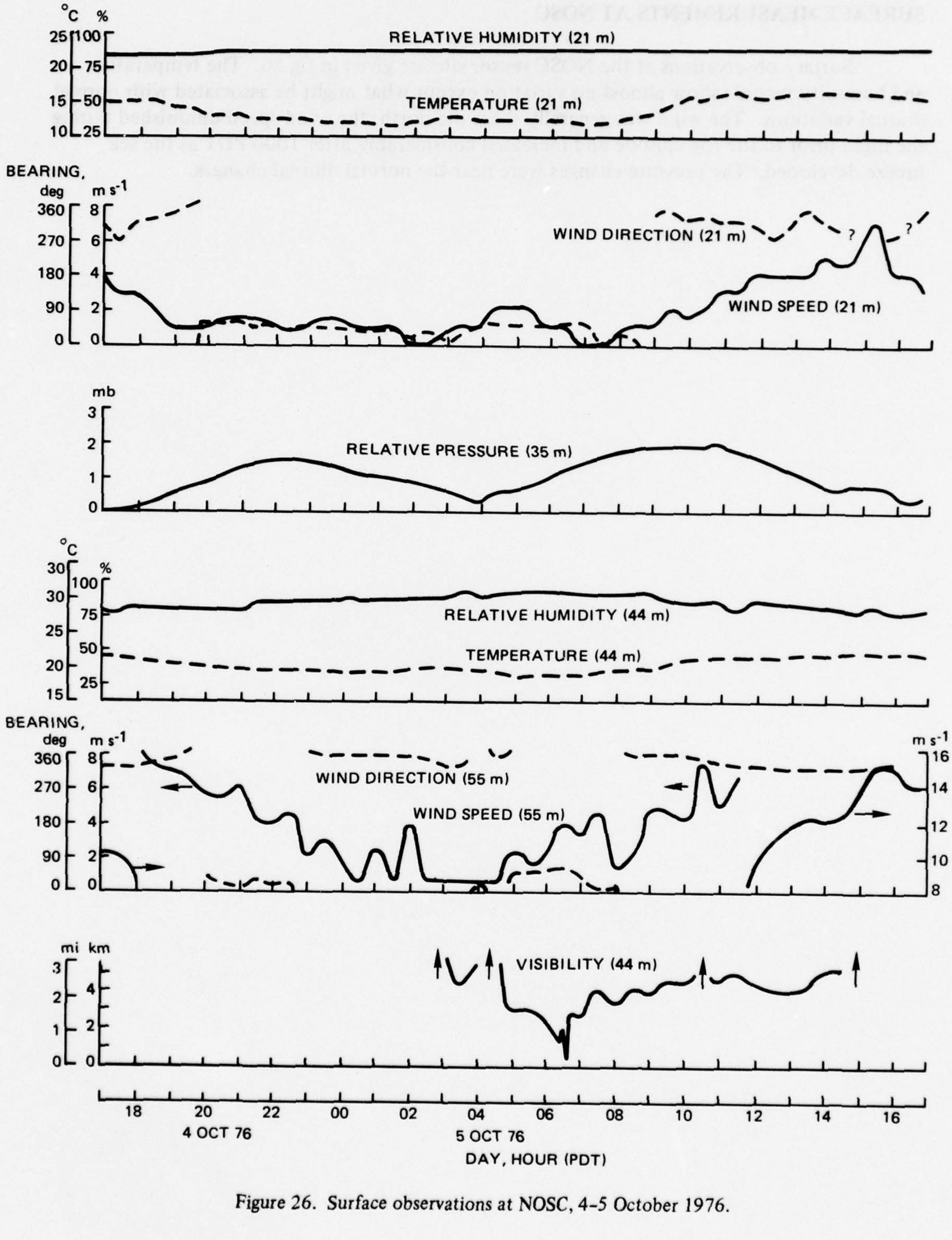

Figure 26. Surface observations at NOSC, 4–5 October 1976.

VERTICAL TEMPERATURE STRUCTURE

Figure 27 presents vertical profiles of temperature measured at and near the NOSC sensor site. The ARA aircraft was 92 km from NOSC on 4 October and 22 km from NOSC on 5 October. The plot of inversion base height and temperature at 500 m in fig 27 shows a temporal pattern similar to the pattern shown in fig 8 for the fog episode on 7–8 October; that is, the inversion base height decreased at a rate of about 23 m h^{-1} about 20 h before the fog episode until the base was near 200 m. During the decrease of the inversion base height, the temperature at 500 m increased by about 7 to 11°C; after the large increase in temperature at 500 m, the temperature decreased a few degrees before the onset of fog. These changes in inversion height and 500-m temperatures suggest that the Santa Anas on 7–8 October and 5 October were weakening after strong, rapid growth prior to the fog episodes.

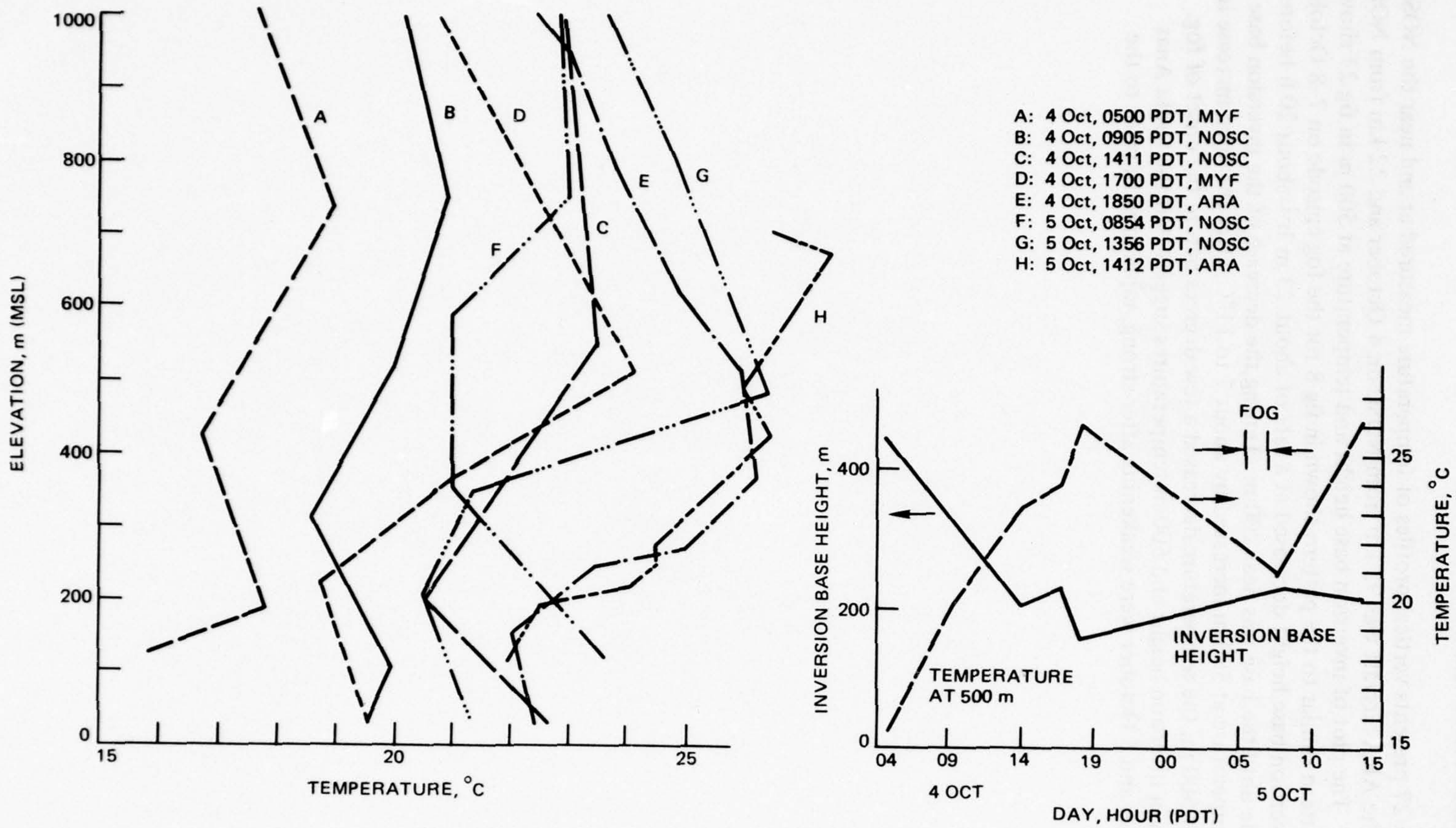

Figure 27. Vertical temperature structure near time of fog episode in San Diego, 4–5 October 1976.

SATELLITE OBSERVATIONS

Figure 28 is an enlargement of a DMSP visual picture at 0805 PDT on 5 October just about 1 h after the fog event at NOSC. The white patch along the coast is fog between Baja California and Los Angeles, where the DMSP IR picture was used to aid in identifying the fog. The R/V ACANIA was in the fog patch southeast of Los Angeles from 0855 to 1045 when the ship was moving southwest. The fog patch near San Diego is small and appears to be connected to the elongated fog patch extending northwest toward Los Angeles.

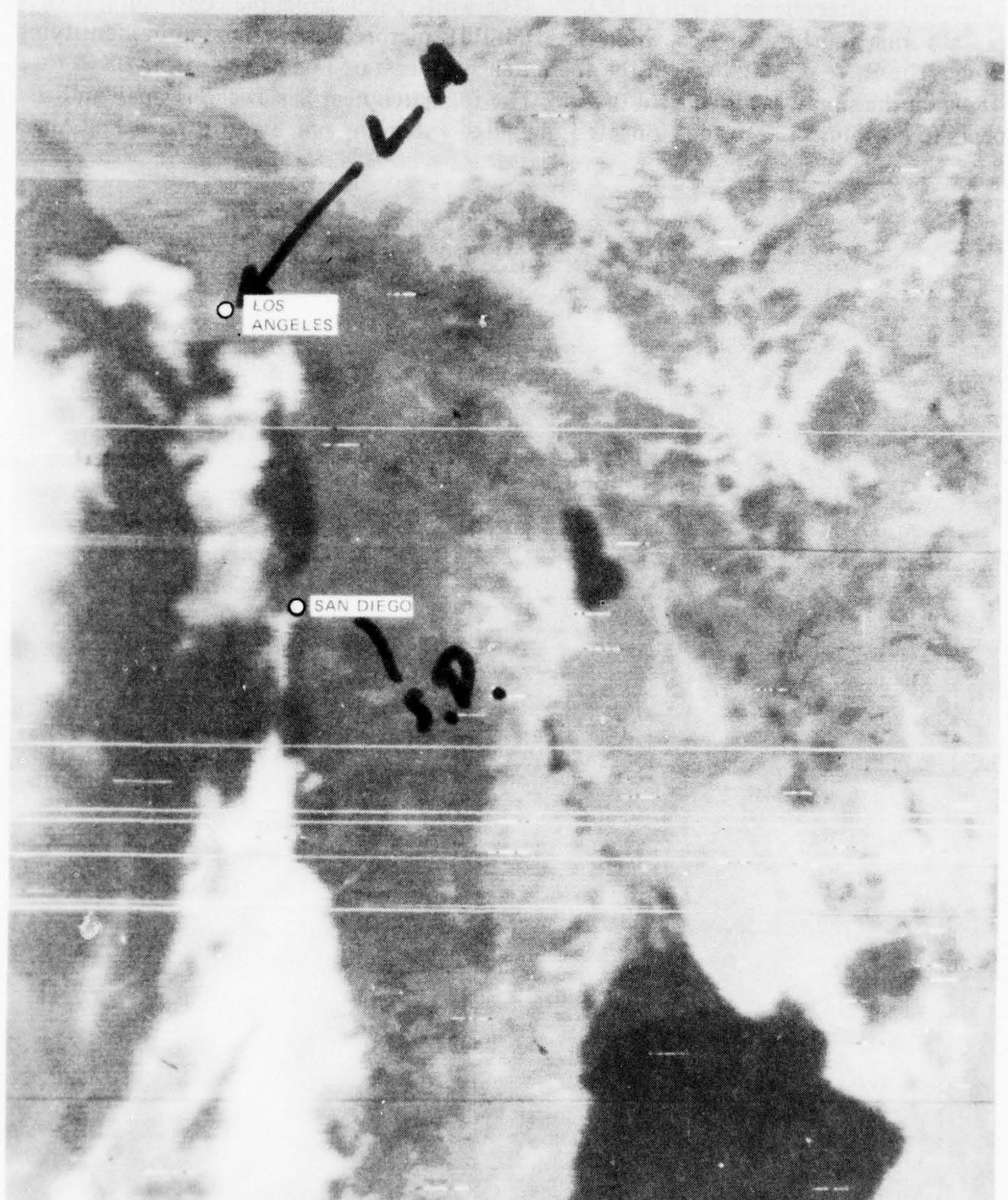

Figure 28. Enlargement of DMSP image at 0805 PDT on 5 October 1976.

MESOSCALE CIRCULATION

Figure 29 gives the mesoscale circulation pattern in Southern California on 4 October at 1400 PDT, 15 h before the fog appeared at NOSC, and gives the extent of the fog patch 1 h after the fog dispersed at NOSC on 5 October, according to the satellite picture at 0805 (fig 28). The fog patch appears to be along a convergence zone between air coming offshore southeast of Los Angeles and air moving toward the coast from a low-pressure region offshore. This convergence would be between dry offshore air and moist air and, according to the SSTs in fig 3, the fog is mostly over warm water in the southern region. The pressure pattern shown in fig 29 is similar to a pattern present several hours prior to a fog frontal passage described by Noonkester and Logue (1976b)[3]. This "frontal-type" fog was considered to be formed in a convergence region.

The fog deck over the coast of Baja California (fig 28) is over the cool water (fig 3) along the coast. The streamlines suggested in fig 29 would carry air over warm water prior to reaching the cool coastal water to form fog in a manner discussed in the previous section.

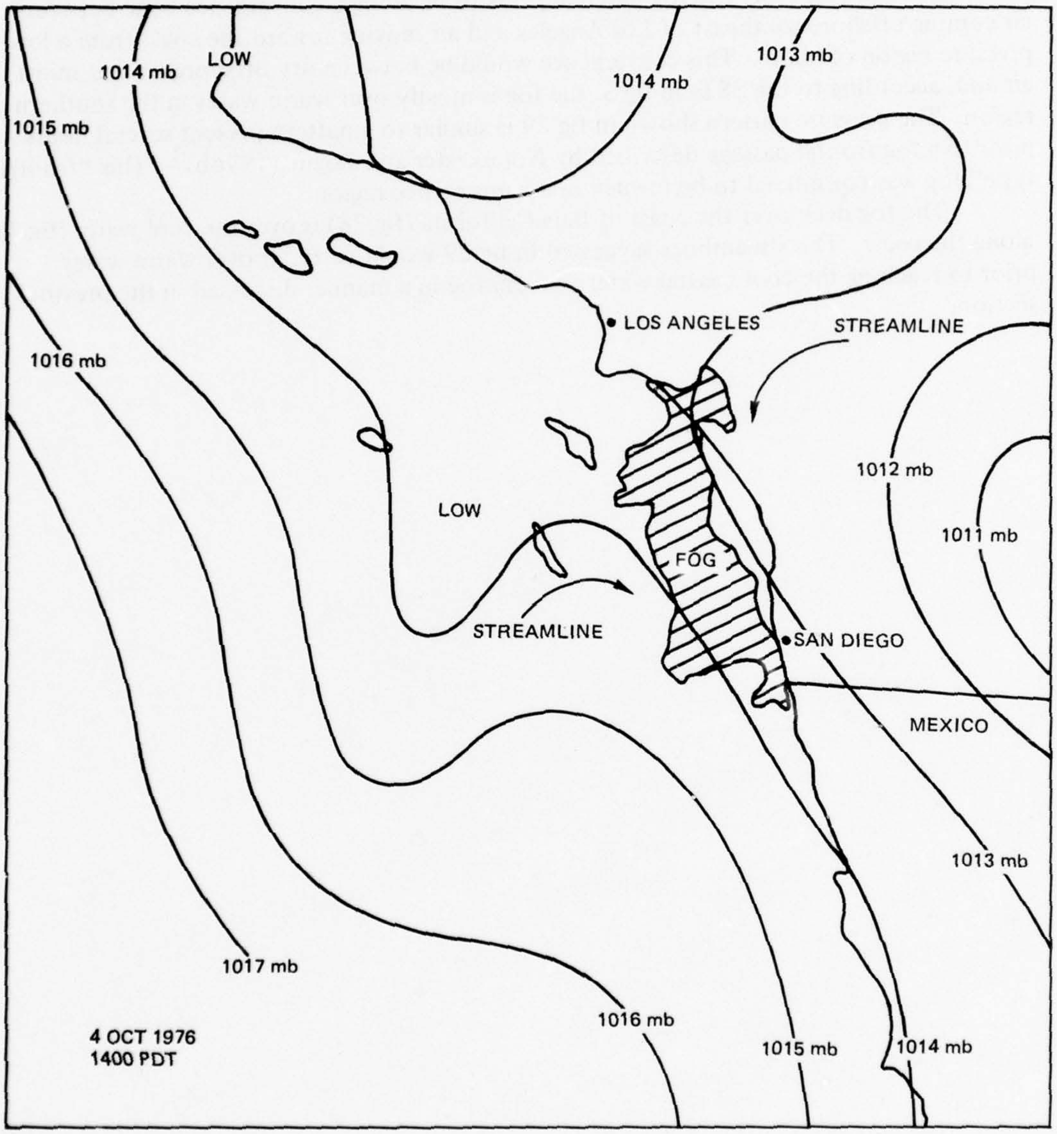

Figure 29. Surface, synoptic pressure pattern with outline of fog patch taken from fig 28.

FOG EPISODE ON 11 OCTOBER 1976

REMOTE SENSOR OBSERVATIONS

Figures 30 and 31 show the ceilometer return, acoustic backscatter, and radar backscatter as a function of time and elevation during the fog event on 11 October. A semicontinuous echo persists between 200 and 300 m on the acoustic record during the event. A semicontinuous radar echo also persists at the same elevation when above the minimum height window of about 200 m. Weaker echoes are present above these semicontinuous echoes in both records. The ceilometer shows a descent of a low cloud base to the ground to reduce the visibility at 0615 PDT by fog. Fog patches moved by the sensors at 0920 and 1100. The changes in visibility and ceilometer record appear to occur without changes in the backscatter echoes of the radar and acoustic sensors.

Figure 32 depicts the temporal variation of the vertical profile of wind direction and speed on 10–11 October, as determined by the acoustic wind sensing system. Except for strong winds from the N and NW above 400 m up to 1900 PDT on 10 October, the wind speeds are exceptionally small. The strong gradient in the wind direction isopleths are insignificant because the wind speeds are small.

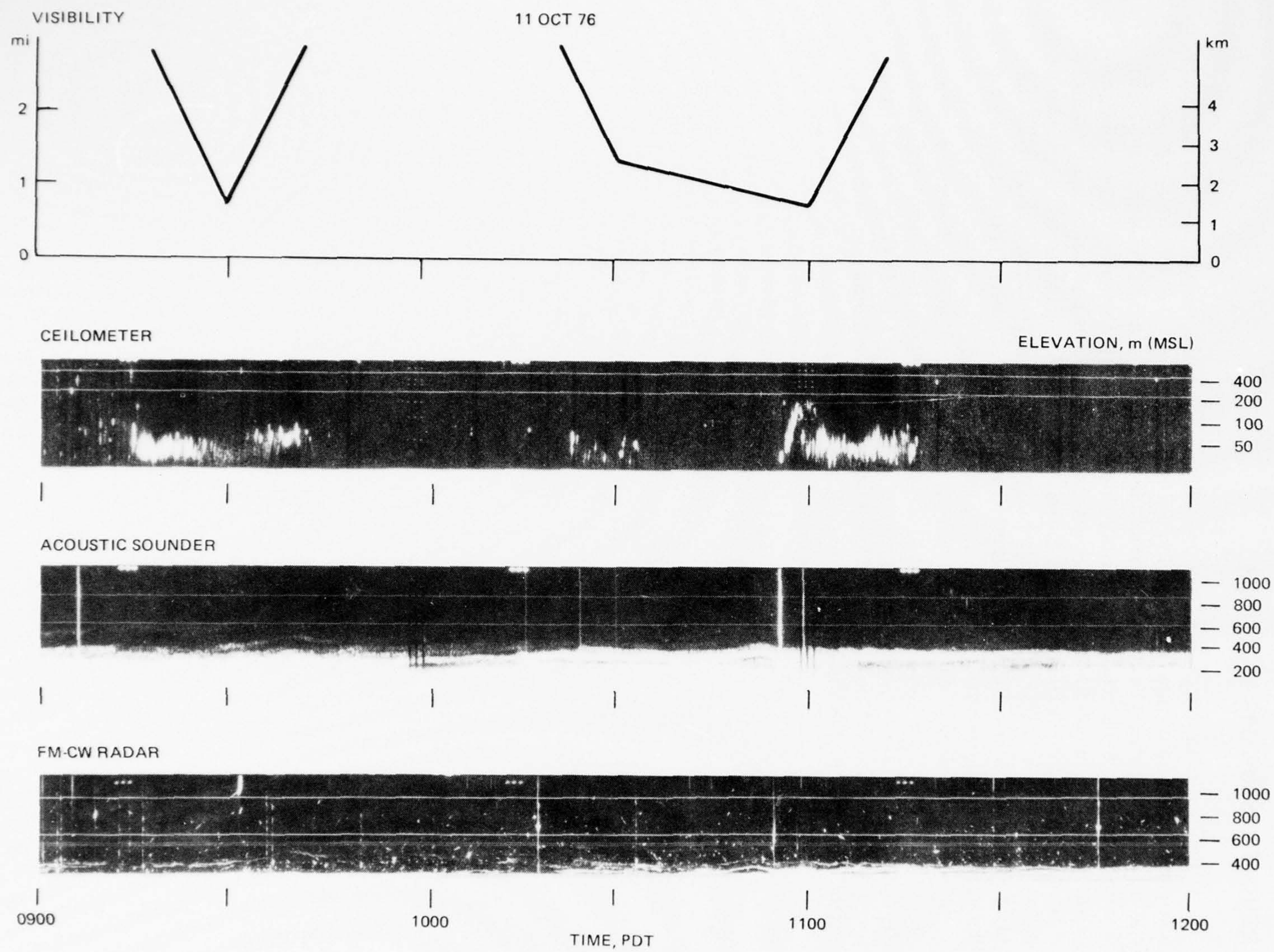

Figure 30. Sensor data taken at NOSC, 11 October 1976, 0900-1200 PDT.

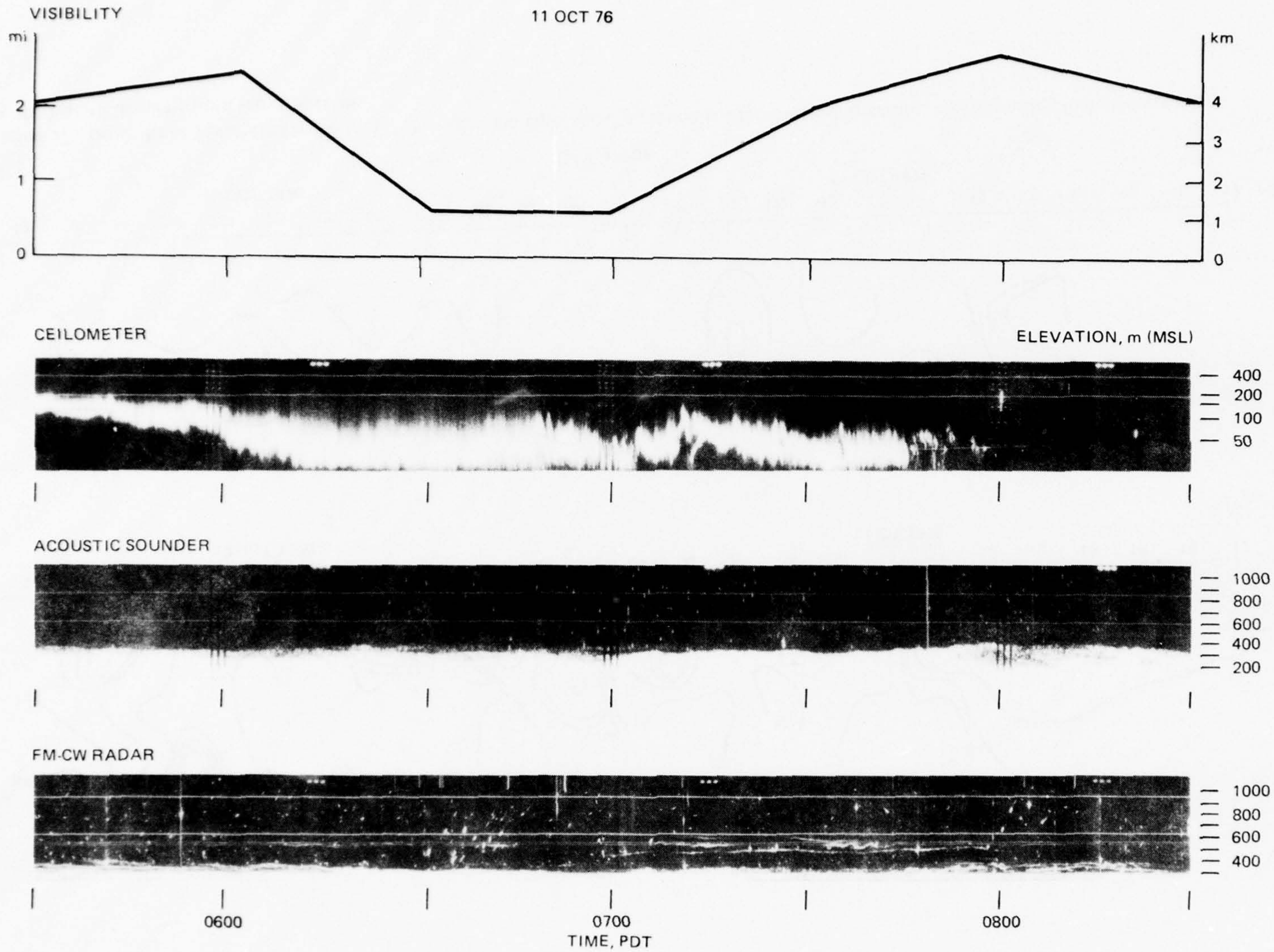

Figure 31. Sensor data taken at NOSC, 11 October 1976, 0530–0830 PDT.

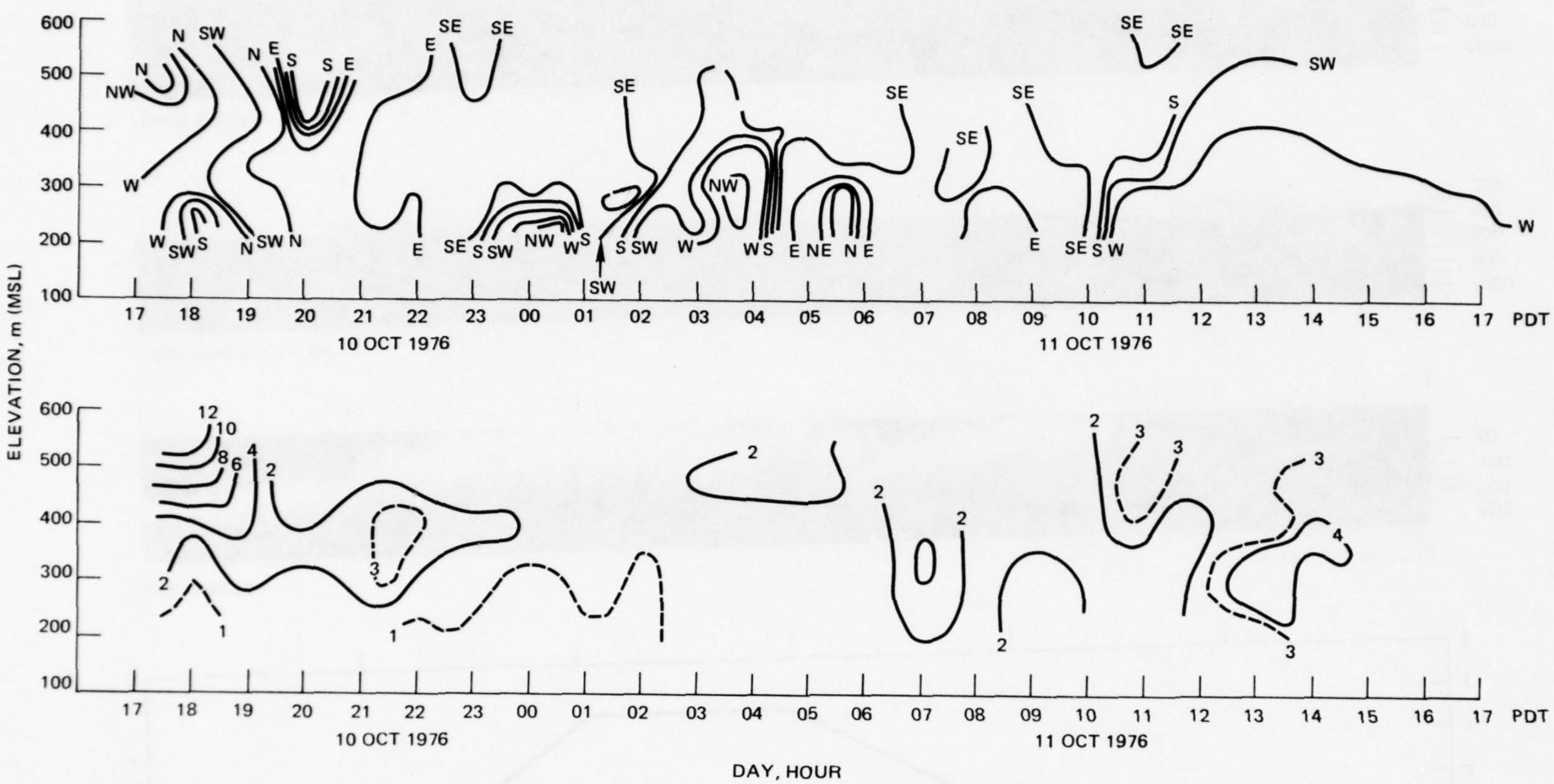

Figure 32. Isopleths of equal wind speed (m s^{-1}, bottom) and equal wind direction (meteorological direction, top) according to measurements by the bistatic acoustic wind sensor system.

SURFACE MEASUREMENTS AT NOSC

Figure 33 presents the surface measurements at NOSC on 10–11 October. Prior to and during the first portion of the fog event on the morning of 11 October, the wind was northerly and light. During the last part of the fog event the wind speed increased from the northwest as the sea breeze developed. The relative humidity and temperature changes in fig 33 approximate a normal diurnal variation. The diurnal pressure change was not as evident during this period as it was during the fog events of 7–8 October (fig 7) and 5 October (fig 26). The visibility was variable during this fog event. This event contained three periods of visibility of less than 1 mi, and was separated by periods of visibility greater than 3 mi.

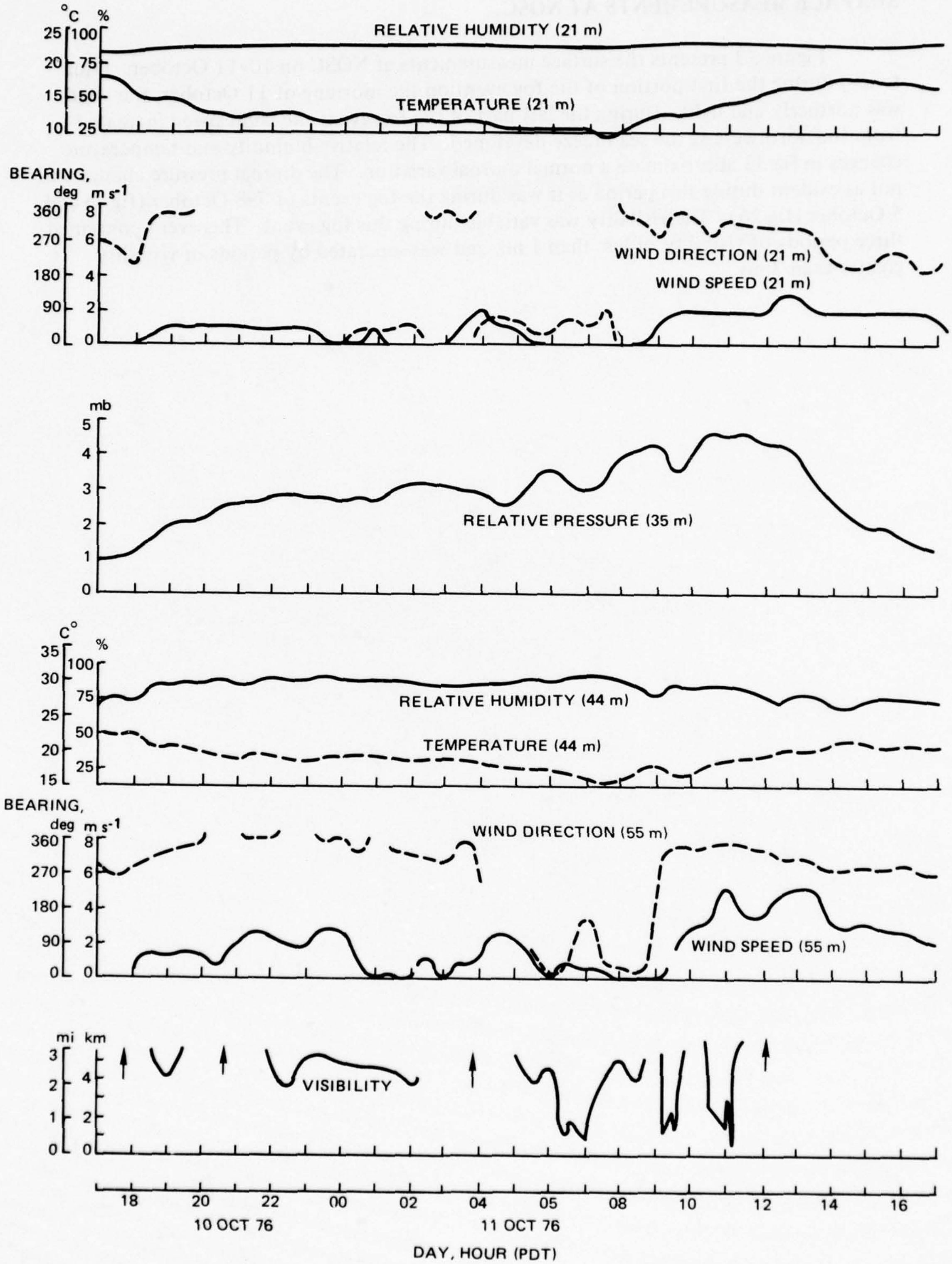

Figure 33. Surface observations at NOSC, 10-11 October 1976.

VERTICAL TEMPERATURE STRUCTURE

Figure 34 gives the inversion base height and the temperature as a function of time, using vertical soundings taken at Montgomery Field (MYF) and off Point La Jolla (see fig 3) (ARB). The temperatures taken by the ARB aircraft appear to be about 3°C too high.

The trends shown in fig 34 are a reversal of the trends shown in fig 8 for 8 October and in fig 27 for 5 October. The absolute value of the rates of change of the base height and temperature is considerably less than the rates shown in fig 8. Thus the fog event on 11 October did not immediately follow changes in the inversion height and 500-m temperatures, which were observed for fog events on 5 October and 7–8 October. However, this fog event could be considered to have followed the rapid intensification of the Santa Ana on 7 October (fig 8). Thus the fog events on 7–8 October and 11 October could be considered to occur during the gradual weakening of a Santa Ana.

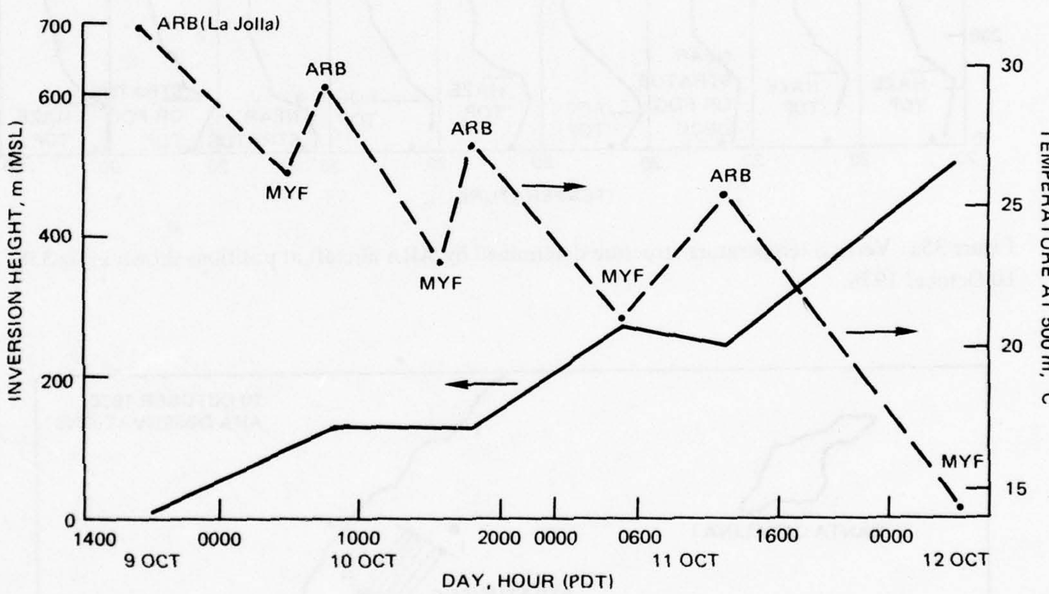

Figure 34. Inversion base heights and 500-m temperatures near a fog event at NOSC, 9–12 October 1976.

A fog bank was observed from shore southwest of NOSC on the morning of 10 October and the ARA aircraft took soundings upwind, downwind, and in the fog itself. The ARA pilot estimated the surface wind was about 2 to 3 knots from 240° near the eastern edge of the fog bank, and noted that the sea surface was calm. Figure 35a shows the vertical temperature profiles and fig 35b shows the location of these soundings (profiles A through F) relative to the fog bank at NOSC. Profiles A through F have temperature inversion bases near 100 m, which were also observed near NOSC at this time (see fig 34).

If the surface winds were westerly through the fog bank, profile E represents upwind conditions. The SST was slightly warmer than the air temperature near the surface in profile E and low-level instability would be expected. This is supported by the slightly

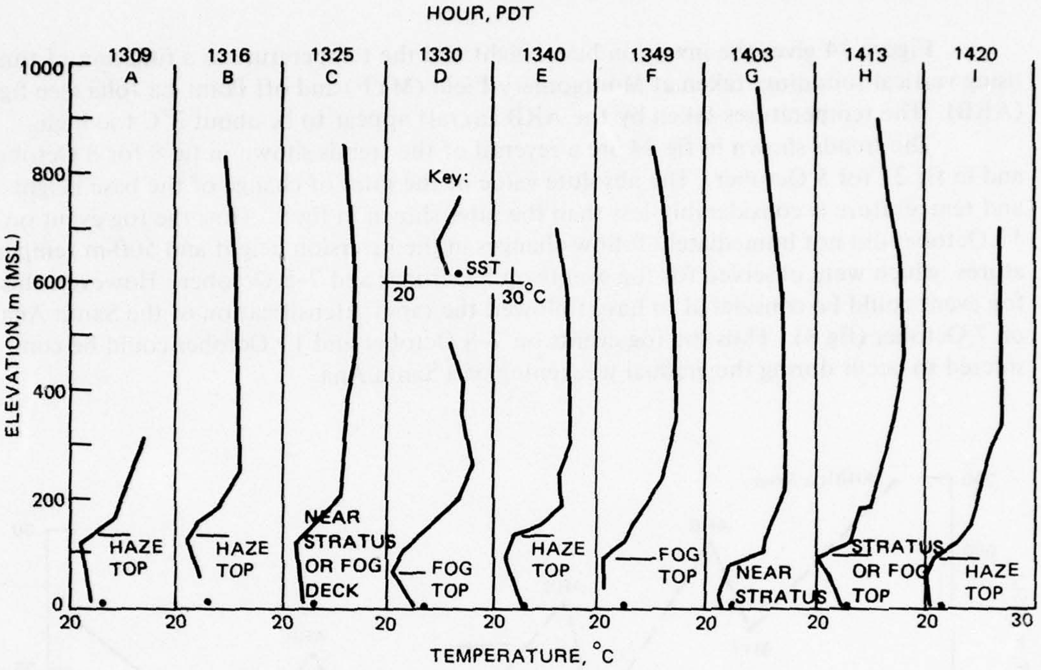

Figure 35a. Vertical temperature structure determined by ARA aircraft at positions shown in fig 35b; 10 October 1976.

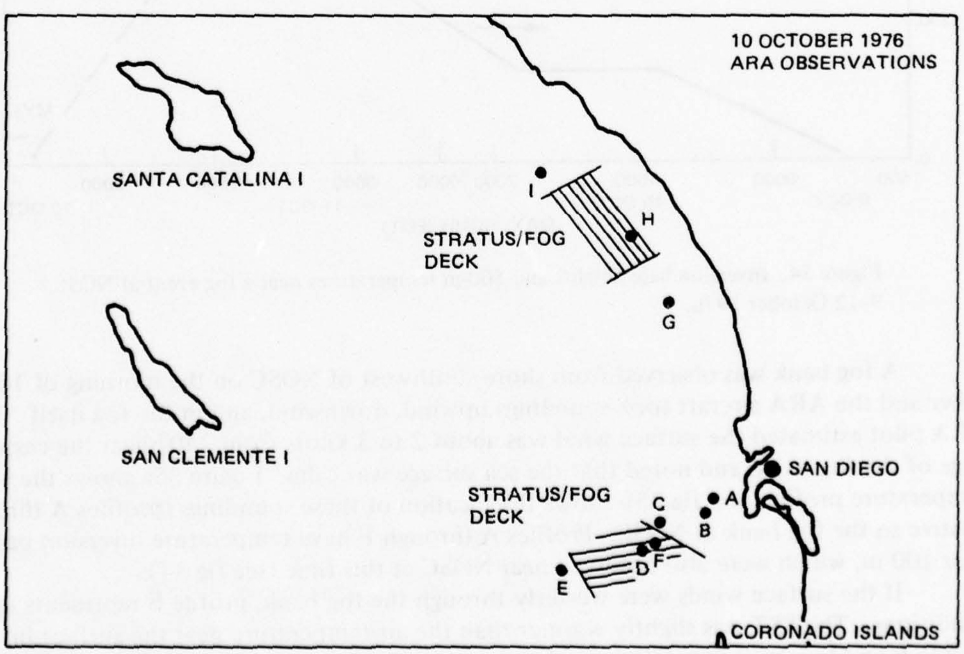

Figure 35b. Position of fog patches and vertical temperature soundings shown in fig 35a.

unstable vertical lapse rate of temperature below the inversion in profile E. This instability would transport moisture upward from the surface to increase the relative humidity below the inversion. Apparently, fog formed in the moist air represented by profile E while moving toward the east, but no fog-forming mechanism is suggested from the ARA data. The SSTs were warmer than the surface air temperature for profiles A through F. Similar soundings were made at a fog bank northwest of NOSC along the coast. Profiles, G, H, and I revealed no formation mechanism. Radiation cooling from the top of the fog apparently was significant because the lapse rate of temperature was unstable below the fog top (profiles D and H in fig 36a), and the temperature was about 1°C less at the inversion base in the presence of fog than the temperature at the inversion base adjacent to the fog deck.

Vertical soundings were taken over the ocean west of NOSC on 11 October by the ARA aircraft. These profiles are presented in fig 36a; the paths transversed while obtaining these profiles are given in fig 36b. Except for profile D, the inversion base heights are approximately equal to the base heights at the NOSC coast, as given in fig 34. Profile D was taken over a large flight path and some horizontal variations may have created a pseudo-profile. However, profile D could be representative of a region not greatly influenced by subsidence above the inversion base. The high inversion base in profile C, taken east of the region represented by profile D, suggests an increase in the inversion base height with distance west of NOSC.

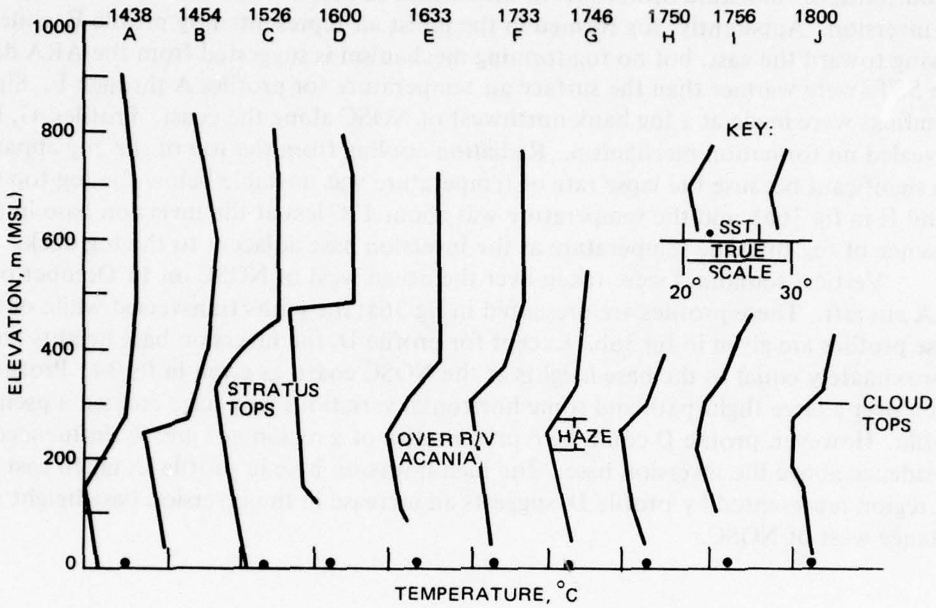

Figure 36a. Vertical temperature structure determined by ARA aircraft at positions shown in fig 36b; 11 October 1976.

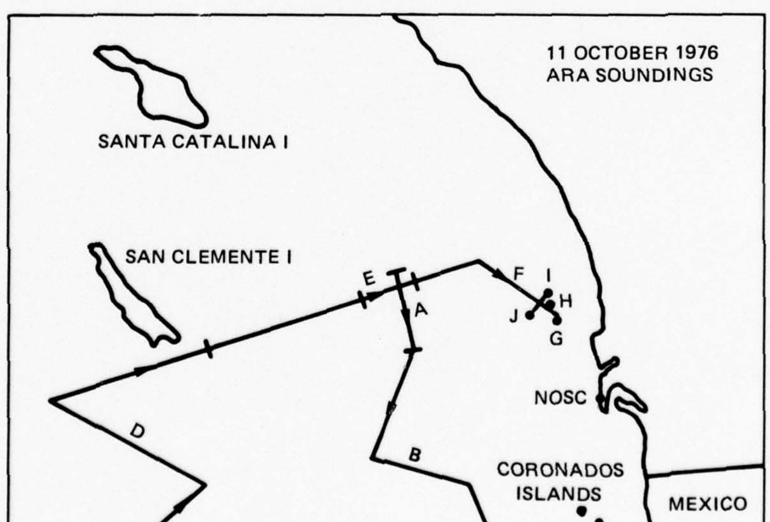

Figure 36b. Position of vertical soundings shown in fig 36a.

SATELLITE OBSERVATIONS

A DMSP IR picture of the Southern California region at 0741 PDT showed fog along the coast from Point La Jolla southward along the Baja California coast. Figure 37 is a visual DMSP picture taken at 0938. No fog or clouds are shown to be present at the NOSC sensor site in fig 37. Fog was observed at NOSC between 0920 and 0930 and between 1100 and 1115. This fog appeared to be thin and patchy according to the ceilometer record in fig 32, and must have been too thin to be observed by the visual DMSP picture taken at 0938.

An unusual cloud structure extends westward from Point La Jolla in fig 37. The cloud has a "corkscrew" appearance and joins a thin stratus cloud deck to the west which has bands extending in a N-S direction and bends westward in the southern region. The bands appear to present an extended, enlarged outline of San Clemente Island. These bands could be gravity waves created in the inversion interface (between the moist, cool marine air below the inversion and the dry warm air above the interface) by the San Clemente vertical protrusion. The bands are about 9 km apart, which would be a large wavelength compared to wavelengths of gravity waves deduced by Gossard, et al (1970)[12]. Profiles F through J, taken near and in the "corkscrew-like" cloud off Point La Jolla, show no structure which might be considered related to the "corkscrew cloud". These cloud structures are probably not related to the fog episode.

[12]Gossard, EE, JH Richter and D Atlas, "Internal Waves in the Atmosphere from High-Resolution Radar Measurements", Journal of Geophysical Research, v 75, p 3523-3536, 1970.

Figure 37. Enlargement of DMSP image at 0938 PDT on 11 October 1976.

MESOSCALE CIRCULATION

Figure 38 shows the surface isobaric pattern in Southern California at 1100 PDT on 10 October and the positions of the two stratus/fog decks observed by the ARA aircraft between 1300 and 1430. According to approximate streamlines, somewhat paralleling the isobars, the air moving into the fog regions would be moving from the west and according to the SST pattern in fig 3, the fogs are over warm water. The true air trajectories are difficult to estimate. Figure 39 gives an estimated air trajectory by ARB and indicates a near reversal at 0900 on 10 October. The trajectory in fig 39 ends near the region of the fog patch shown in fig 35b and 38. The sequence of events leading to fog formation along the ARB trajectory would be difficult to construct.

Figure 40 shows the surface isobaric pattern at 0800 PDT on 11 October and fig 41 gives the ARB estimated air trajectory ending at 1500 on 11 October. Streamlines, based on the isobaric patterns in fig 40, would suggest that air moved over warm water and onto the cool waters near NOSC where fog might form (see fig 3 for the SST pattern). The air trajectory in fig 41 somewhat substantiates this possibility.

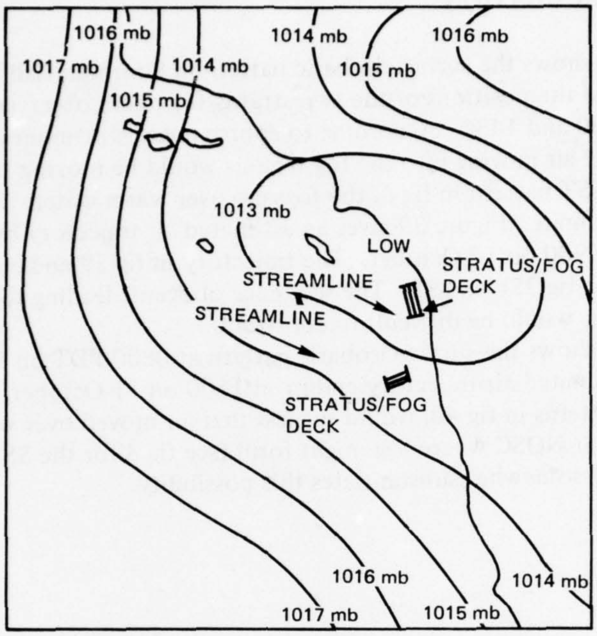

Figure 38. Surface, synoptic pressure pattern;
10 October 1976, 1100 PDT.

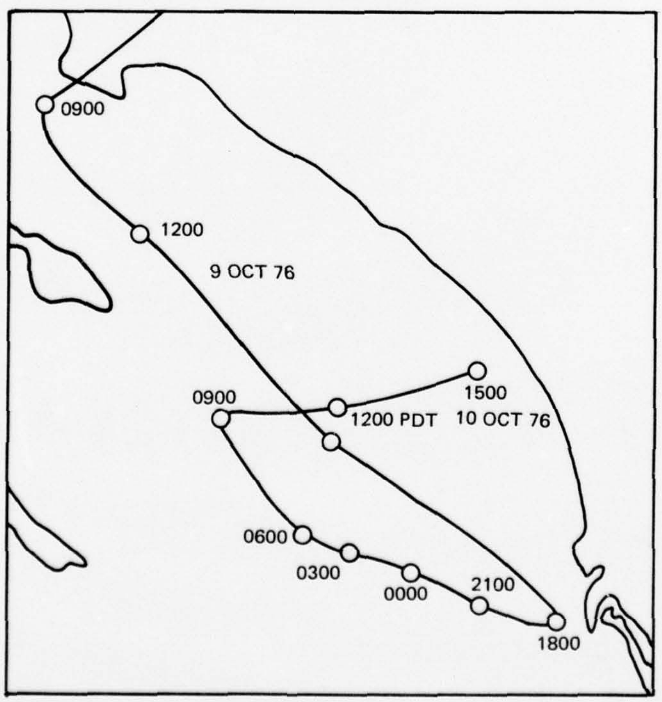

Figure 39. Estimated air parcel trajectory ending at 1500 PDT on
10 October 1976, according to analysis by ARB (MMI).

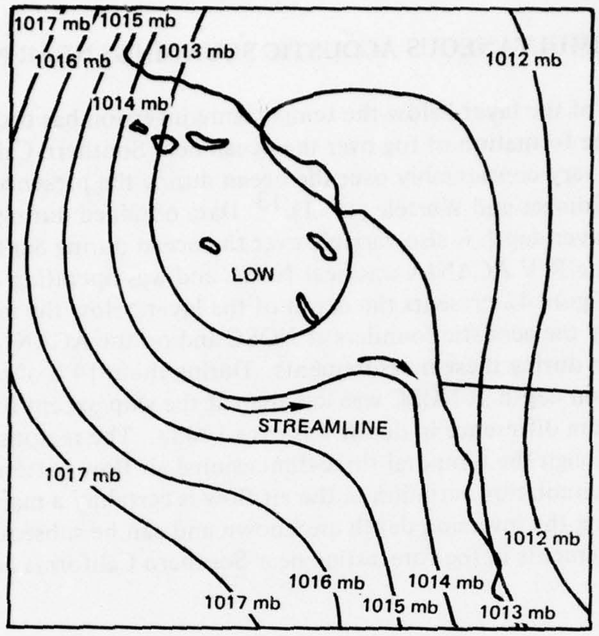

Figure 40. Surface, synoptic pressure pattern;
11 October 1976, 0800 PDT.

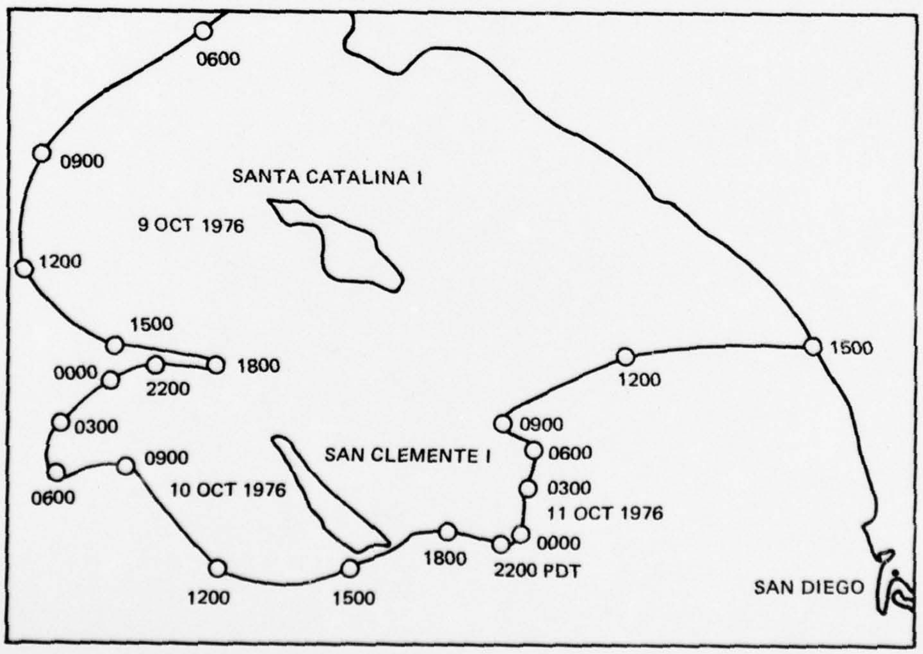

Figure 41. Estimated air parcel trajectory ending at 1500 PDT on
11 October 1976, according to analysis by ARB (MMI).

SIMULTANEOUS ACOUSTIC SOUNDINGS NEAR NOSC

The depth of the layer below the temperature inversion has been found to be a critical factor in the formation of fog over the ocean near Southern California. This depth has been found to vary considerably over the ocean during the presence of spring/summer stratus clouds by Edinger and Wurtele (1971).[13] Data obtained during CEWCOM-1976 indicate that this layer depth is also variable over the ocean during Santa Ana conditions. On 5–6 October, the R/V ACANIA was near NOSC and was operating their acoustic sounder aboard the ship. Figure 42 presents the depth of the layer below the inversion as simultaneously measured by the acoustic sounders at NOSC and on the ACANIA, and gives the position of the ship during these measurements. During these 14 h of simultaneous observations, the inversion depth at NOSC was less than at the ship except for a 2-h period at night. The maximum difference in depth was over 100 m. The reasons for these differences are not known although the temporal three-dimensional air flow pattern might reveal some causes. Mesoscale circulation variation in the air flow is certainly a major factor. Until the processes controlling the inversion depth are known and can be subsequently forecast, appreciable improvements in fog forecasting near Southern California are not expected.

[13] Edinger, JG, and MG Wurtele, Marine Layer Over Sea Test Range, report by University of California for Pacific Missile Range, report TP 71-2, 15 April 1971.

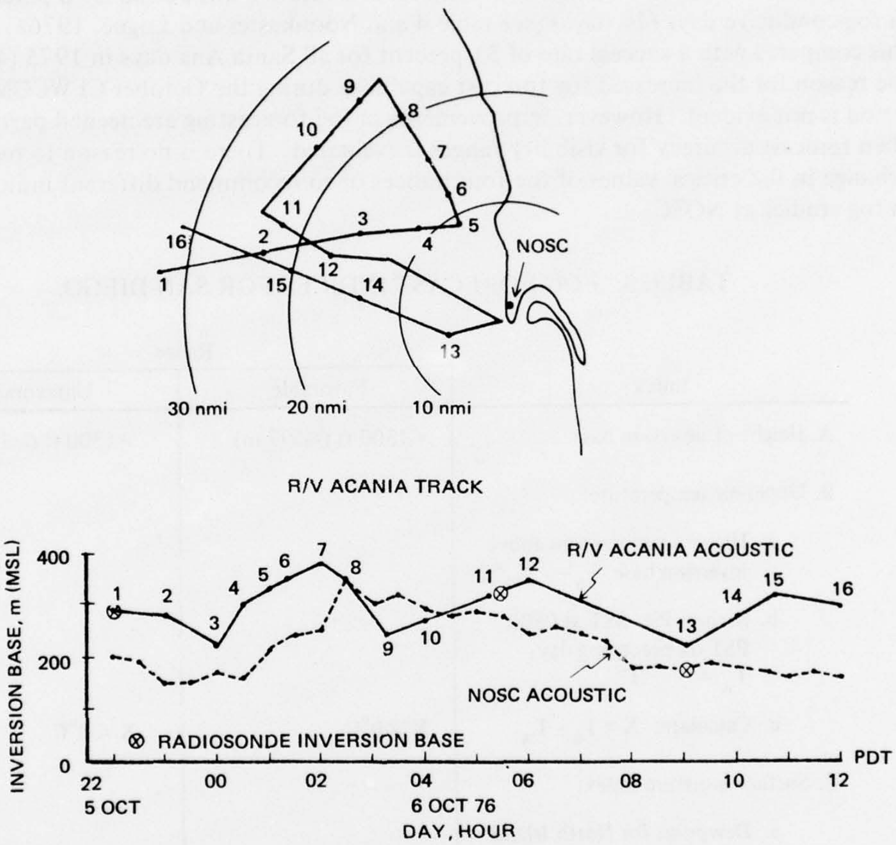

Figure 42. Inversion base heights measured simultaneously at NOSC and on the R/V ACANIA (NPS) by acoustic echo sounders, 6 October 1976.

FOG FORECASTS AT NORTH ISLAND

Forecasters at the Naval Weather Service Facility at North Island, San Diego, use four indices (Leipper, 1948)[7] to guide them in making daily forecasts of fog. These indices are defined in table 3. The values of these indices for the October period of CEWCOM-1976 are given in figure 43, using the radiosonde data taken at Montgomery Field (MYF). Table 4 summarizes the favorability of the indices for October and gives the forecast and observed visibility for each cay at North Island. The success rate for this period is 70 percent based on fog-conducive days (10 days) (see table 4 and Noonkester and Logue, 1976a, 1976b)[2,3]. This compares with a success rate of 51 percent for all Santa Ana days in 1975 (43 days). The reason for the increased fog forecast capability during the October CEWCOM-1976 period is not evident. However, improvements in fog forecasting are needed particularly when forecast accuracy for visibility ranges is evaluated. There is no reason to recommend a change in the critical values of the four indices or to recommend different indices based on fog studies at NOSC.

TABLE 3. FOG FORECAST INDICES FOR SAN DIEGO.

Index	Range	
	Favorable	Unfavorable
A. Height of inversion base	≤1300 ft (≤397 m)	>1300 ft (>397 m)
B. Upper-air temperature:		
a. Highest temperature above inversion base, T_a = ___ °C		
b. Scripps Pier SST at 0800 PST at preceding day, T_w = ___ °C		
c. Calculate: $X = T_a - T_w$.	$X \geq 0°C$	$X < 0°C$
C. Surface moisture index:		
a. Dewpoint for North Island at 1630 PST on preceding day, T_c = ___ °C		
b. Calculate: $Y = T_c - T_w$.	$Y \geq -5°C$	$Y < -5°C$
D. Radiation index:		
Mixing ratio W at 10 000 ft (3050 m).	W ≤3.5 g/kg	W >3.5 g/kg

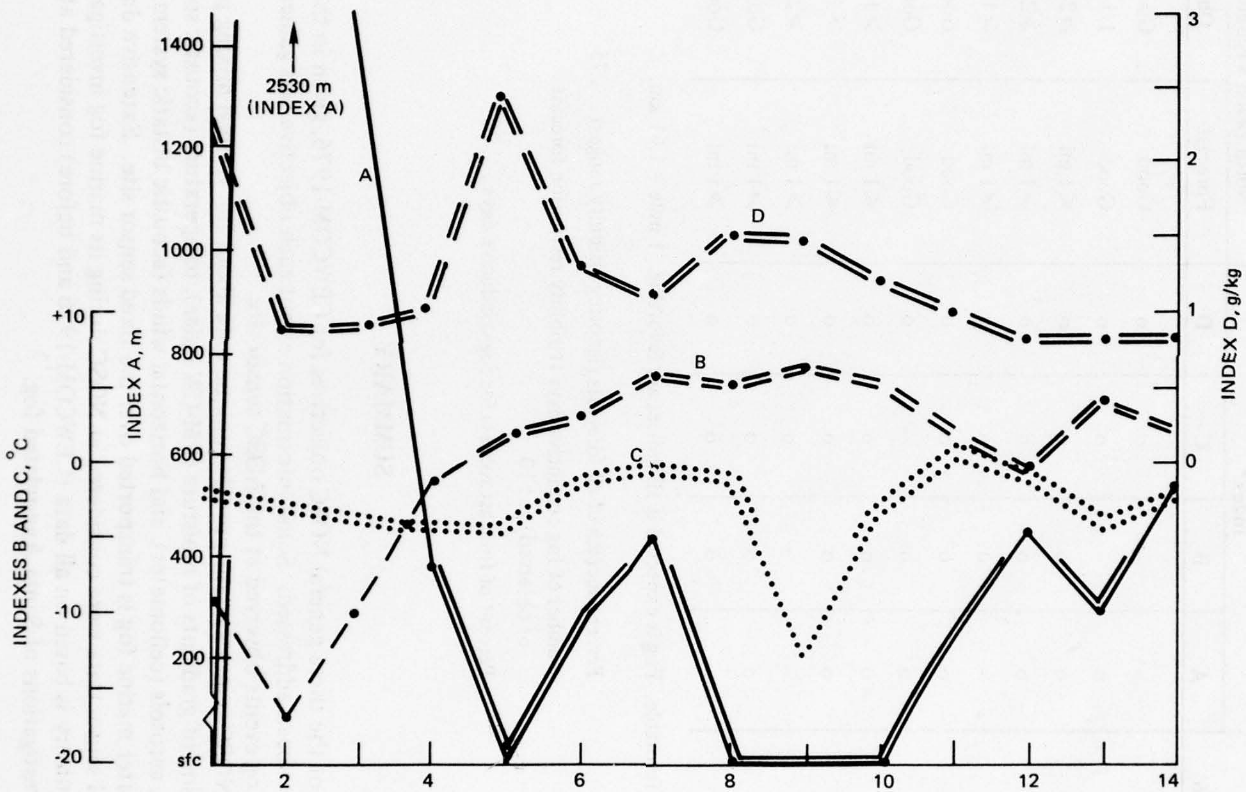

Figure 43. Fog forecast indices (see table 3) each day from 1 through 14 October 1976. Double lines mean index is favorable for fog.

TABLE 4. FAVORABILITY OF FOG FORECAST INDEX (SEE TABLE 3) AND FORECASTS AND OBSERVATIONS OF VISIBILITY RESTRICTIONS FOR DAYS DURING OCTOBER 1976. (SEE FIG 43.)

October 1976	Index* A	B	C	D	North Island Visibility Forecast	Observed
3	–	–	o	o	Good	Good
4	o	–	o	o	Good	1/16 mi
5	o	o	o	o	≤1 mi	≥2-1/2 mi
6	o	o	o	o	≥1 mi	≥2-1/2 mi
7	–	o	o	o	≥1 mi	≥1/16 mi
8	o	o	o	o	Good	Good
9	o	o	–	o	Good	Good
10	o	o	o	o	≤1 mi	≥1/16 mi
11	o	o	o	o	≤1 mi	≥2-1/2 mi
12	–	–	o	o	≥1 mi	≥2-1/2 mi
13	o	o	o	o	≥1 mi	Good
14	–	o	o	o	≥1 mi	Good

*"o" means favorable. Fog is expected if all indices are favorable. 1 mile = 1.61 km.

Percent success of all forecasts (ignoring visibility ranges) . . . 75

Number of fog conducive days (visibility restriction forecast or observed) . . . 10

Percent of forecast success for fog-conducive days . . . 70

SUMMARY

Each of the three general NOSC objectives for CEWCOM-1976, given in the BACKGROUND, has been addressed. Some information about each objective was gained for each of the three fog events observed at the NOSC sensor site.

The NOSC sensor system provides unique data about the vertical mixing processes and distribution of gradients of moisture (FM-CW radar), temperature (acoustic sounder, radiosondes), aerosols (ceilometer), and horizontal winds (acoustic bistatic system) before, during, and after marine fog is transported over the fixed sensor site. Extensive data other than the local sensor data were considered at NOSC during its marine fog investigations. The following summary is based on all data (CEWCOM-1976 and before) considered at NOSC during its investigations of Santa Ana-related fog.

FM-CW RADAR

Semicontinuous, weak echoes are obtained from the top of the moist marine layer (base of the temperature inversion) before, during, and after fog events. Intermittent layered echoes are sometimes observed above the inversion base, occasionally with unstable breaking Kelvin-Helmholtz waves. Few echoes are observed below the region of the inversion base. The intensity of the semicontinuous echo and the presence of the intermittent layers above indicate that vertical mixing is more prevalent above the inversion compared to mixing above stratus clouds in Southern California. The general absence of echoes below the inversion base suggests the general presence of a uniform moisture field in the moist layer.

The height of the semicontinuous layer echo at the inversion base is predominantly between 100 and 300 m (200 m being a frequent height) during hours spanning a fog event. No characteristic inversion height, echo types, or changes preceding, during, or after fog events have been identified.

The radar provides a continuous record of the height of the inversion, the most critical parameter for marine fog forecasting in Southern California for both stratus cloud and Santa Ana-related fogs. This height and its changes provide a continuous evaluation of the intensity of the Santa Ana subsidence. The ocean region over which the inversion height is representative generally increases as the intensity of the Santa Ana increases. The height may represent an ocean region within 50 km only during a weak Santa Ana, and may represent an ocean region within 150 km during a strong Santa Ana.

ACOUSTIC SOUNDER

The acoustic sounder provides about the same information as the radar, particularly when operated in a high vertical resolution mode, except that more echoes are observed above and below the semicontinuous layer, representing mixing near the inversion. These additional echoes often mask the echo from the inversion base region. The low-level echoes often fill the region below the inversion base. These echoes indicate mixing along a gradient in potential temperature which, according to vertical temperature soundings during fog, is a negative gradient (a decrease in potential temperature with elevation). Echoes above the inversion are usually layered, must represent vertical mixing created by turbulent mixing along the positive potential temperature gradient, and may indicate some characteristics of the subsidence not yet isolated. The layered echoes above the inversion base are consistently more frequent than during stratus cloud conditions.

ACOUSTIC WIND PROFILES

Only a few fog events have been observed when acoustically determined winds were available. Based on these events, the temporal pattern of vertical profiles of horizontal winds is considerably variable before, during, and after fog events, and no fog-related pattern is evident. The wind appears to be more homogeneous below the inversion or fog top than above. The height resolution and the sampling rate have been generally insufficient to assess the role of wind shear at and above the fog top, but one observation provided strong evidence that wind shear could instigate significant vertical transportation of moisture out of the moist subinversion region. This observation should prompt increased efforts for more detailed wind profile measurements by acoustic systems simultaneous with high range resolution measurements of moisture (FM-CW radar, etc) and heat transportation (acoustic sounding, etc) in the lower atmosphere, and also should prompt a more critical theoretical analysis of the role of wind shear in the entrainment processes at the top of a mixed layer. Such shear regions and vertical moisture transportation may often prevent the formation of fog or clouds.

CEILOMETER

The filming technique used to record the ceilometer returns has proven to provide excellent cloud-base and structure information when the clouds are low (below 400 m). The tangentially dependent vertical scale provides a height range resolution which improves with a decrease in elevation of the cloud base almost down to the surface. The range resolution is about 5-10 m near 50-m elevation. Cloud thickness can be determined by using simultaneously measured cloud base heights from the ceilometer and measured cloud top heights from the FM-CW radar or acoustic sounder (inversion base echoes).

Ceilometer records have revealed several variations of cloud/fog height changes during the onset and termination of the fog event. Being restricted to heights below the inversion, cloud bases associated with fog events are observed to be below 300 m and usually below 200 m. Fog onsets are often sudden, and without any elevated cloud base preceding them. However, cloud base descents to the surface are common; the descents have occurred within a few minutes or over a 1- to 2-hour period. Once surfacing to form a fog, cloud bases may remain at the surface for several hours or for only a few minutes; the fog is often intermittent for several hours. Fog termination generally can be considered to be a reverse of an onset sequence, not particularly the sequence initiating the event. There is a tendency for the ceilometer-base heights to change (increase or decrease) rapidly during the termination phase of the fog event.

VISIBILITY

Visiometer records reveal a variation of surface visibility which, when examined as a function of time, varies in a manner similar to the cloud-base heights measured by the ceilometer. The rates of change of visibility during the onset, the main phase, and the termination of the fog are comparable to the associated cloud base height changes. This relation would be expected because the density of the cloud aerosols at and below the cloud base controls both the ceilometer echo heights and the scattered light used to measure visibility by the visiometer.

The statistical variance of the visibility for periods less than about a minute is often large. The difference in the envelopes of maximum and minimum visibility during a fog event can be used to judge the variance. Some of these envelopes were determined. The variance has occasionally been near zero but differences in the limit envelopes sometimes differ by several kilometers.

The minimum visibilities recorded during Santa Ana fogs are sometimes less than 100 m (<1/16 mi), which is seldom attained during fog associated with stratus clouds.

Standard weather records taken along the coast and nearby islands have revealed apparent random differences in visibilities near times of fog events at NOSC. Fog events are sometimes separated by several hours at sites separated by only a few kilometers. Fog events at San Clemente Island appear to be particularly unrelated to fog events near San Diego.

VERTICAL TEMPERATURE STRUCTURE

Vertical temperature profiles taken along the coast during Santa Ana fogs have revealed inversion base heights within about 50 m of the height of the semicontinuous echo of the radar or acoustic sounder. The temperature gradient ($\Delta T \cong 10°C$ in 200 m) and temperature increases above the inversion base are sometimes large compared to non-Santa Ana conditions, particularly prior to fog events, but Santa Ana fog is sometimes associated with weak inversion conditions. The gradient of temperature below the inversion often indicates unstable conditions, particularly in fog.

HORIZONTAL VARIATION IN TEMPERATURE STRUCTURE

Essentially no data on the horizontal variation in vertical temperature structure were available prior to CEWCOM-1976 for Santa Ana fog conditions. Conclusions must be based on the data of 7, 8, 10, and 11 October taken by aircraft (fig 35 and 36). These data indicate little horizontal change of vertical temperature structures along the coast out to at least 50 km. Data at San Nicolas Island, San Clemente Island, and San Diego on 7–8 October indicated the presence of a horizontally homogeneous vertical temperature structure for at least an 18-hour period (fig 9) during strong Santa Ana conditions.

ARA soundings in and near two fog banks on 10 October showed colder temperatures on the top of fog than found at the inversion base on either side of the fog, and unstable lapse rates of temperatures below the inversion in the fog. This is additional evidence that radiational cooling at the top of the fog is a significant factor in fog maintenance.

Offshore vertical temperature profiles on 11 October showed a gradual increase of inversion base heights over the ocean from the coast toward San Clemente Island. Simultaneous acoustic sounding on the R/V ACANIA and at NOSC on 5 and 6 October indicated considerable horizontal, temporal variations in the inversion base height over horizontal distances up to 60 km. These observations were made during weak Santa Ana conditions. Apparently, horizontal homogeneity is more likely during strong subsidence conditions.

MESOSCALE CIRCULATION

An accurate time series of synoptic maps depicting the instantaneous air flow at several levels below 1 km over the Southern California region out beyond the islands west of the coast has been shown to be the greatest need in an investigation of marine fog, and undoubtedly will be the greatest need in forecasting Santa Ana fogs. Until techniques are developed to considerably increase the hourly data density over the ocean region, little improvements in fog forecasting can be expected.

Considerable evidence indicates that subtle and strong mesoscale and submesoscale circulations are forming, moving, and dissipating off and near shore during Santa Ana conditions. These small-scale circulations control the surface air flow over the ocean with varying SST gradients, control the divergence/convergence zones, and partially control the inversion depth during Santa Ana-related fog conditions.

Although based on meager data, air trajectories have been determined for some fog events. These trajectories indicate a continental origin of the air in the Santa Ana fog, which agrees with the low visibilities observed in Santa Ana fogs. Some of these air trajectories, which have tortuous paths, may have several reversals in conditions leading to fog. Some fog may be formed by a series of processes along its path. For example, subinversion air may first be carried over warmer water where moisture is added into the cool layer. This near-saturated air may then be carried into a convergence zone where vertical motion creates cooling and condensation. In contrast, the convergence may cause the inversion to rise so that saturation is not attainable at the surface. The variations in the convergence/divergence regions and inversion height changes undoubtedly create horizontal variability in fog events even without considering the sea surface temperature. The great variation in the horizontal and vertical distribution of aerosols (visibility, ceilometer records, etc) observed in the marine fog studies at NOSC supports these suggested possibilities.

SEA SURFACE TEMPERATURES

The only fog events studied when SSTs were available at NOSC were during CEWCOM-1976. The SST pattern constructed (fig 3) appears to be unique for the Southern California region in its detail. Although the reliability of the pattern or temperature values has not been verified, the major features of the pattern are considered to represent average conditions during the October period.

The SSTs are potentially related to fog events, but the lack of reliable air parcel trajectories prevented establishment of any definitive relationship between air trajectories, SSTs, and fog formation or dissipation.

SATELLITE OBSERVATIONS

Santa Ana conditions are characterized by clear (cloudless) skies over the nearby ocean and land, so that satellite visual and IR pictures can be used to isolate fog patches. High-resolution IR and visual pictures by the DMSP system permitted the location of fog during the CEWCOM-1976 study. The spatial resolution of the Geostationary Operational Environmental Satellite (GOES) images* was generally inadequate to isolate fog near Southern California. Satellite observations were not critical to NOSC for fog studies prior to CEWCOM-1976.

Fog patches were recorded by the DMSP photographs for two of the three fog episodes observed at NOSC. Fog was apparently too tenuous to be observed by satellite during one fog event. The spatial extent of fog on two events was easily established by DMSP satellite pictures and was related to mesoscale circulation and SST conditions. On one fog day, fog patches were potentially related to SST gradients; on another day, a large fog

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*Provided by Pacific Missile Test Center, Point Mugu, California patch was potentially related to a convergence zone. These data clearly show the great potential of satellite data for fog investigations. Without these satellite pictures during Santa Ana conditions, the spatial coverage of fog would not likely be known and could not be related to circulation and SST conditions.

SURFACE OBSERVATIONS

Surface observations of standard meteorological elements like temperature, humidity, wind, and pressure could not be uniquely related to fog events. Apparently, conditions described by these local observations provide little, if any, information on fog events near San Diego.

FOG FORECASTING AT NORTH ISLAND

The reliability of daily fog forecasts made by the weather forecasters at the Naval Weather Service Facility at North Island, San Diego, was evaluated for the year 1975 and for the October CEWCOM-1976 period. The evaluation included an objective forecast technique and a subjective forecast which had guidance from the objective forecast. The fog forecasting accuracy at North Island was found to be little better than random except during the short CEWCOM-1976 period. This evaluation was based on a "fog-conducive day" definition which was considered necessary to avoid the effect of "no-fog" persistence forecasting. (That is, fog at North Island is statistically unlikely each day of the year. A persistent "no-fog" forecast would give a 72 percent forecast success rate.)

This evaluation is the only known effort to determine the reliability of fog forecasts made for naval operations in recent years. Such evaluations are critically needed to aid in the isolation of good and poor forecast techniques and to aid in the selection of regions requiring efforts to improve fog forecasts. Such evaluations are needed for all naval forecast units where fog forecasts can be advantageously used. Without these, naval fog forecasting needs cannot be known.

The objective technique at North Island was based on four simply calculated indices. Only one index, inversion depth, was examined for reliability because widely varying horizontal conditions, not measured by any index, were found to control the formation and dissipation of fog near San Diego. The inversion depth must be less than about 400 m to support a fog deck. Although this appears to be a necessary condition, it is clearly not a sufficient condition.

CONCLUSIONS ON SENSORS

Fixed, surface-based sensors provide excellent, continuous information about the vertical structure of Santa Ana fog carried over the sensors but provide meager information about fog formation or dissipation. Aircraft provide good information on spatial variations concerning slow changes (1 to 4 hours), but provide intermittent and less economical data. Satellite data, particularly DMSP data, provide excellent pictures of visual and IR variations in a mesoscale region but the pictures are spaced many hours apart, at times not always advantageous to the experiment. Collectively, all sensors provided a good general pattern of fog evolution.

SANTA ANA FOG FORMATION

The formation and dissipation of marine fog associated with Santa Ana conditions are concluded to depend on the horizontal variation in (1) inversion depth, (2) surface and near-surface air trajectories, (3) sea surface temperature pattern, (4) difference between air and sea surface temperature along air trajectory, and (5) low-level convergence patterns (vertical motion). Santa Ana fog appears to form in regions where SSTs decrease along the direction of surface air flow and in low-level convergence zones after subsidence aloft has attained a maximum.

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