

AD-A016 958

MARINE FOG STUDIES OFF THE CALIFORNIA COAST

Eugene J. Mack, et al

Calspan Corporation

Prepared for:

Naval Air Systems Command

March 1975

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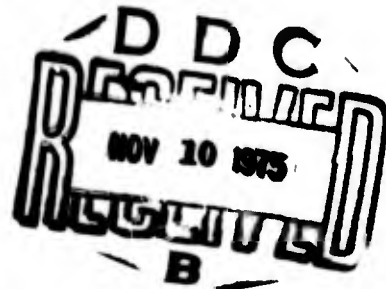
ADA 016958

*MARINE FOG STUDIES
OFF THE CALIFORNIA COAST*

Third Annual Summary Report
Project Sea Fog

Calspan Report No. CJ-5607-M-1

Prepared For:
NAVAL AIR SYSTEMS COMMAND
WASHINGTON, D.C. 20360
CODE AIR-370C



MARCH 1975
CONTRACT NO. N00019-75-C-0053

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ABSTRACT

For the third consecutive year, measurements of the microphysical and micrometeorological characteristics of marine fog occurring off the California coast were obtained. Observations have shown that marine fog may form at sea off the West Coast in the following manner: (1) by the lowering of a stratus base to the surface; (2) by the advection of cold nearly saturated air over warmer water; (3) by formation in coastal valleys and advection onto protected bays via land breeze drainage; (4) associated with low-level mesoscale convergence and subsequent vertical motions; and (5) in organized patterns of small fog patches occurring at the upwind edge of fog-stratus systems.

While boundary layer exchange processes may be responsible in some instances for triggering fog formation, data are presented which conclusively demonstrate the importance of radiative processes at fog top and dynamic effects, such as mesoscale convergence patterns, in promoting fog development and persistence. Data are also presented which describe the mesoscale organization of fog-stratus systems which frequently occur off the West Coast. These observations show that organized "streets" of fog patches at the upwind edge of fog-stratus systems are responsible for accelerated conditioning of the air mass for more extensive fog formation closer to the coast.

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ACKNOWLEDGMENTS

The authors are indebted to those personnel of the Atmospheric Sciences Section of Calspan who participated in the data acquisition and analysis phases of this study.

We would again like to express our appreciation for the fine cooperation and willing assistance of the staff at the Naval Postgraduate School, particularly to Drs. D. F. Leipper and G. E. Schacher and to Messrs. T. H. Calhoun and J. G. Norton. Special thanks are due to Captain W. Reynolds and the crew (R. Winton, S. Bliss, S. Boyd, T. Mallory, and C. Weatherly) of ACANIA whose willing cooperation and diligent efforts are greatly appreciated. We are particularly appreciative for the efforts of G. E. Schacher and L. May in construction of the bow sampling platform.

Finally, we would like to express our gratitude to Mrs. Joyce Terrano for her swift and accurate typing of this manuscript.

Section 1

INTRODUCTION

For the past three years, Calspan Corporation, under contract from the Naval Air Systems Command, has been engaged in an investigation of the physics of marine fog occurring off the coast of California. The study has been performed jointly with the Naval Postgraduate School (NPS) aboard the NPS oceanographic research vessel ACANIA. Results of the first two years' efforts are summarized in annual summary reports (Mack et al., 1973a and 1974). This report summarizes accomplishments of the third year's efforts in light of knowledge acquired during the previous two years of study.

Briefly, the objectives of this program have been as follows:

- (1) To develop and establish the reliability of shipboard procedures and measurement techniques for characterizing fog occurring at sea;
- (2) To locate and observe areas of fog formation and dissipation;
- (3) To characterize and describe the meteorological and physical features of the fogs; and
- (4) To determine the mechanism(s) responsible for fog formation and dissipation and to synthesize physical models of the fog life cycle.

To date, five field investigations have been conducted off the California coast, and fogs have been observed forming in response to a variety of local influences. At least five distinctly different types of fog have been observed: (1) those which develop as a result of lowering stratus clouds; (2) those which form in coastal valleys and flow out onto protected bays via a land breeze; (3) those which form over patches of warm

water; (4) those associated with mesoscale convergence; and (5) patches forming in an organized manner downwind of areas of cold water. A list of all fogs observed to date on this program is provided in Appendix A.

This year's effort was directed primarily toward obtaining measurements at sea in the upwind edge of marine fogs. To this end, a three-week field investigation was conducted off the coast of northern California during the period 19 August through 5 September 1974. During the period 22-27 August, an extensive fog-stratus developed off the coast and observations were obtained in a variety of fog conditions occurring in the vicinity of Eureka, to a distance of approximately 75 n mi offshore and along the coast to about 100 n mi south of Eureka. A total of 71 hours of observations in fog were accumulated; in excess of 100 fog water samples and 300 drop size spectra were acquired. The cruise track of ACANIA from departure at Eureka (1600 PDT, 22 August) to arrival at Monterey on 28 August is depicted on the navigation chart in Figure 1.

During this period a number of fog types were observed occurring in an organized manner apparently associated with the large scale wind field and the distribution of cold upwelling water along the coastline. These observations, together with knowledge gained in the previous years' studies, have led us to consider the mesoscale phenomena associated with fog. It appears that heat and moisture exchange with the sea surface gradually condition the low level atmosphere for fog formation. Several local phenomena may be responsible for triggering fog in a given location. Once local fog patches occur, radiation from the fog liquid water accelerates air cooling, lifts the inversion base from the surface, and enhances exchange processes across the sea surface, all of which promote more rapid conditioning of the atmosphere for more extensive fog formation. Data from which these conclusions were drawn are presented and discussed in detail in Section 5.

For the first time, at least one fog was shown to be associated with mesoscale convergence and a system of organized vertical motions. Data are presented for this fog which occurred over an area of approximately 700 n mi² between Point Arena and Cape Mendocino (south of Eureka). These data and the importance of organized vertical motion as a mechanism for fog formation and persistence are discussed in Section 3.

Subsequent to the initial ten-day cruise, a four-day period of observation was conducted in Monterey Bay. During the period, data were obtained in three bay fogs which were formed in air flowing into the bay from the Salinas Valley. These data are presented and related to previous measurements of bay fog in Section 4.

Results of studies of all marine fog types observed on this program (i.e., program accomplishments to date) are summarized in Section 2. A summary of fog microphysics data from all fogs analyzed to date is provided in Appendix B.

A brief outline of the principal conclusions derived from this investigation of marine fog and our recommendations to NASC for improving the efficiency and overall quality of the Navy's Marine Fog Investigation are provided in Section 6.

Instrumentation set-up is briefly described in Appendix C.

Section 2

SUMMARY OF MARINE FOG OCCURRENCE OFF THE WEST COAST: AN OVERVIEW

During the course of three years of study of fogs occurring off the coast of California, fog has been observed to form at sea through a variety of mechanisms after the maritime layer has been conditioned by turbulent exchange of heat and moisture with cold underlying water.

(1) Widespread fog has been observed to occur at the surface as a result of the thickening of stratus cloud layers. Radiative cooling at cloud top produces an increase in liquid water and instability within the cloud. Subsequent turbulent transport (and drizzle) of liquid water to below cloud base causes the gradual downward propagation of cloud base.

(2) Local fogs have been observed to form in cool, nearly saturated air advecting over warmer water. Subsequent turbulent exchange and enhanced evaporation from the sea surface lead to mixing of warm, moist surface air with cool, moist air at higher levels and initial condensation in a shallow layer. Radiative cooling of this thin layer lifts the inversion base from the sea surface and further fog development is promoted by radiative cooling and enhanced mixing beneath the locally induced, low-level inversion.

(3) Local fogs have been observed to occur in protected bays in air draining from coastal valleys. The data indicate that these valley fogs flow out onto the bay via nocturnal land breezes and spread out to sea until overcome by prevailing winds offshore. Continued radiation from the fog over the bay and mixing of the cold foggy air with warmer air at sea probably promote additional fog growth.

(4) Widespread fog has been observed associated with low-level, mesoscale convergence patterns induced in the vortices shed downwind of prominent geographical features along the coast. Liquid water is generated

by persistent upward motions and augmented by that generated by radiative cooling at upper levels of the cloud. The excess liquid water produced by radiative processes is carried by return flow to constitute fog at the surface.

(5) The widespread, organized occurrence of local fog patches has been observed at the seaward edge of large scale fog-stratus systems. As air approaches cold upwelling water along the coast, individual fog patches are triggered by boundary-layer exchange processes over discontinuities in sea surface temperature. Radiative cooling of the shallow fogs establishes a local low-level inversion and accelerates modification of the air mass beneath the inversion. Successive fogs farther downwind in the conditioned air mass can grow larger and, in turn, cause a deepening and further conditioning of the air mass, setting the stage for widespread fog formation.

Two features of fog formation have been found to be common to all types of fog observed on this study off the West Coast: (1) the necessity of a capping inversion (either of synoptic scale or locally induced) sufficiently low to permit occurrence of water vapor saturation near the surface; and (2) the influence of long wave radiation to provide sufficient cooling to promote fog growth and persistence. These factors may also have a profound influence on marine fog forming elsewhere or by other mechanisms.

In virtually every case studied, the temperature of the fog was lower than the temperature of the underlying water. Exceptions appear to be limited to cases in which fog advected over patches of very cold water. Exchange of heat from the air to the sea surface, therefore, cannot be the predominant mechanism responsible for the growth and persistence of fog after it has formed off the California coast.

2.1 The Dynamics of Marine Fog Formation

- Fog formation by lowering stratus

The formation of stratus has been observed frequently to precede the occurrence of fog along the California coast (e.g., Mack et al., 1972). This phenomenon in which fog develops as the stratus base propagates to the surface has been reported several times at sea (Mack et al., 1973a) in previous years on this investigation (see Appendix A) and on numerous occasions in coastal studies on shore (e.g., Rogers et al., 1974).

The mechanism postulated to explain the lowering of a stratus deck to produce fog at sea is as follows: Radiative cooling of the stratus deck generates an increase in liquid water content (LWC). Such cooling also increases stability at and immediately above cloud top and causes an unstable lapse to exist within the cloud. With continued cooling the instability must eventually extend to beneath cloud base. As a result, turbulent transfer (and to some extent gravitational settling of drops) causes foggy air to mix with clear air beneath cloud base. In the unsaturated region beneath the cloud, liquid water evaporates to produce a dew point increase and to simultaneously add to the cooling rate at these levels. Thus water from within the cloud is transported to subcloud layers, causing cloud base to propagate downward. (No doubt a small fraction of observed increases in water vapor content in the sub-cloud layer are due to increased net evaporation from the sea as radiation cools the air to a temperature below that of the sea surface.)

Observations have also been obtained throughout the life cycles of stratus clouds which formed at the top of the marine layer. Stratus had formed in response to synoptic scale influences including the height and strength of a capping inversion, upwelling of cold waters along the coast (extending perhaps several hundred miles out to sea), and subsequent cooling of the marine layer by advection over cold coastal waters. At sea, stratus persisted both day and night, but over the coast and within 30 n mi upwind,

the stratus exhibited a diurnal cycle of formation and dissipation. Diurnal variation of the stratus along the coast was attributed to a land-sea breeze mechanism which promoted convergence and vertical motions at upper levels of the marine layer (Neiburger, 1944).

Extensive measurements obtained in 1973 (Mack et al., 1974) indicate that the stratus typically grows to depths of approximately 400 m before sunrise. Similar results had been reported by Leipper as early as 1948, who concluded that fog occurrence from stratus is dependent on the existence of a capping inversion (and hence cloud top) at an altitude no higher than about 400 m above the surface. The observations suggest a limit on the depth over which radiative cooling and turbulent transport can cause downward propagation of cloud base over California coastal waters. (This feature, of course, must be related to the temperature and dew point distribution below cloud base.) A similar dependence on a maximum inversion height of about 400 m has been established for all marine fogs both previously and subsequently observed along the California coast by these authors.

- Fog formation over warm patches of water

Fog has been observed on several occasions to form when cold, nearly saturated air advects from cold to warmer water. The mechanisms responsible for fog formation and persistence in this situation have been postulated as follows: As cool air next to the surface encounters warmer water, increased instability and turbulent exchange and enhanced evaporation from the sea results in a thin layer of saturated air and initial condensation. Radiation from this very thin fog layer immediately produces a local, very shallow and extremely steep inversion. Continued advection over increasingly warmer water produces more vigorous mixing (augmenting that caused by radiational cooling at fog top) beneath the local inversion and the fog grows in depth in the downwind direction.

Two mechanisms have been considered for the vertical growth of those fogs with downwind distance. One possibility is that because of the extreme instability beneath the fog top, vertical circulations are initiated, and each upward moving parcel of air penetrates the inversion by a small amount and mixes with the warmer, almost saturated air above to produce condensation at slightly higher levels. A second possibility is that clear, almost saturated air approaching the fog wedge from the upwind direction is forced upward by the local inversion and thus cools adiabatically until condensation occurs at levels immediately above the initial inversion. Radiation from this level moves the inversion upward.

There is no doubt that once condensation begins radiative cooling of the fog plays the dominant role in maintaining turbulent exchange within the fog layer, intensifying the inversion at fog top and generating liquid water, thereby promoting development and persistence of the fog (Mack et al., 1973a and 1974).

- Fog formation in protected bays

By far the most frequently encountered (for logistical reasons) fog type to date on this program has been what we have termed "bay" fogs (eleven listed in Appendix A). Although they occur in air of mixed continental/marine origin, these fogs nevertheless pose a substantial threat to navigation in heavily travelled coastal areas. Commonly, these fogs form in air flowing out of coastal valleys into protected bays under the influence of a land breeze. Typically, bay fogs may persist for upwards of four hours, extend over 20 to 100 mi², and are among the most dense observed on this investigation. A maximum inversion height of about 400 m appears from our data to be a necessary condition for formation of this fog type (Mack et al., 1974).

- Fog formation associated with low-level convergence

During the current investigation, a fourth fog type was observed in which low-level mesoscale convergence and subsequent vertical motions, along with radiative cooling, were responsible for fog formation and persistence. The physical model postulated to explain the occurrence of this fog is simplified as follows: liquid water is produced aloft by adiabatic cooling brought about by persistent upward air motions and is augmented by liquid water generated by radiative cooling at upper levels. The excess liquid water produced by radiative processes is then carried to the surface by return flow (and to some extent by gravitational settling) to constitute fog at the surface. The data and analyses from which this hypothesis was drawn are discussed in greater detail in Section 3.

The convergence pattern and system of organized vertical motions responsible for the fog studied in detail were associated with a vortex shed from Cape Mendocino. Photographs from meteorological satellites show that under appropriate wind flow, vortices frequently occur downwind of most of the major points along the West Coast. If it can be shown that fog, and not cloud, is well correlated with the occurrence of such vortices, then satellite information when combined with appropriate synoptic data (e.g., wind direction, inversion height, etc.) can provide an important tool for forecasting fog near coastlines.

- Mesoscale organization of fog-stratus systems off the West Coast

Additional observations obtained during the current investigation, together with knowledge acquired on previous studies, have led us to consider a mesoscale concept of fog formation along the West Coast. Satellite photographs show that fog-stratus systems frequently form and persist for days over thousands of square miles in that region. During the past year's investigation, data were obtained from three crosswind traverses through such a system.

In the current study, individual fog patches (sometimes <0.5 n mi wide, only several miles long and always oriented with the wind) were observed at the seaward edge of the system. Immediately downwind similar but progressively larger patches (with dimensions of perhaps up to 5 x 20 n mi) existed within otherwise clear air. One fog patch studied in detail was -9 n mi long, associated with a local area of cold water and appeared to persist over the cold water for a period of at least 2.5 hr while the ambient wind caused approximately 35 n mi of air to pass through the fog.

Even farther downwind (and closer to the coast), it appeared that individual fogs became so large that adjacent patches merged to produce a band of continuous obscuration. Several miles closer to land the fog lifted from the surface producing a wide band of stratus which persisted, with occasional breaks, toward the coast. Within 15 to 20 n mi from the coast, fog was again found at the surface, apparently oriented along and associated with the coastline. (These observations are discussed in detail in Section 5.) Satellite photographs of the area suggest that the sequence described above is characteristic of many of the widespread fog-stratus systems that occur off the West Coast.

While only limited data from one fog-stratus system are available, a preliminary physical model of a mesoscale concept of fog formation is developed as follows: Far at sea air flowing coastward encounters cooler water and undergoes a gradual cooling which conditions the air for fog formation. Eventually local fogs are triggered by boundary layer heat exchange over "pockets" of cold or warm water. Radiation from the tops of these shallow fog patches establishes a local inversion and promotes local low-level instabilities which enhance exchange of heat and moisture between the air and sea. The presence of the cold fog represents a sink for moisture evaporating from the sea and therefore further enhances net evaporation. These upwind fog patches, however, are too small to be stable so that dynamic effects quickly cause dissipation, and the associated evaporation promotes further cooling of the air aloft. The combined results of these phenomena are accelerated

cooling of the lowest layer of air which transfers the inversion base from the surface to a slightly elevated level and accelerated addition of moisture to the air mass beneath the low-level inversion. The processes can provide accelerated conditioning of the air mass for more significant fog formation.

Upon reaching the next surface water temperature discontinuity, a new fog forms in the preconditioned air mass and consequently can grow larger and to greater depths and persists longer than the first fog. Thus, the accelerated conditioning of the air mass is even greater, and the inversion base is moved to still higher levels. As the unstable layer beneath the inversion deepens in the downwind direction, vertical motions become better organized to form bands of near continuous fog and stratus. Return flow must be responsible for breaks commonly observed in the stratus farther downwind.

Because of the complexity of the system and existence of data from only three cross sections of one system, the analysis is still preliminary in nature and cannot be extended beyond this point. The importance of the observation is that a mechanism has been identified which appears to indicate that small patches of fog which are triggered by any of a variety of mechanisms (identified earlier) can, by their presence, accelerate the conditioning of an air mass for more extensive fog formation.

Perhaps of equal significance is the fact that satellite photographs for the period of observation show that small fog patches along the upwind (seaward) edge of large fog-stratus systems are observable from current meteorological satellites. With further verification of these patches as fog (and not stratus), detection of these features on satellite photographs would provide a method for determining fog presence many miles at sea.

Section 3

THE IMPORTANCE OF ORGANIZED VERTICAL MOTIONS IN COASTAL FOG

It was concluded more than half a century ago by Taylor (1917) that cooling of an air mass by diffusion of heat to a cold subsurface could not of itself be responsible for the formation of deep fog. Yet until recently, numerical modeling of coastal fog off the West Coast was based entirely on that process. Only after it was demonstrated on this study (Mack et al., 1973a), that radiation controlled the temperature distribution of some coastal fogs was that phenomenon incorporated in the models.

In this section, data are presented which conclusively demonstrate that, while boundary layer heat exchange is important in establishing the conditions under which fog forms, that mechanism cannot be responsible for the growth and persistence of at least some coastal fogs. Furthermore, these data show that a system of organized vertical air motions exist in some fogs which, along with radiational cooling, can explain the initial supersaturation, as well as the growth and persistence of the fog. These conclusions are drawn from analysis of data obtained in a coastal fog on 26 and 27 August 1974.

3.1 The Extent and Microphysics of the Fog of 26-27 August 1974

The fog-stratus system which existed prior to and during the fog under discussion is illustrated in the three satellite photographs presented in Figure 2. Although micrometeorological data from an extensive portion of this system are presented in Section 5, the particular fog to be discussed here existed within approximately 15 n mi of the coast over a 65 mile region south of Cape Mendocino. This fog was sampled during a 20-hour period (~1600, 26 August to 1200, 27 August) ending at the approximate time that the last photograph in Figure 2 was taken.

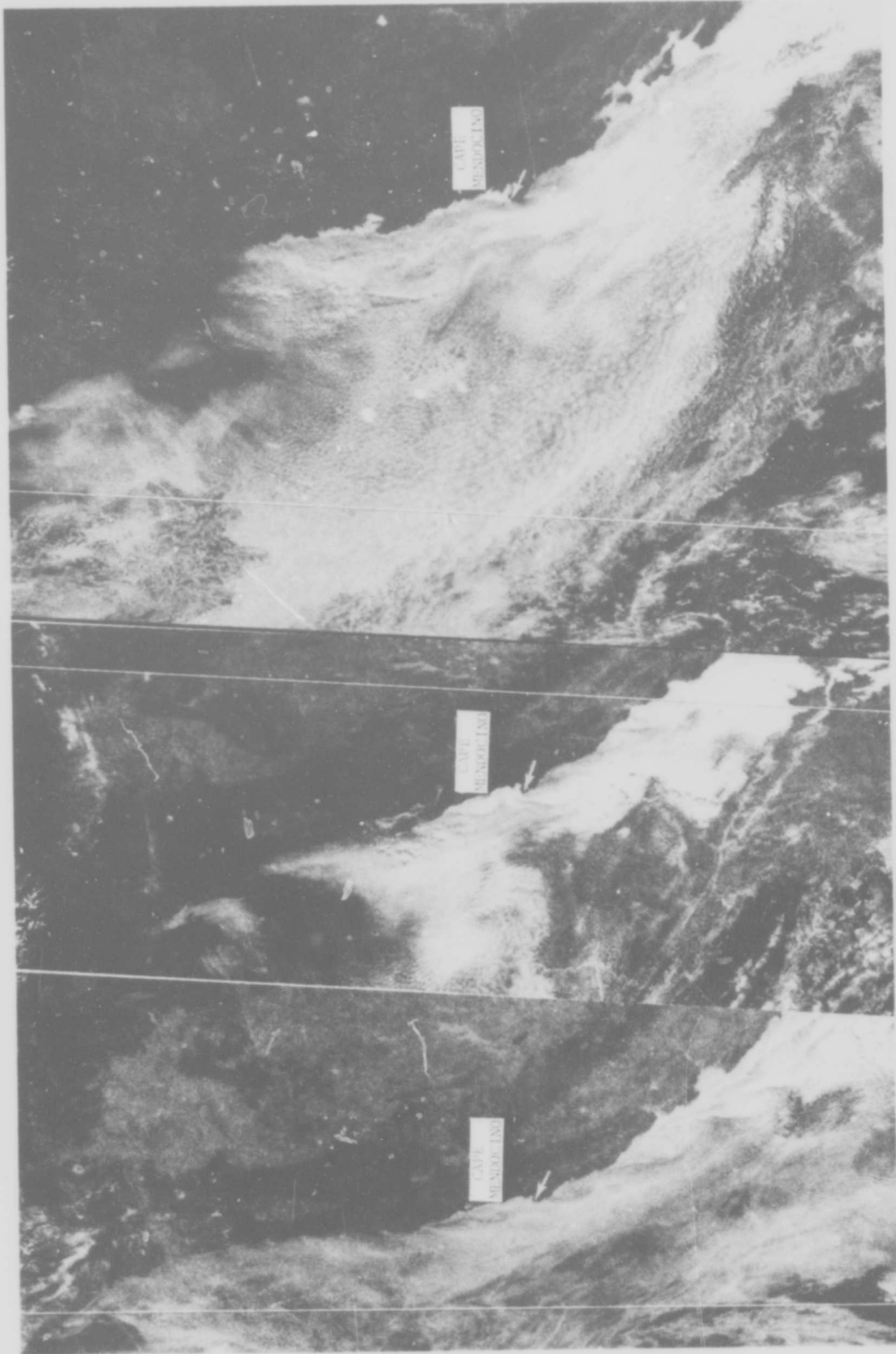


Figure 2 NOAA II SATELLITE PHOTOGRAPHS OF THE CALIFORNIA COASTAL AREA
NEAR MID-DAY ON 25, 26 AND 27 AUGUST 1974

An enlargement of the pertinent region in the photo of 27 August which clearly shows the outline of the fog at that time is presented in Figure 3. This shape should be compared with the shape of the surface-level 1000 m visibility isopleth presented in Figure 4 which was derived from ACANIA data. From the similarity of the shape at noon on 27 August and that determined during the previous 20 hours of surface observations, it is apparent that the fog existed in a quasi-steady state during the experimental period. The satellite photographs of 25 and 26 August indicate that the conclusion may be extended with somewhat less validity to a 48-hour period. It is this conclusion which provides justification for treating the data acquired over a 20-hour period as synoptic in the analysis which follows.

Figure 5 shows the distribution of surface water temperature obtained from the ACANIA data. Quite obviously the position of the outer edge of the fog is correlated with the 11° to 12°C isotherm, with fog existing over colder water and clear air over warmer water.

Figure 6 presents visibility isopleths within the fog and 20 m height wind data obtained at discrete locations where the ship was stopped specifically to acquire these data. A visibility minimum of approximately 100 m existed within the upwind (northern) third of the fog and visibility gradually improved in the southerly direction.

Drop size distributions measured during the 20-hour interval are presented in Figure 7. These data were combined with simultaneous visibility data (summarized in Figure 6) to provide estimates of fog liquid water content (LWC) and drop concentration which are presented in Figures 8 and 9, respectively. Obviously the relative drop-size distribution did not vary drastically through the fog. Variations of turbidity and LWC from maximum in the northern portions of the fog to minimum in the southern portions were due primarily to changes in drop concentration. This was, no doubt, due in part to the coalescence of some droplets to form the drizzle observed throughout substantial portions of the ship's track.



Figure 3 AN ENLARGEMENT OF THE AREA AROUND CAPE MENDOCINO AT 1020 PDT FROM THE NOAA II PHOTOGRAPH FOR 27 AUGUST 1974

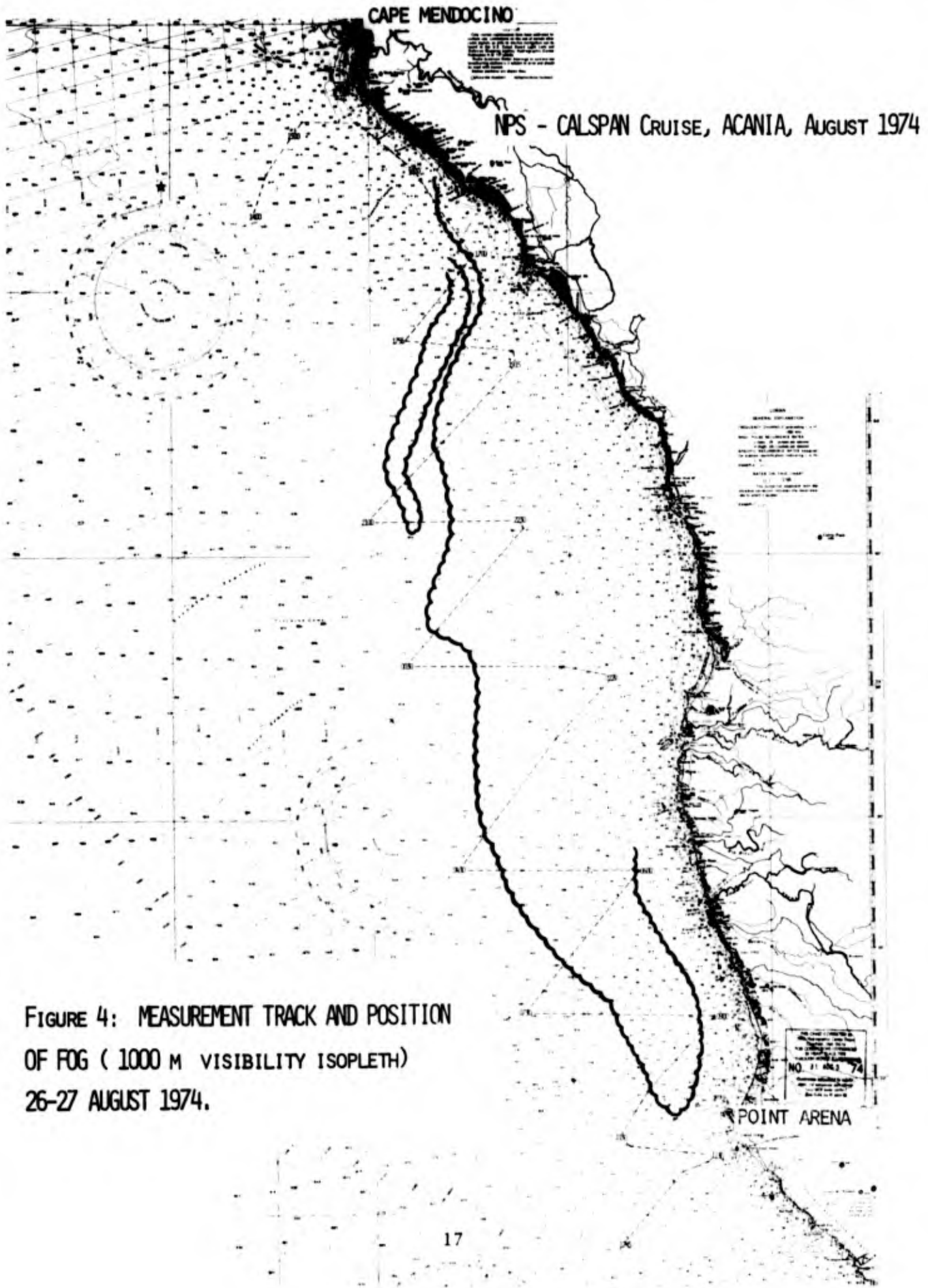


FIGURE 4: MEASUREMENT TRACK AND POSITION OF FOG (1000 M VISIBILITY ISOPLETH) 26-27 AUGUST 1974.

NPS - CALSPAN CRUISE, ACANIA, AUGUST 1974

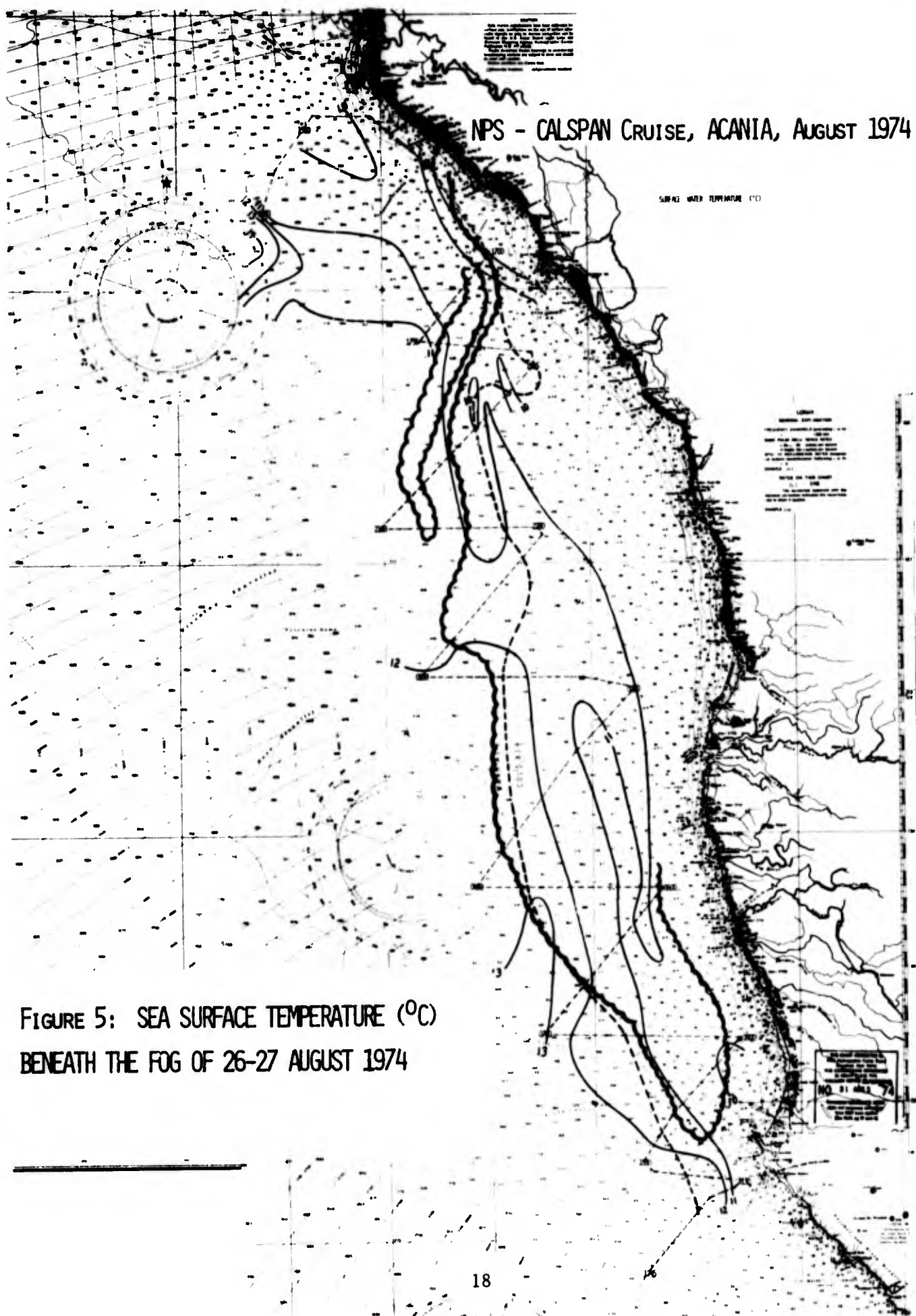


FIGURE 5: SEA SURFACE TEMPERATURE (°C)
BENEATH THE FOG OF 26-27 AUGUST 1974

NPS - CALSPAN CRUISE, ACANIA, AUGUST 1974

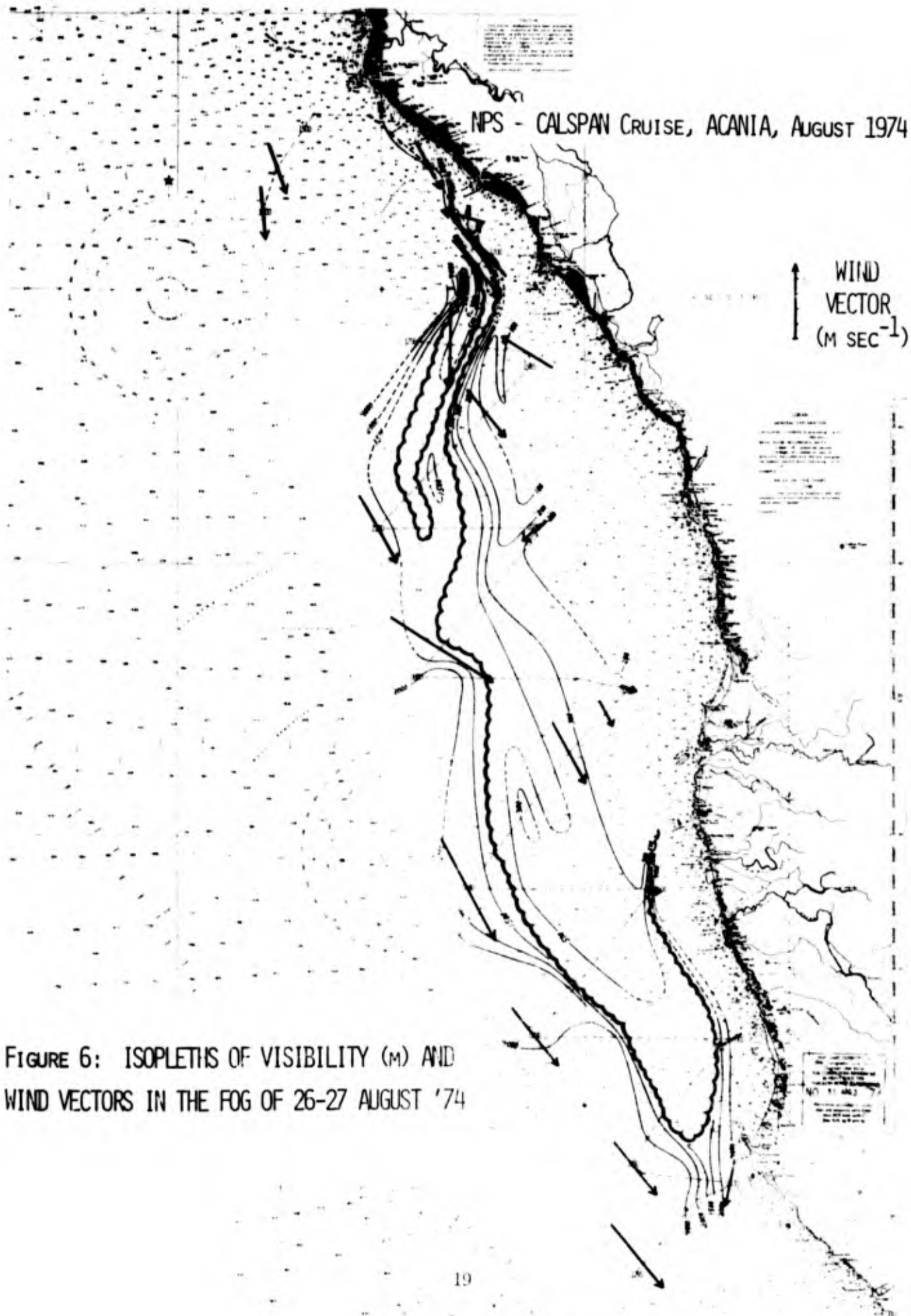


FIGURE 6: ISOPLETHS OF VISIBILITY (M) AND WIND VECTORS IN THE FOG OF 26-27 AUGUST '74

NPS - CALSPAN CRUISE, ACANIA, AUGUST 1974

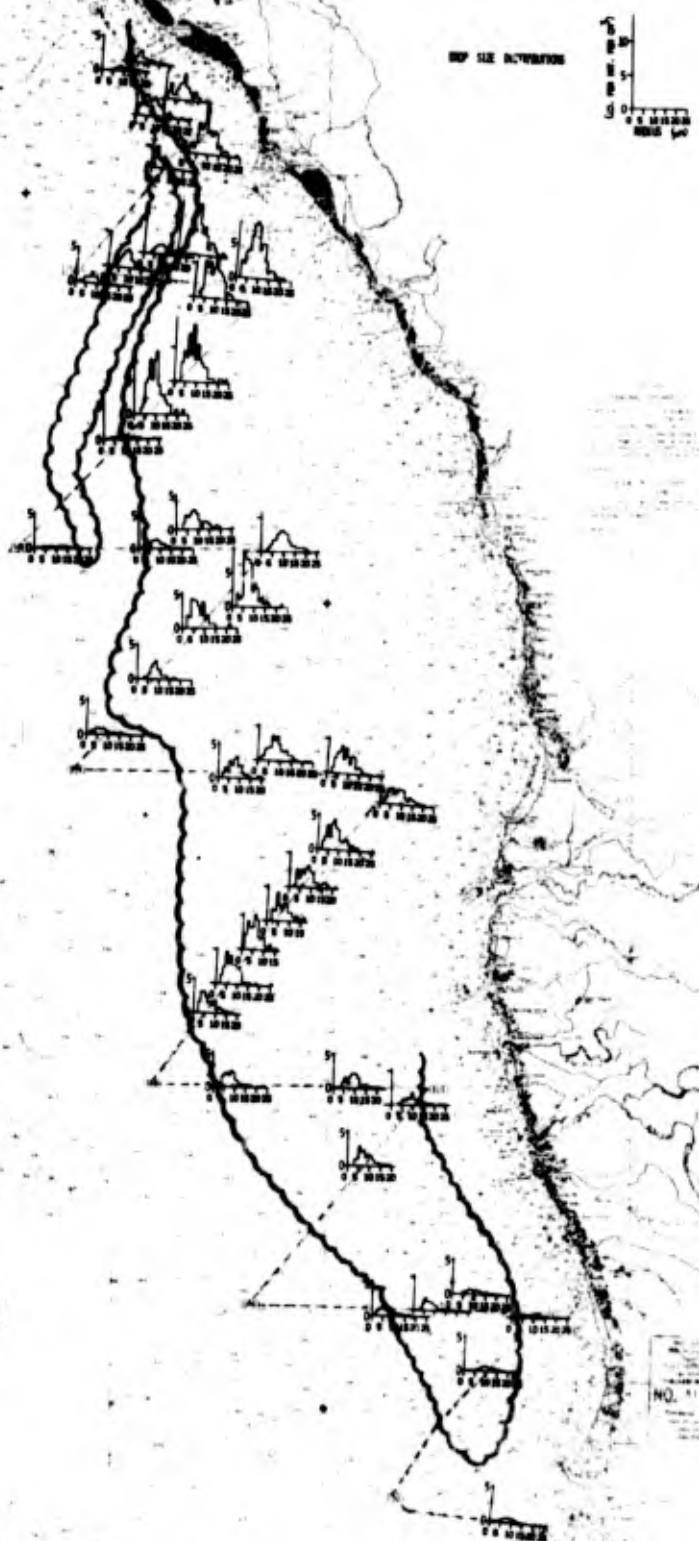


FIGURE 7: DROP SIZE DISTRIBUTIONS IN THE FOG OF 26 - 27 AUGUST 1974

NPS - CALSPAN CRUISE, ACANIA, AUGUST 1974

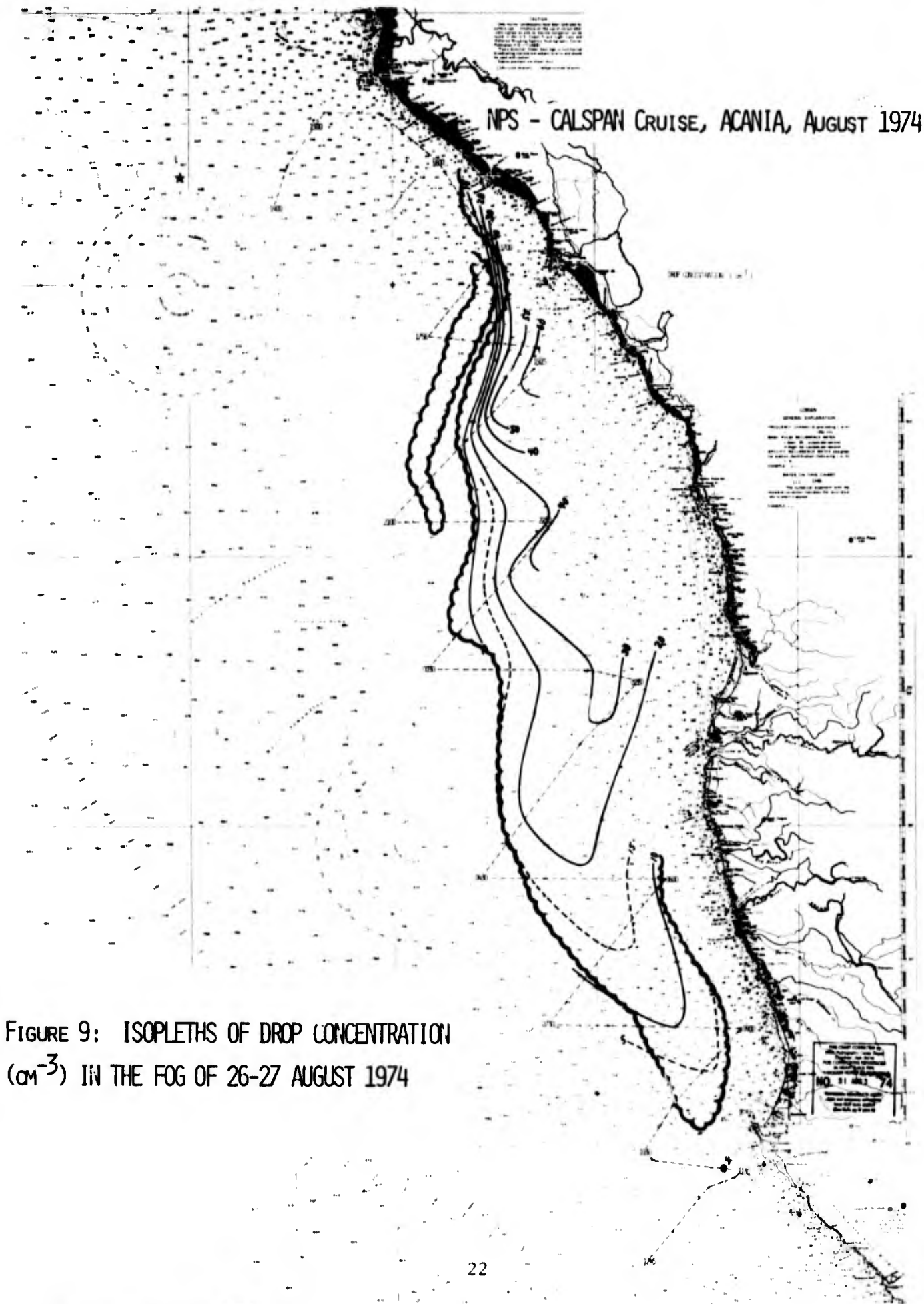


FIGURE 9: ISOPLETHS OF DROP CONCENTRATION
(cm^{-3}) IN THE FOG OF 26-27 AUGUST 1974



Samples of fog water were also obtained throughout the areal extent of the fog. As was the case for all the fogs observed on this cruise, no trends were discernible in the analyzed data. These data have been summarized and may be found, listed as "coastal fog", in Appendix B.

3.2 Low Level Convergence: A Mechanism for Fog Formation and Persistence

The wind vectors in Figure 6 are shown scaled in length with wind speed according to the key presented in the legend. Wind speed and direction along the outer edge of the fog were consistently similar to winds observed from ACANIA throughout the previous 4 to 5 days within an area of 100 n mi north and 100 n mi west of Cape Mendocino, i.e., 3 to 7 m sec⁻¹ from 320 to 340°. Winds within the fog were, in general, substantially lower in magnitude and highly variable in direction. Quite obviously a convergence pattern existed at the 20 m level.

With low level convergence evident even from casual inspection of raw data, an attempt was made to estimate the mean low level divergence from available data. Computations of divergence were made by dividing the experimental region into triangular subregions with vertices defined by locations at which adjacent (in space) wind measurements were available. The vertices of each triangle were then advected with observed wind at that location for an arbitrarily selected time to define a new triangle. The relative change in area of each triangle per unit time constituted the estimate of mean divergence in that initial region. Results are presented in Figure 10.

It is obvious from the computations that a persistent pattern of low level convergence existed within the fog. The most important feature of the computations is that with two exceptions in the obviously chaotic wind pattern at the northern end of the fog, divergence values are consistently negative. The magnitude of computed values, ranging from -0.7×10^{-4} to -2.7×10^{-4} sec⁻¹, should be viewed only as indicative of the scale of mean divergence in the roughly 700 n mi² area throughout the experimental period.

NPS - CALSPAN CRUISE, ACANIA, AUGUST 1974

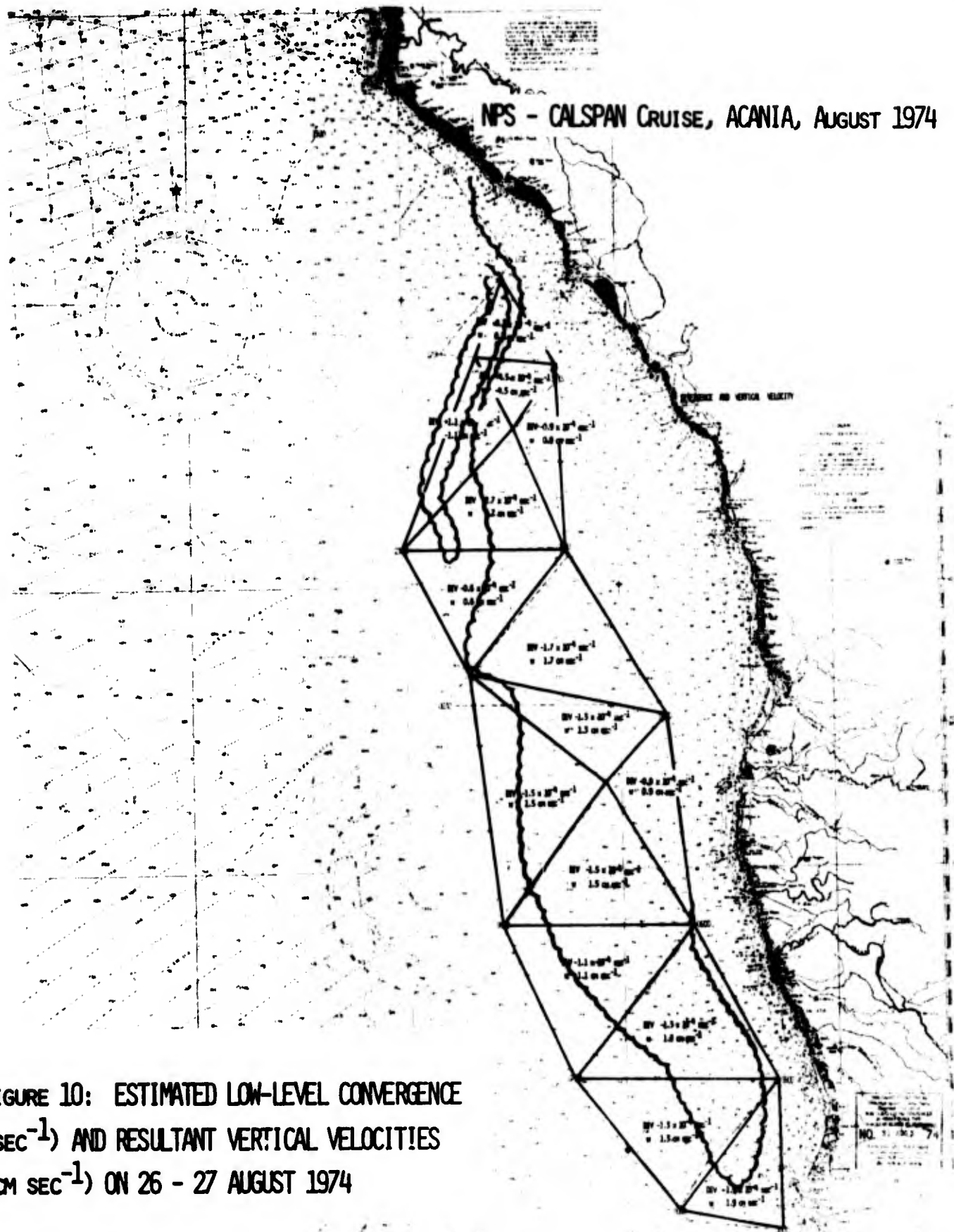


FIGURE 10: ESTIMATED LOW-LEVEL CONVERGENCE (SEC^{-1}) AND RESULTANT VERTICAL VELOCITIES (CM SEC^{-1}) ON 26 - 27 AUGUST 1974



Estimates of mean convergence were used to compute the mean upward velocity of the air after entering near fog base. These estimates, based on the assumption that convergence computed from 20 m winds persisted through the lowest 100 m layer of this 400 m thick fog (estimated from Oakland sounding), are also shown in Figure 10. The data show that mean upward motions of the order of 1 to 2 cm sec⁻¹ existed in the region of fog throughout the measurement period.

Obviously these estimates of mean upward motion are indicative only of net upward motion. Such a persistent pattern of mean flow must be the result of a well-organized system of up- and down-drafts that persisted through the period. It is believed that this system is associated with the well-defined vortex pattern shed from Cape Mendocino and evident in each of the three satellite photographs (Figure 2) taken at the conclusion of and during the day prior to the measurement period.

With the presence of organized up- and downdrafts within the fog, it is necessary to consider the influence of these motions on liquid water. A wet adiabatic expansion of air rising 100 m from an initial temperature of 10°C at sea level will produce a liquid water content at the 100 m level of about 220 mg m⁻³. If it is assumed, therefore, that clear, saturated air enters the fog base and rises wet adiabatically to the 400 m fog top, LWC at the fog top would be about 900 mg m⁻³. However, if this same air descended once again to fog base, wet adiabatic compression would cause the evaporation of exactly the same amount of water, and fog would not exist at the surface.

To explain the observed coastal fog, therefore, some non-adiabatic process must exist in association with these vertical motions. Evidence of such a process exists in the temperature data presented in Figures 11 and 12. Figure 11 shows representative vertical temperature profiles observed below 20 m in the fog. It is apparent from these data that upwind of the fog the air is consistently warmer than the water. These are the conditions necessary

IIPS - CALSPAN CRUISE, ACANIA, AUGUST 1974

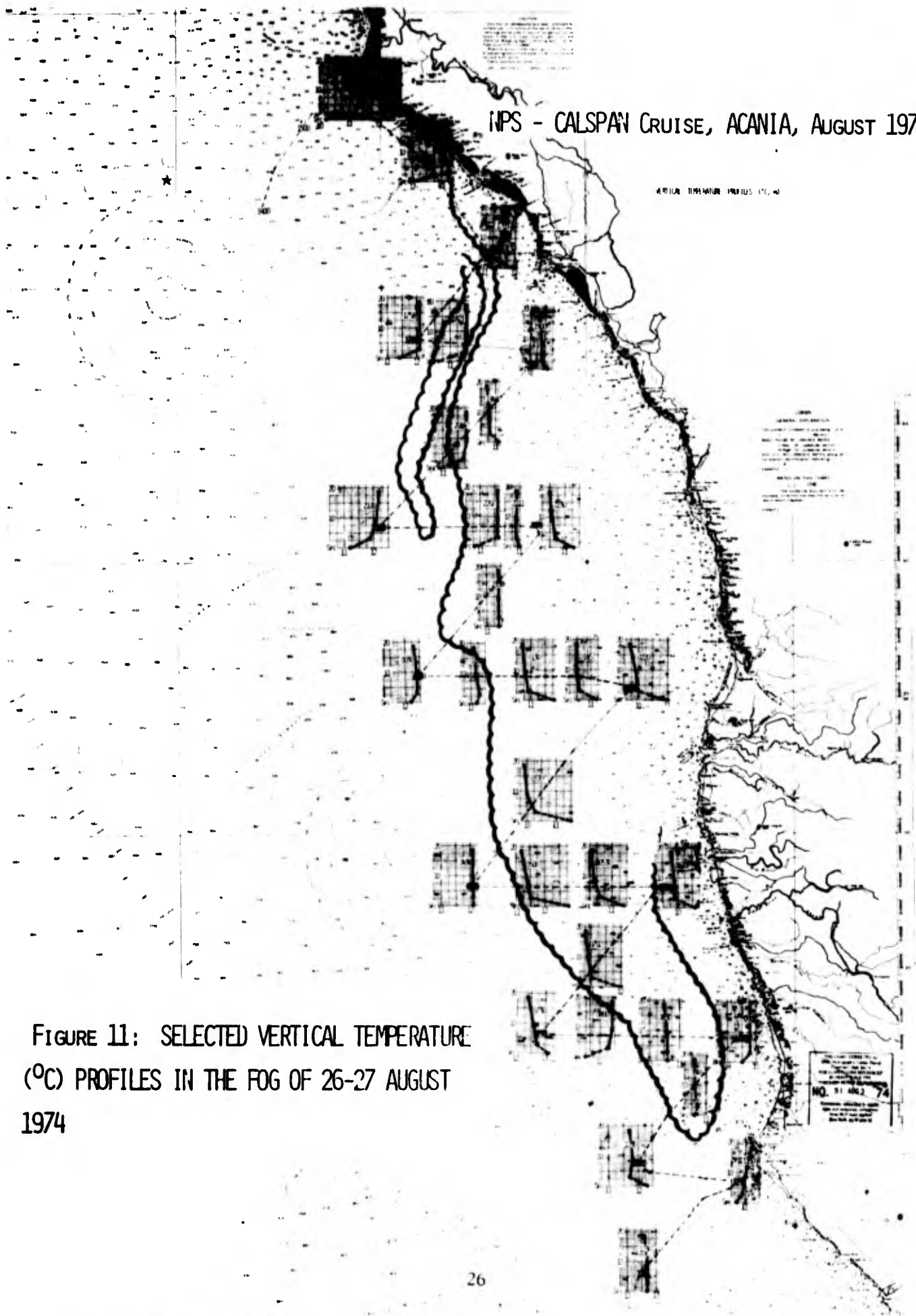


FIGURE 11: SELECTED VERTICAL TEMPERATURE (°C) PROFILES IN THE FOG OF 26-27 AUGUST 1974

NPS - CALSPAN CRUISE, ACANIA, AUGUST 1974

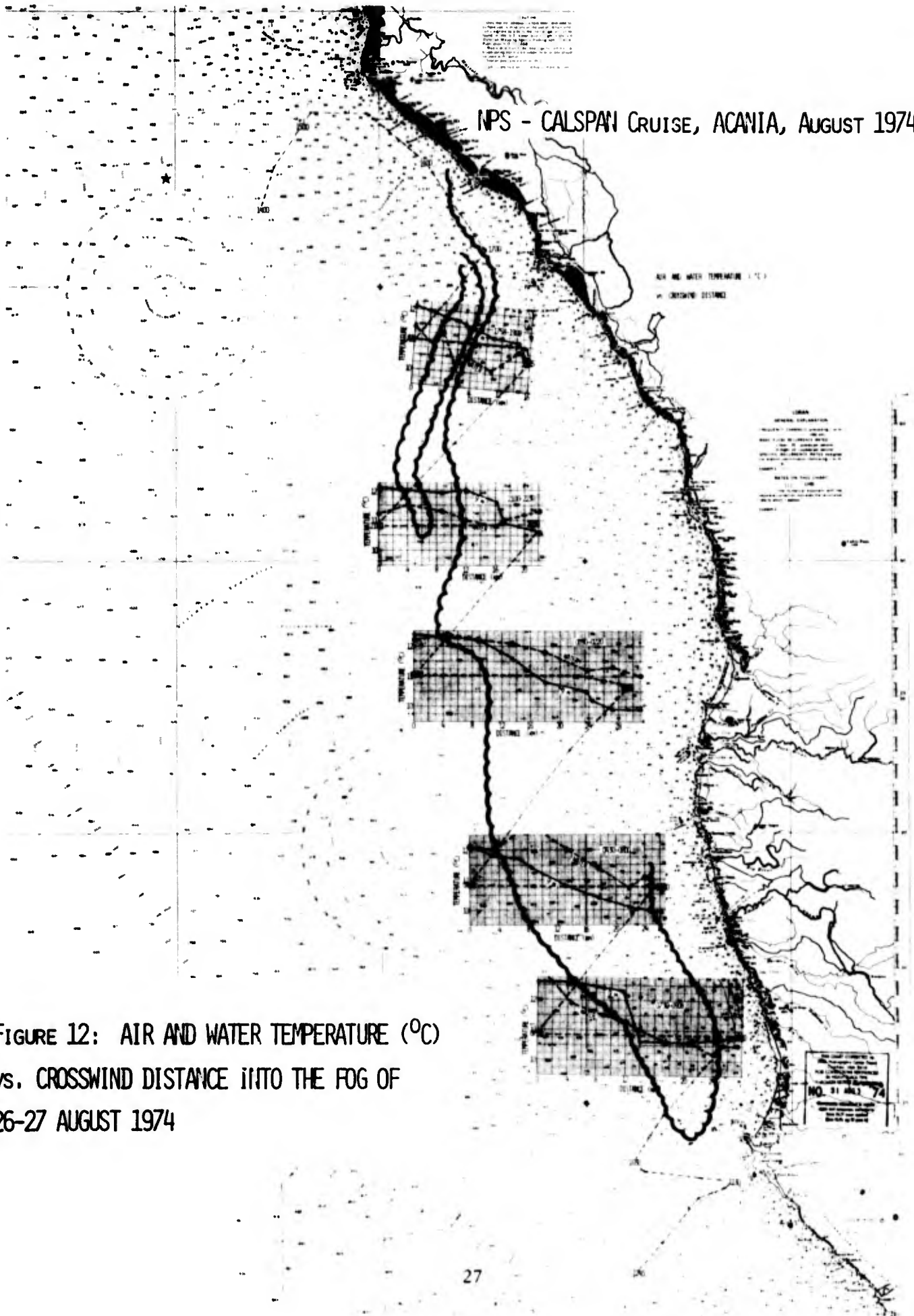


FIGURE 12: AIR AND WATER TEMPERATURE (°C)
vs. CROSSWIND DISTANCE INTO THE FOG OF
26-27 AUGUST 1974



to establish the atmospheric characteristics conducive to fog formation by exchange of heat from the air to the water. Except for the very upwind edge of the fog, however, the air within the fog is always colder than the water. The direction of heat transfer between air and sea is reversed near the fog boundary. Obviously loss of heat to the water cannot account for the growth and persistence of the fog. Equally obvious is that the low level temperature lapse within the fog is conducive to convective activity. It is more easily noted from Figure 12 that the total low level cooling within the fog amounted to 1° to 2°C regardless of the direction of streamlines that existed. Some non-adiabatic process did exist.

Previous studies have shown that during daylight hours the coastal hills east of the fog are warmer than the air within the fogs (Rogers et al., 1974) and that the air in the inversion above the fog is warmer than the fog. In addition, data presented in Figures 11 and 12 show that the air to the west and the water beneath the fog were both warmer than the air within the fog. The observed cooling, therefore, could not have occurred as a result of heat transfer to these surfaces. Therefore, the only mechanism that can account for the observed cooling is radiation from the fog top. With the liquid water contents present (perhaps up to 900 mg m⁻³) resulting from wet adiabatic expansion, direct radiative cooling is limited to the uppermost layers of the fog (Korb and Zdunkowski, 1970). Since cooling occurs only near the fog top but is readily observable at the fog base, this analysis provides direct evidence of strong vertical motion.

The data presented to this point leads to the postulation of the following processes to explain the existence of the fog, including the liquid water at the surface. As air rises through the fog, liquid water is generated by wet adiabatic cooling. Radiation causes substantial cooling at the fog top resulting in an increase in liquid water. With subsequent descent and warming of this air, an amount of liquid water approximately equal to that generated during the ascent is evaporated. The LWC generated by the radiative cooling remains, however, to constitute liquid water at the surface.

Since the only liquid water expected at the surface with this model would be that due to the radiative cooling, the upper limit of LWC at the surface can be estimated simply by noting the amount of cooling of air at the surface. From Figure 12 it is apparent that net cooling at the surface amounted to 1° to 2°C. Assuming initially clear but saturated air at 12°C and no water losses, 1°C cooling produces approximately 600 mg m⁻³ of liquid water. Under the assumption of the model then, with no losses, one should expect between 600 and 1200 mg m⁻³ of liquid water at the surface.*

Observed liquid water content data were presented in Figure 8. Both the mean and the maximum liquid water contents, 130 and 300 mg m⁻³ respectively, are substantially smaller than the upper limit estimated from the model.

Some of the deficiency in liquid water is undoubtedly due to drizzle which occurred throughout much of the observational period. While no measurements of drizzle rate were made on the ACANIA, previous studies (e.g., Mack et al., 1972) in coastal fog on the shore at Vandenberg AFB indicate typical drizzle rates of about 25 g m⁻² hr⁻¹. If this rate had persisted throughout the entire fog and 6 hours were required for an air parcel to move from the northern to southern end of the fog, the total precipitation losses would amount to about 370 mg m⁻³, assuming a 400 m thick fog. This represents only about one-third of the total deficiency estimated on the basis of temperature changes between northern and southern extremities of the fog. Any other air trajectories would cause smaller water depletions due to drizzle.

Some other reason must be responsible for the deficiency of observed LWC as compared with the calculated values presented above. It is readily calculated that the observed LWC would be produced through the observed cooling

* Since air entering at the 100 m level would suffer a net wet adiabatic compression in reaching the surface, these values could be reduced by one-half of 220 mg m⁻³ but, as will be seen, such reduction is of no consequence to the ultimate conclusion.

if the incoming air was characterized by relative humidities between 85 and 95% at the southern and northern extremities respectively. There is no need, therefore, to invoke the assumption that the convergent air at low levels was saturated before entering the fog in order to account for the observed LWC. In view of the fact that the low-level air entering the fog along the northern and western edges was clear, there is no reason to believe that it was saturated.

3.3 Summary

The observed temperature distributions within the fog show that the process of turbulent exchange of heat from the air to the water cannot be responsible for the growth and persistence of fog after its initial formation.

The physical model outlined below is capable of explaining the entire life cycle of the fog in a manner that is consistent with all observed data. This model consists of the following:

1. The interaction of northwest winds with the coastal land mass near Cape Mendocino produces a persistent convergence pattern in low level winds downwind from the Cape. The low level convergence results in a persistent system of organized vertical air motions with net upward flow of the order of 1 to 3 cm sec⁻¹ averaged over the entire area of fog.

2. Upward motion of initially unsaturated, clear air entering the region of fog at its northern extremity produces initial condensation through expansion. Radiation from this liquid water produces additional cooling and increases liquid water content at the fog top. Subsequent warming as cold air descends from fog top to fog base causes evaporation, but the quantity of liquid water generated by radiative cooling remains to constitute the observed liquid water at the surface.

3. Low level ventilation of the fog persists along the entire western edge of the fog and is responsible for net upward flow throughout the foggy area. The continued cooling by radiation at the fog top as this air becomes involved in the organized vertical circulation is responsible for the persistence of the fog at the surface.

The model presented above is based on observations made in one fog at a specific location. Numerous satellite photographs show the existence of similar vortex patterns downwind of many of the points along the Pacific Coast. We suspect that the model has general applicability in such regions.

Since we have generally found that the air in fog very quickly becomes colder than the water over which it forms, we believe that transfer of heat from air to water is seldom, if ever, responsible for growth and persistence of coastal fog. The general features of the model presented above (items 2 and 3) would be effective in fog generation, growth and persistence with any mechanism that stimulates low level convergence, and we suspect that the model may have even wider applicability than to fog events occurring downwind of coastal points. Mechanisms which can stimulate convergence include, among others, local patches of warm water downwind from cold water, frictional effects at the coast and the sea breeze front which is located over water at night. The presence of organized vertical motions in fog-stratus systems evident in satellite photographs (such as presented later in Figure 26) at large distances from coastlines suggests even greater applicability of the basic model concepts.

Section 4

BAY FOG: MARINE FOG FORMATION THROUGH CONTINENTAL INFLUENCES

Because of scheduling requirements, the ACANIA was moored in Monterey Bay between 28 August and 5 September 1974. Limited observations were made at the dock during that period and three additional "bay fogs" were investigated during the final four days of the cruise. For logistical reasons, this type of fog has been one of the most frequently encountered on this research program. In this section, we will describe and discuss the observations made during these four days, which comprised 21 hours of fog data acquisition, including 95 drop samples and 30 fog water samples.

4.1 Observations

While in the harbor, nightly recordings of visibility and some visual observations showed that on the morning of 30 August a considerable reduction in visual range was caused by drizzle from low stratus clouds, and that early on 31 August fog, dense at times, reduced visibility in the Monterey harbor area to 100-200 m; however, due to the ship's immobility on those days, no further data acquisition was attempted.

Upon resumption of the cruise on 1 September, a modified observational procedure was adopted on the basis of previous experience with bay fogs. As Figure 13 (from last year's report) shows, typical bay fog penetrations and crosssections were previously obtained in the central area of the bay. However, since most evidence had tentatively pointed to fog formation and/or transport by land-breeze drainage out of the Salinas Valley, the ACANIA was stationed approximately 2 km from shore near Moss Landing in order to improve chances for witnessing early stages in the evolution of the fog. Initial detection of imminence of fog was by observing obscuration of terrestrial or celestial light sources.

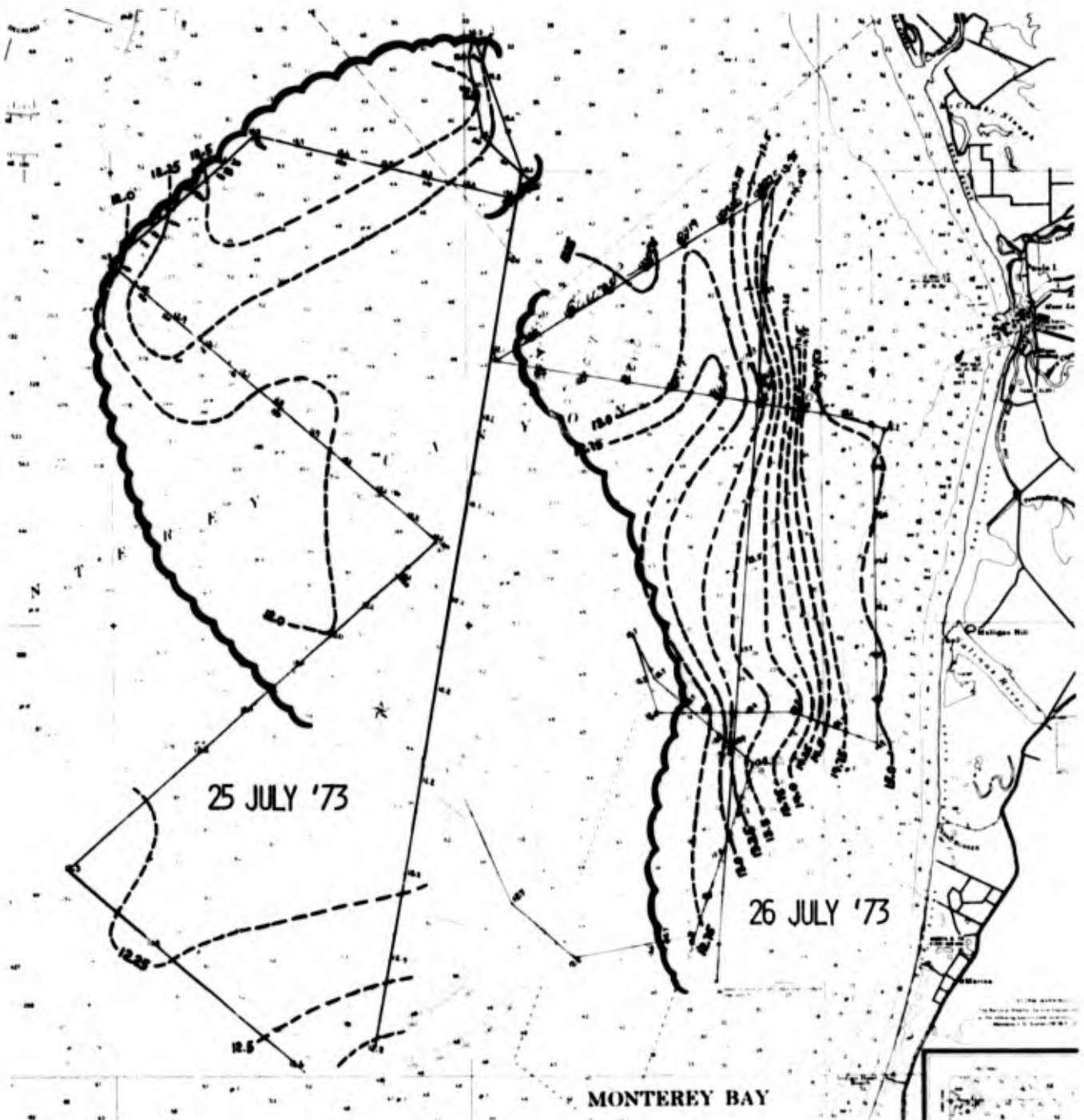


FIGURE 13. THE EXTENT OF BAY FOGS OBSERVED ON 25 AND 26 JULY 1973.

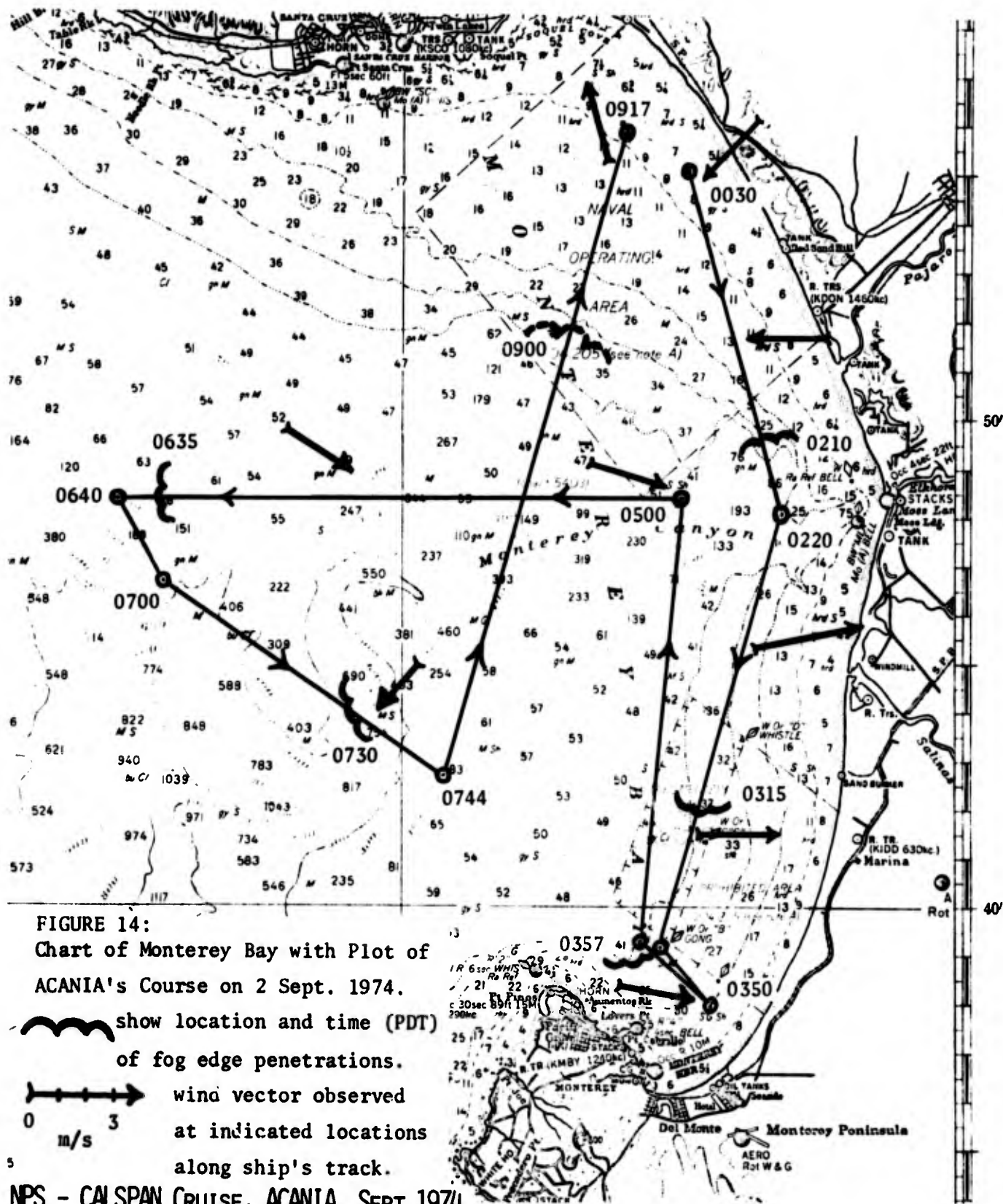
(Dashed lines are isotherms of sea surface temperature.)

NPS - CALSPAN CRUISE, ACANIA, JULY 1973

While approaching the planned position off Moss Landing during the first hour on 1 September, a thin overcast of undetermined altitude had developed. Light easterly winds accompanied a gradual dimming of lights on the power plant smoke stacks at Moss Landing by 0200 and of the moon by about 0300. Appearance of ground level lights indicated haze conditions until 0240 when horizontal visibility 2 km offshore dropped to 500 m, and gradually to 250 m. This fog patch was soon followed by a second one, denser (visibility 150-200 m) and wider (1 hr or about 10 km measured by the wind speed) than before. The wind which had shifted to SE by 0430 was unquestionably draining cold air out of the Salinas Valley. The shallow vertical extent of the fog was evidenced by occasional sightings of the moon. It is interesting to note that the overcast was still present after the fog had left.

By moving in a general downwind direction toward Santa Cruz, the fog was again sampled for 1.5 hrs (150-300 m visibility). Winds near shore were calm. Several km SW of Santa Cruz, while approaching the fog edge, moderate drizzle was noticed for the first time. Sailing further west it was observed that a solid stratus cloud extended about 25 km out to sea but was broken beyond that point.

By late afternoon, the skies over the bay had cleared and remained cloudless until early on 2 September when the ACANIA was again stationed near shore north of Moss Landing in anticipation of another fog situation. Winds were initially from NE, then gradually veered to E while the ship was moving on a SSE course along the shoreline to investigate a suspected obscuration in the vicinity of Moss Landing. About 30 min before actually penetrating the fog at 0210, a thin, low cloud layer was observed overhead moving in the same direction as the surface wind. The position where the fog edge was encountered is marked on the chart in Figure 14, together with the ship's track and additional fog penetrations on that day. The 14 km of fog experienced while moving along the shore toward Monterey consisted of three patches with visibilities of 500 m, 100 m, and 200 m. At the southern edge of the fog (0315), visibility increased abruptly to about 1 km, but a solid overcast, as evidenced by obscuration of the moon, extended southward as far as could be seen.



On the return course, the ACANIA entered the fog area again about 3 km N of Monterey where visibility changed from ~800 m to 250 m. Apparently the fog edge had advected ~6 km southward during the intervening 42 min. Visibility remained quite constant at the low value during the subsequent 15 km northward leg of the track. At a point 28 km W of Moss Landing, the western edge of the fog was reached after sailing through areas with visibilities predominantly 300-150 m and occasional thin spots where the visio-meter indicated 700 or 800 m. Two more points were added to the fog area's delineation by moving SE and then NNE; however, during the last leg of the cruise, visibility improved gradually such that the northern edge was no longer well defined. A further distinction of this last segment was the occurrence of drizzle--almost rain in the southern portion. During the subsequent return to Monterey, visibilities of 2-5 km were recorded and general dissipation of the fog was evident. Periodically-measured winds are also entered in Figure 14, and the question immediately arises, how could this fog be advected from the land out into the bay with winds predominantly from the west? This problem will be addressed later under Section 4.2.

After a day with clear skies over the bay and stratocumulus to the west, ACANIA was again positioned ~3 km off Moss Landing late on 2 September in order to monitor any developments that might lead to renewed fog formation on the following morning. The wind gradually shifted from W at 1800 over S to E at midnight and subsided in speed from about 5 to 2 m sec⁻¹. During the same period, a stratocumulus layer had advanced eastward to the shoreline, and a lower-level cloud mass appeared to slowly approach the coast from the east. While surface visibility remained unimpeded, the marking lights on top of the power plant smoke stacks (about 80 m high) became obscured and mid-level lights dimmed. Within the first hour of 3 September, the light surface winds changed to N and then NW. Continued monitoring of the height to which the smoke stacks were obscured showed that the low cloud layer had lowered to near the ground and then abruptly lifted as winds shifted to northwesterly. Between 0300 and 0430 another wind shift to easterly was again followed by lowering of the stratus for a short duration. Despite a continuing

land breeze until at least 0800, no visibility degradation below the 50 m altitude level was observed. Although no substantial ground level obscuration was detected in the Moss Landing area, it is not certain whether the same conditions prevailed farther south. (In that direction we occasionally noticed faint indications of a low cloud mass.) Since local fog occurrence seemed imminent throughout the night, a move to a different observation point was not considered advantageous.

The situation on the night of 3-4 September very much resembled that of the previous evening except that no clouds were sighted prior to midnight, and that the land breeze, once established around 2100, remained steady between E and SE (at ~ 2 m/s) during the entire night. Soon after midnight, thin, low stratus patches began again to move from land to over the observation position, and a brief obscuration of the stack lights renewed anticipation of fog. Between 0100 and 0230 we noted clear skies except for some thin cirrus overhead and an obscuration of shore lights 10 km to the south. Increased haze and a gradual drop in visibility at about 0300 shortly preceded the total dimming of all lights at Moss Landing. The fog edge advected over the ship at 0325. Shallowness of the fog layer was indicated by the moon remaining brightly visible.

In order to determine if particular changes occurred in the fog while it advected out to sea, its downwind edge area was sampled six times by alternately allowing it to drift over the stationary ship and then sailing downwind out of it. These multiple fog edge probings are shown in Figure 15. The top row of diagrams depicts low level vertical temperature profiles at three positions in the Bay before and after the fog advected over the drifting ship. It is interesting to note that near shore the air cooled more than 1°C just prior to arrival of the fog edge, whereas in subsequent penetrations cooling by about 0.8°C occurred simultaneously with the visibility degradation. Temperatures as a function of the ship's position are shown on the bottom diagram of Figure 15, demonstrating the sharp temperature increase when moving downwind out of the fog. Both temperature plots clearly show that the water

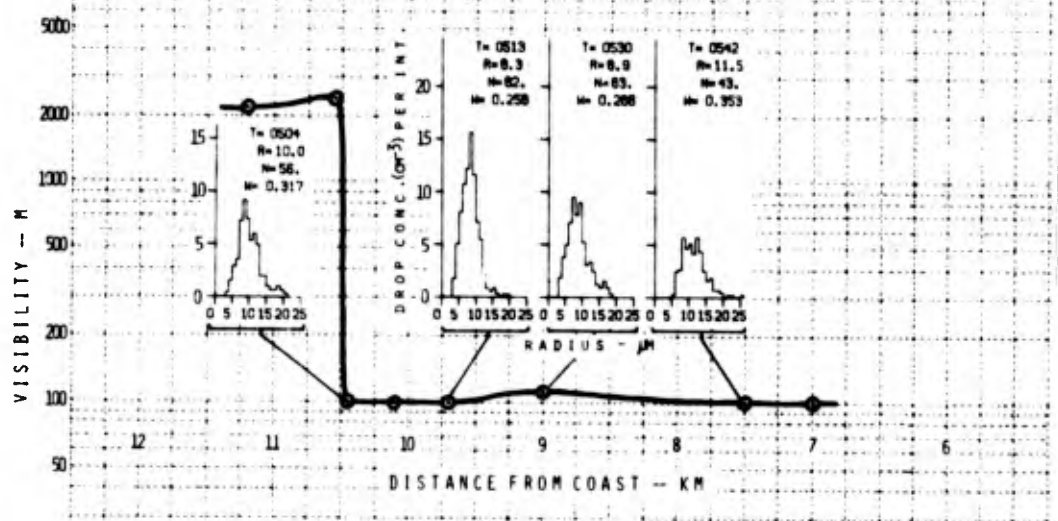
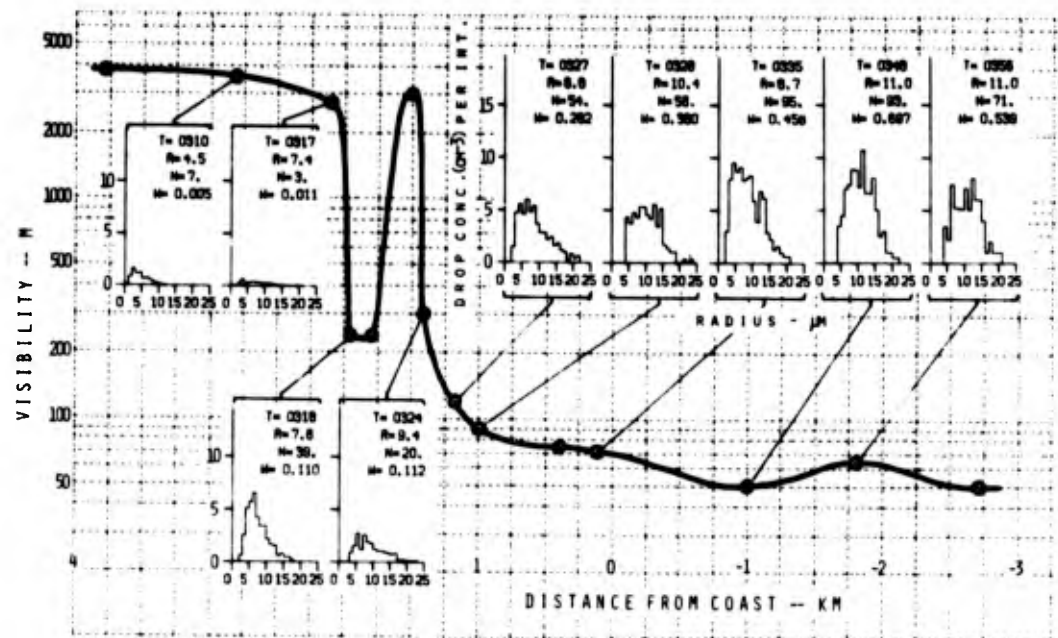
was most of the time more than 1°C warmer than the foggy air and slightly warmer than the air outside the fog.

A comparison of the wind speeds (entered along the ship's track on Figure 15) with the progress of the fog edge seems to indicate that the fog edge did not advance as fast as the winds. On the other hand, it is noteworthy that the winds shifted from NW to SE when the fog edge passed by at 0635. (These data show evidence of strong convergence patterns, but the consequences of possible convergence at the edge of this fog are unknown.) As the fog edge reached 25 km off the coast, its westward motion had slowed down considerably, possibly a result of interaction with prevailing northwesterlies in that region. At 26 km from the coast, just beyond the now-stationary fog edge, the edge of a stratus deck extending to the west could be observed.

On the return trip to the coast, conditions remained virtually unchanged except that the land breeze was gradually dying down to give way to northerly or NW winds which did not appear to affect the structure of the fog.

Around 1030, while heading south along the coast, the initial stages of fog dissipation were noticed: visibility at the surface was fluctuating between 150 m and 2000 m, and an ill-defined southern edge of the fog was encountered about 9 km S of Moss Landing (not shown on chart). While surface visibilities were several km, the sky was covered by a stratus overcast which was broken further to the south in the vicinity of Monterey.

Further details of the multiple penetrations of the fog of 4 September are given in the following diagrams: Figures 16 and 17 depict the visibility changes and drop size spectra in the area of the fog edge. In Figure 16 data are shown for each of the three positions in the Bay (progressively farther to sea from top to bottom) where the fog advected over the drifting ACANIA. Figure 17 shows data obtained while sailing out of the fog edge at three



NPS - CALSPAN CRUISE, ACANIA, SEPT 1974

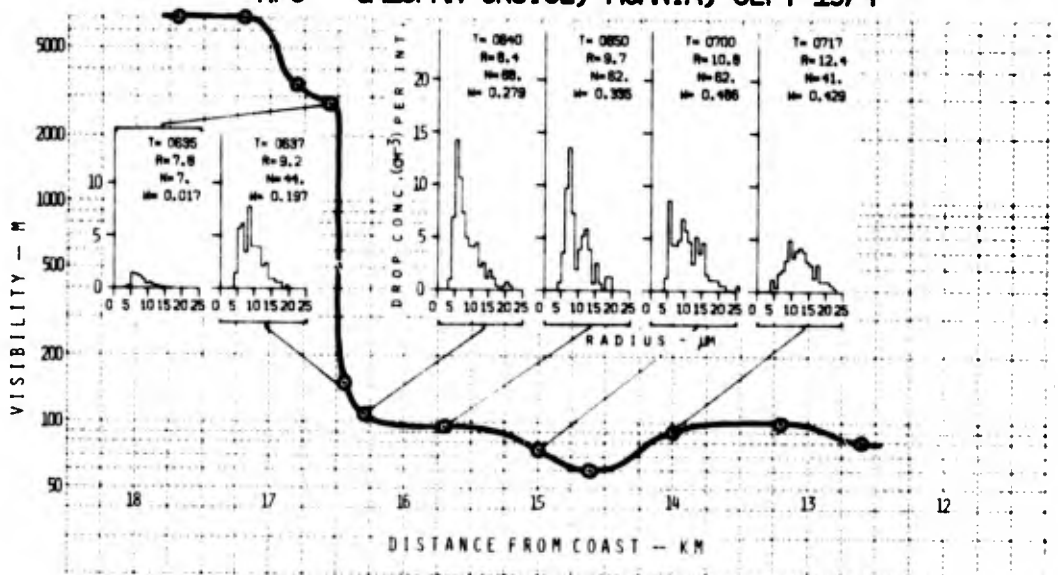
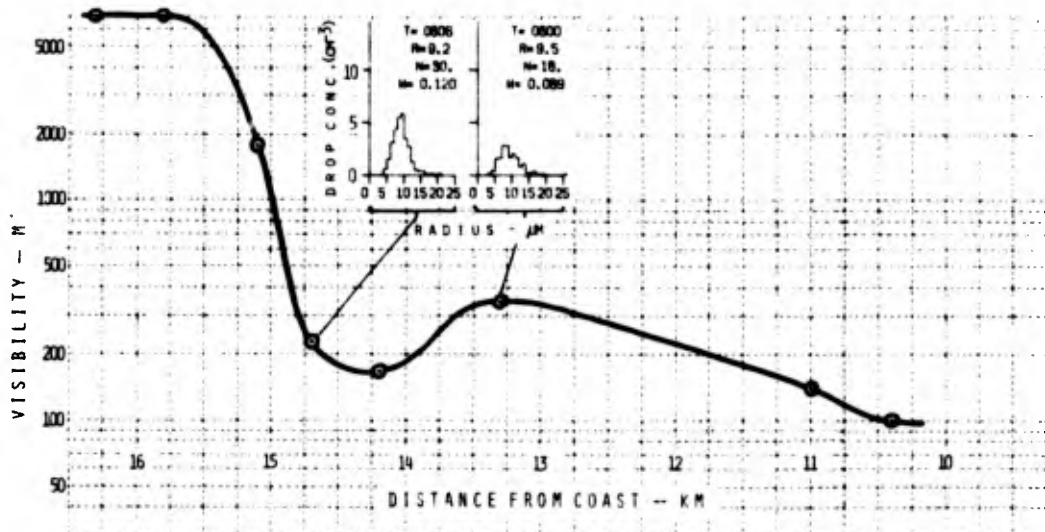
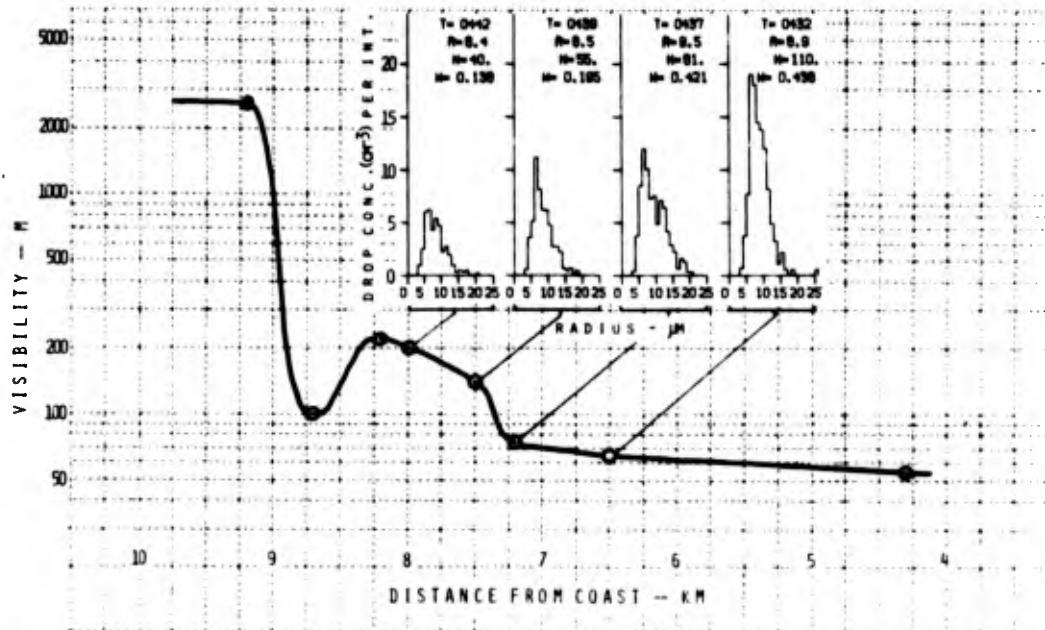


FIGURE 16: 4 SEPT. 1974, MONTEREY BAY -- VISIBILITY AND DROP SIZE DISTRIBUTIONS FOR THE 3 POSITIONS WHERE THE FOG ADVECTED OVER THE DRIFTING SHIP.



NPS - CALSPAN CRUISE, ACANIA, SEPT 1974

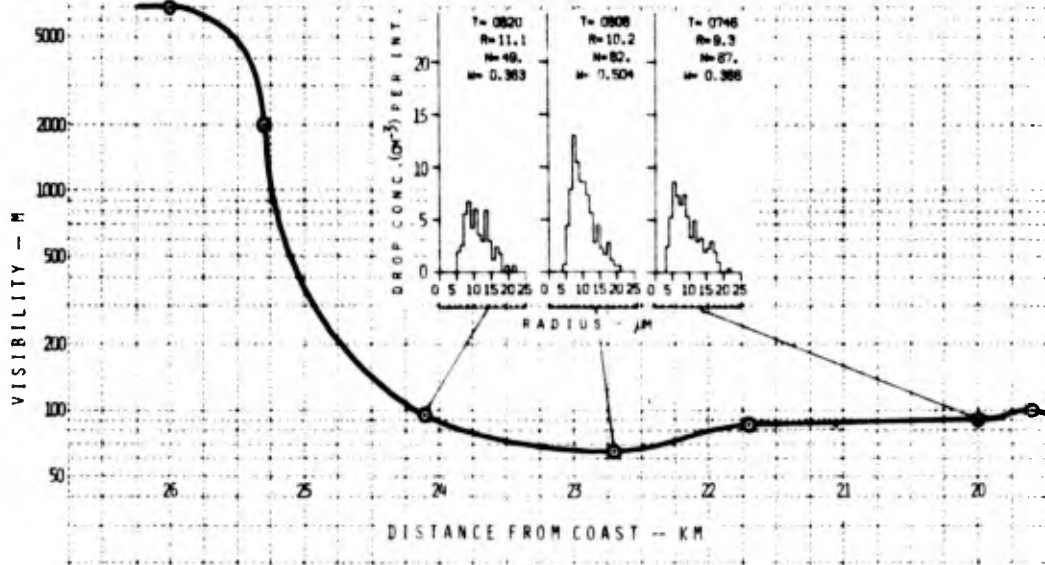


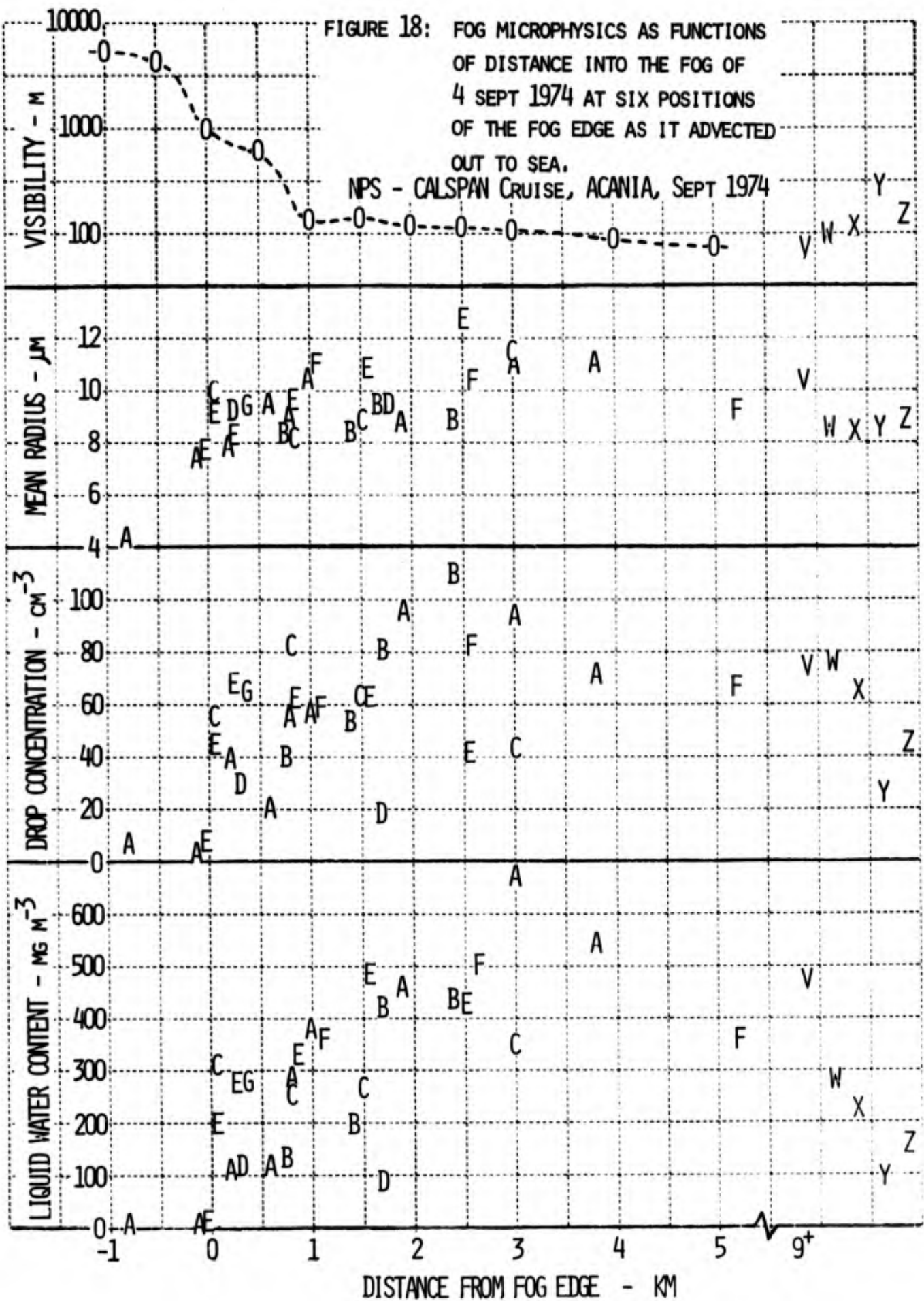
FIGURE 17: 4 SEPT. 1974, MONTEREY BAY -- VISIBILITY AND DROP SIZE DISTRIBUTIONS OBTAINED WHILE SAILING DOWNWIND OUT OF FOG.

positions. (For better comparison, temporal and mixed spatial and temporal variations were transformed into functions of distance from shore by taking into account the speed of the ship and the velocity of the fog edge motion.) Since it was obviously not possible to sample the same parcels of air several times, random variations are to be expected. The visibility recordings confirm the visual observations of the edge having the appearance of a "wall of fog". Only at 25 km from shore was the visibility change more gradual--possibly a first indication of dissipation.

The drop size distributions show no dramatic variations--rather, the expected correlation with visibility. A compilation of the microphysics data is presented in Figure 18 where the letters A-F designate measurements taken during the six consecutive fog edge probings, respectively. All data are shown as functions of distance from the fog edge. (Note that the visibility trace is an average of all six encounters.) Despite the considerable scatter, it is easy to see that mean radius, drop concentration, and liquid water content increased with distance into the fog. One might mention at this point that visual observations (i.e., obscuration of moon) suggested an increase in fog depth with distance into the fog. It is also evident from Figure 18 that no significant correlation exists between these data and distance from the coast (A being nearest, F farthest out). The letters V to Z indicate measurements taken sporadically on the return track to the coast.

Comparison of the average microphysics data obtained in bay fogs on the current study, with those of our previous studies (e.g., Mack et al., 1974), shows good agreement. The data from all bay fogs observed on this program have been averaged and are compared with average data from all marine fog types observed on this program in Appendix B. Likewise, data from chemical analysis of fog water samples are remarkably similar to those of previous bay fog samples. These data, which exhibited no trends as functions of position within the fog, are also summarized in Appendix B.

FIGURE 18: FOG MICROPHYSICS AS FUNCTIONS OF DISTANCE INTO THE FOG OF 4 SEPT 1974 AT SIX POSITIONS OF THE FOG EDGE AS IT ADVECTED OUT TO SEA, NPS - CALSPAN CRUISE, ACANIA, SEPT 1974



4.2 Discussion

Although only the data from the fog of 4 September have been thoroughly analyzed (due to funding limitations), preliminary examination of the raw data from 1-3 September indicates that the fog of the 4th was quite representative of the period. In search of mechanisms responsible for bay fog formation, it is necessary to review last year's findings.

It is unquestioned that these fogs are a diurnal phenomenon associated with a night time land breeze flowing from the Salinas Valley. Offshore breezes were observed in all ten bay fogs sampled to date. The one exception was the case of 2 September 1974 when onshore breezes were observed in the southern part of the fog. However, considering the frequent wind shifts observed and the impossibility of simultaneous measurements at different places with one ship, it is conceivable that on that day the land breeze may have brought fog earlier to the southern portion of the bay. The fog would not have been observed since ACANIA approached the bay near Santa Cruz after completing a seaward probe. It is therefore reasonable to maintain the premise that a land breeze from the Salinas Valley is an essential element for bringing fog into the Bay. Drainage winds may not have been able to overcome the prevailing northwesterlies in the unprotected southern portion of the Bay, thus causing advection of the fog (in that region) back onto shore on 2 September.

In the past bay fogs were encountered around the hours of sunrise and some significance was addressed to this observation. This year's fog appearances at earlier times seem to refute that idea, but the basic fact remains that this fog type appears in the early morning hours and dissipates before noon.

The question whether fog is formed when the offshore flow reaches the water or whether the fog is mainly formed in the Salinas Valley and then drained out into the Bay is difficult to answer on a case-by-case basis.

The fogs were always preceded by clear skies during the evening, thereby allowing considerable radiative cooling of the valley surface. In addition, observations taken very close to shore definitely indicated a low cloud mass moving westward (offshore). Also in support of the latter assumption, satellite photographs for several bay fog occurrences (on file) show a cloud feature clearly associated with the bay fog and extending a considerable distance up the Salinas Valley. Substantial evidence exists, therefore, which indicates that the frequently occurring "bay fog" in Monterey Bay is a radiation-valley fog which advects onto the Bay in the early morning via land-breeze drainage winds. The fog advects out to sea (in the Bay) until it encounters stronger prevailing NW wind and is then stopped or turned to a southeasterly direction by those stronger winds. It also seems probable that as the cold, clear drainage air (that which preceded the onset of fog just off shore on 4 September, for example) mixes with warmer maritime air over the water some enhancement of the fog is produced.

In our previous studies of bay fog, the height of a capping inversion has been found to exert a profound influence on fog occurrence. However, to properly determine such a dependence in an extremely local phenomenon, as are valley circulations, requires local in-situ measurements (vertical temperature soundings). These have not been available and the correlation remains unconfirmed.

Section 5

OBSERVATIONS OF A MESOSCALE ORGANIZATION OF FOG OCCURRENCE OFF THE WEST COAST

Satellite photographs, such as those shown earlier in Figure 2, frequently show that fog-stratus systems form and persist for days off the coast of California. During the period 22-27 August 1974, such a fog-stratus system developed over an extensive area off the coast, and data were acquired on three crosswind traverses through the system extending in one instance to ~65 n mi offshore from Eureka. The data presented in this section were obtained on the three east-west tracks which were conducted from 0520, 23 August to 0200, 25 August and are depicted on the chart in Figure 1.

5.1 Cross Sections through the Fog-Stratus System of 23-25 August 1974

A NOAA II satellite photograph of the fog-stratus system off the California coast at 1046 PDT on 24 August 1974 (mid-point of the third crosswind track) is presented in Figure 19. The satellite photograph shows thick clouds just offshore of Eureka which gradually thinned in the westward direction, giving way to the mottled appearance of individual cells (30-60 n mi offshore) and finally to large, clear areas approximately 70-100 n mi offshore. (The mottled appearance is more clearly evident in regions both north and south of the area studied.)

Surface-level observations from ACANIA revealed similar features and confirmed that much of the cloud was actually fog. At the seaward edge of the system small, shallow, individual fogs (cells in the satellite photograph) were observed which had formed in "streets" at the surface. The cells were elongated along the wind direction and had lifted off the surface downwind of the main fog patch. Farther downwind the individual fogs were deeper (evidenced by the degree of obscuration of the sun) and of increasingly larger dimensions. Ultimately, the individual fogs were so large that adjacent fogs had merged to form a nearly continuous band of obscuration in a line oriented

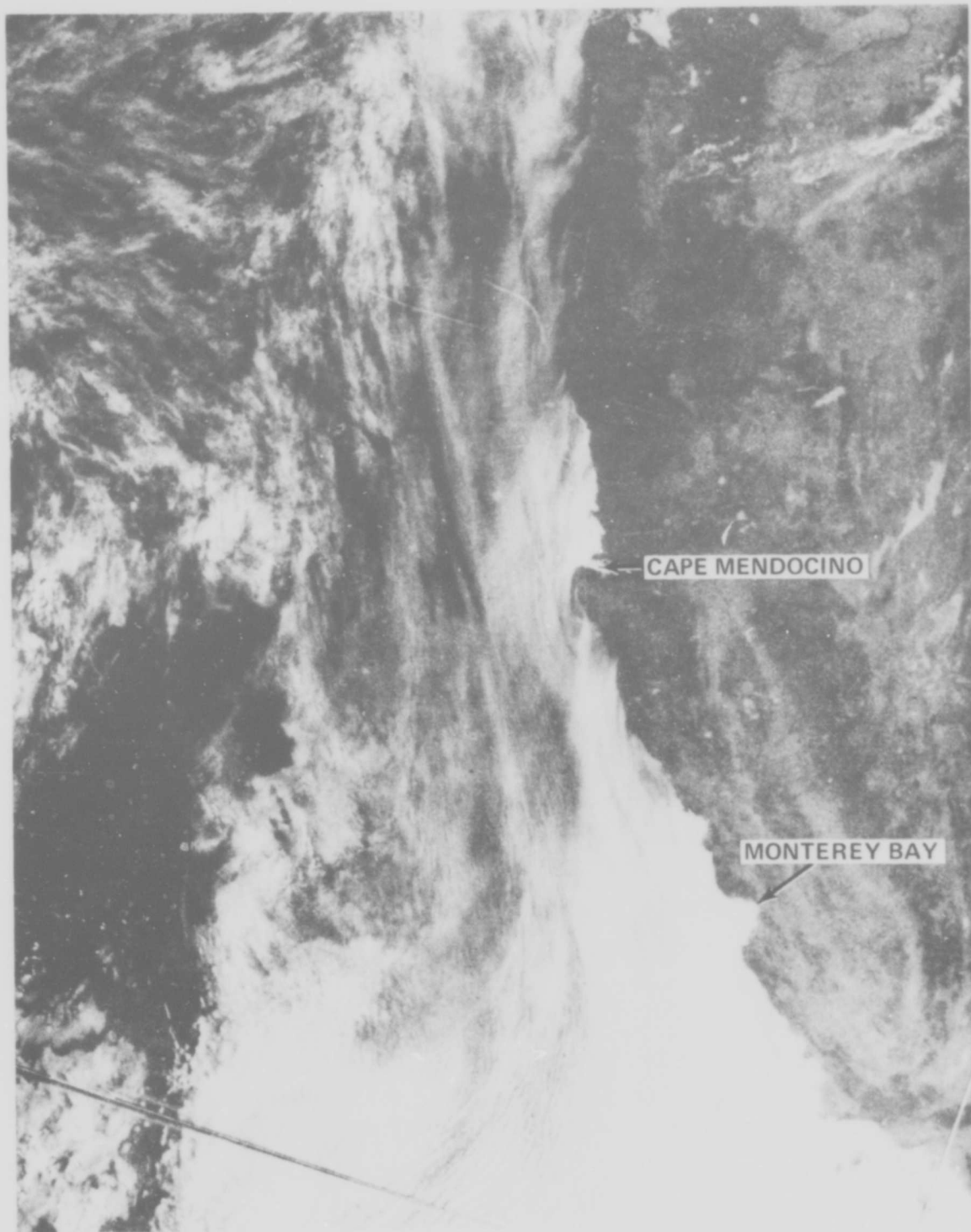


Figure 19 NOAA II SATELLITE PHOTO OF A FOG-STRATUS SYSTEM OFF THE WEST COAST AT 1046 PDT, 24 AUGUST 1974.
(Photo courtesy of D.F. Leipper, Naval Postgraduate School.)

in a direction between that of the prevailing wind and the coastline. Several miles closer to shore the fog lifted from the surface producing a wide band of stratus which persisted, with occasional breaks, toward the coast. Within 15 to 20 n mi from shore, fog (accompanied by drizzle) was again found at the surface, apparently oriented along the coastline.

These observations, along with micrometeorological data obtained during the crosswind probes, are presented in Figures 20A, 20B, and 20C. On Figure 20A, data are shown for the track heading out to sea, 0540-1645, 23 August; on Figure 20B, from 1700, 23 August to 0030, 24 August heading coastward; and on Figure 20C, for the track heading seaward again, 0340-1630, 24 August. For each track visibility, water temperature, air temperature and selected vertical temperature profiles (to 20 m) are plotted as functions of distance out to sea. (For clarity, only the temperature data for the 3 m height are drawn.) The plots are also annotated with time marks, visual observations, and wind measurements where available.

The three cross sections show approximately the same trends in sea surface temperature as a function of distance offshore. Coldest water existed within a few miles of the coast. Average surface temperature then increased consistently with distance offshore out to 60 n mi with the exception of a major band of very cold water, which apparently shifted westward from 24 to 32 n mi offshore between the first and third cross section. Other minor fluctuations of temperature with offshore distance were observed on each of the cross sections, but these were not observed on successive tracks.

Changes in air temperature were at times directly correlated with sea surface temperature. On two of the three tracks, for example, air temperature decreased over the major band of cold water. On the third, air temperature increased over that band. Similarly, air temperature increased slightly in apparent response to warm water 48 miles out on the third cross section (Figure 20C), but no response was observed over the same area during the previous tracks. In fact, air temperature decreased as water temperature

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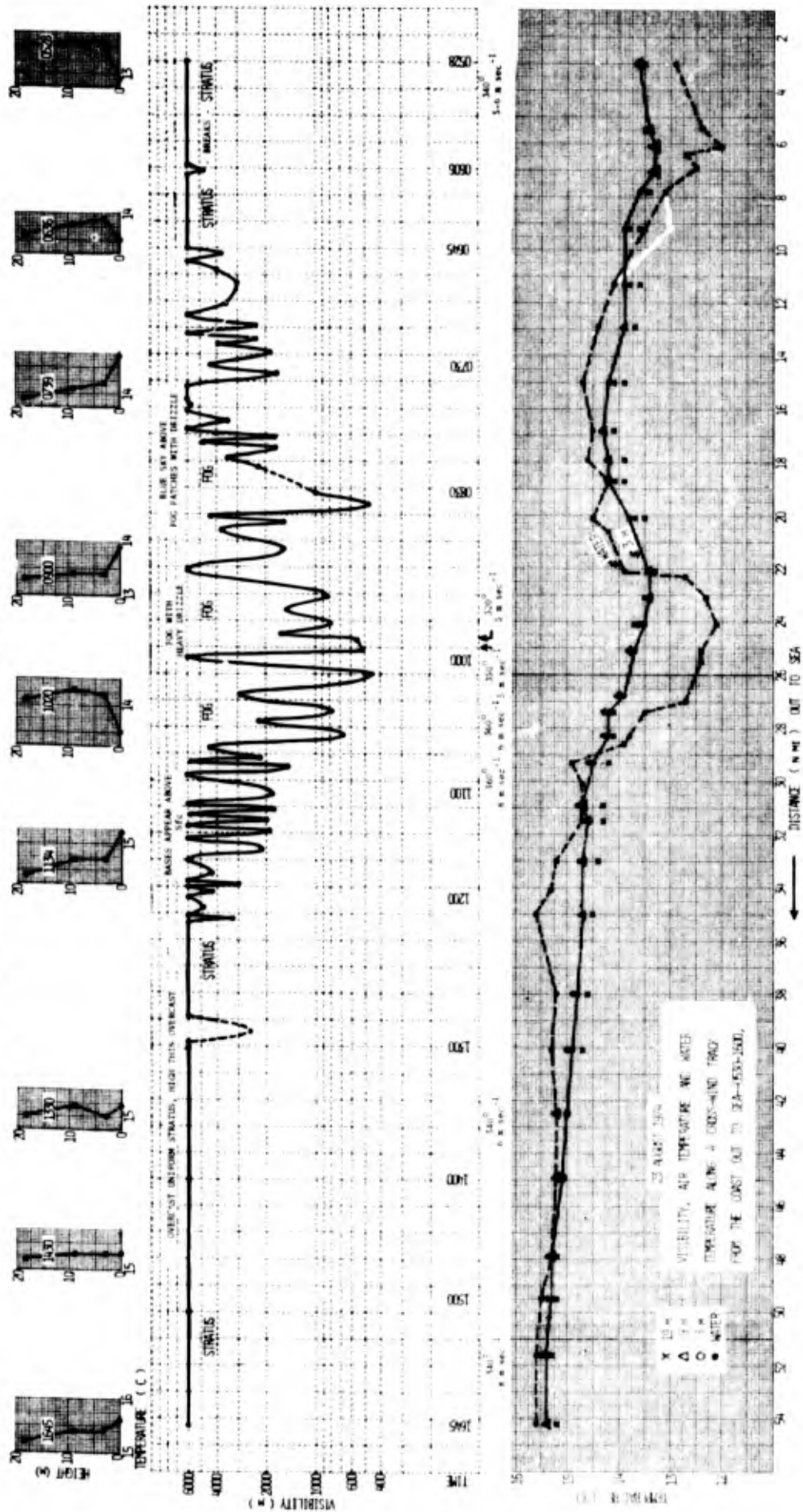


FIGURE 20A: VISIBILITY, AIR TEMPERATURE AND WATER TEMPERATURE ALONG A CROSSWIND TRACK FROM THE COAST OUT TO SEA--0530 - 1600PDT, 23 AUGUST 1974

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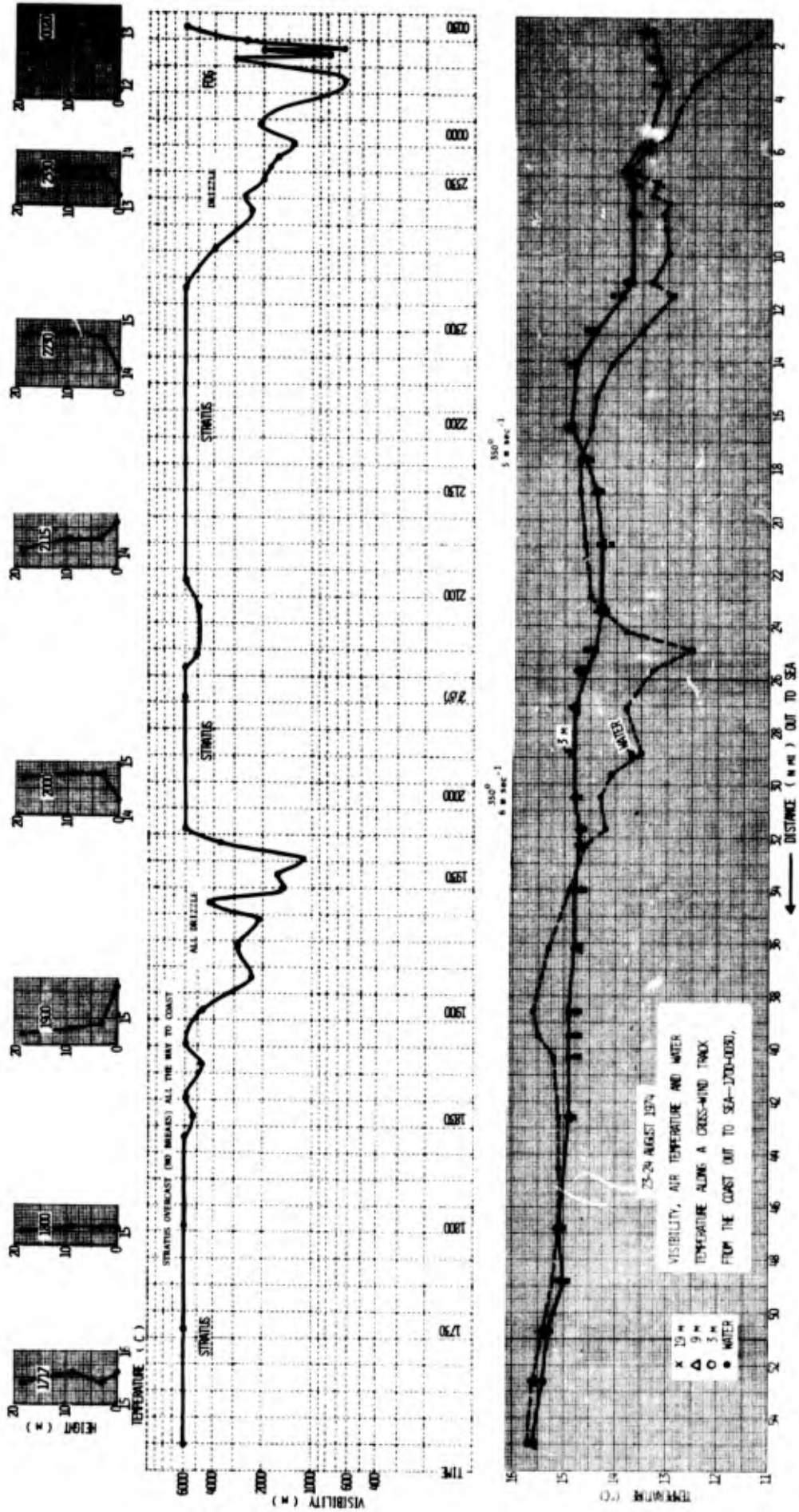


Figure 20b: VISIBILITY, AIR TEMPERATURE AND WATER TEMPERATURE ALONG A CROSSWIND TRACK FROM THE COAST OUT TO SEA--1700 - 0030PDT, 23 - 24 AUGUST 1974

increased in this area on the earlier tracks. This lack of correlation in small scale features is not surprising considering that the tracks were cross wind and that surface temperature distribution upwind of the tracks is unknown. The only conclusion that can be drawn from these data is that average air temperature decreased 2 to 2.5°C within 60 n mi from shore. There appears also to have been a slight cooling trend during the two-day period.

Data presented in Figures 20A, B and C also show that the air temperature along the three tracks was always colder than the sea surface except over the two areas of extreme cold water. The data suggest that either the sea surface was much colder upwind or that radiative processes at fog-cloud top were responsible for cooling of the air mass. Inspection of the vertical temperature profiles clearly indicates that cooling from below (i.e., colder water upwind) could not have been the predominant mechanism. With the exception of fog over the major band of cold water, all data show fog to be colder than the underlying water. Even in those cases of fog over the band of cold water, the 20 m temperature is always colder than the 3 m air temperature. Thus, while evidence exists of heat exchange from the air to cold water in the very low levels, the data show that no significant heat loss to the surface is occurring from as low as 20 m. The superadiabatic lapse above 3 m can only be caused by cooling from above (i.e., radiation from the fog top) with such a vertical temperature distribution. Thus the data demonstrate that transfer of heat from the air to the sea surface could not have been responsible for persistence of the observed fogs. As we have concluded from studies of all fogs observed at sea on this program, the importance of radiative processes to fog development and persistence should not be underestimated.

The visibility data presented in Figures 20A, B and C show that surface level features (fog) evident in the first crosswind probe had completely dissipated by the time of the return track (to the coast) but had reformed in a slightly different pattern by the time of the third crosswind track. The differences in mesoscale features evident from track to track represent temporal variations (possibly diurnal) which did not persist for periods in excess of about 8 hours. That major fog areas were associated with regions

of abruptly colder water is also evident from comparison of the visibility and sea surface temperature data. As before, the two sets of data are not expected to be precisely correlated because the upwind water temperature distribution is not known.

5.2 Fog Patches at the Seaward Edge of a Fog-Stratus System

Numerous individual fog patches were penetrated at the seaward edge of the fog-stratus system during the crosswind probes of 23 and 24 August. The fogs, in a semi-steady state condition, appeared to form at the surface and then lift off the surface at some distance downwind producing a stratus "tail." In general, the fog patches varied in size in the crosswind dimension from 2-5 n mi wide closer to the coast to sometimes <0.5 n mi wide farther to sea near the edge of the system. Blue sky existed between fog patches, even though a very thin overcast was present during the initial track. Several times the outline (vertical profile along the wind direction) of an isolated fog was visible in the distance, giving the distinct appearance sketched at the top of Figure 21.

The variability of the visibility records presented previously in Figure 20 reflects the nature of this fog situation. At times ACANIA cruised through the densest portions of particular fog patches in different stages of their life cycles; at other times, through a fog edge or even under the trailing stratus. As a result, minimum recorded visibilities for individual fogs range (in Figure 20) from several thousand meters to <400 m.

At about 1800 PDT on 24 August near the end of the the third crosswind probe, ACANIA sailed under the trailing stratus from one such fog. Recognizing the situation, the ACANIA was immediately headed upwind into the fog, and the visibility trace shown at the bottom of Figure 21 was recorded. The sketch of the vertical profile at the top of the figure was deduced from visual observations and the visibility record of this particular fog patch.

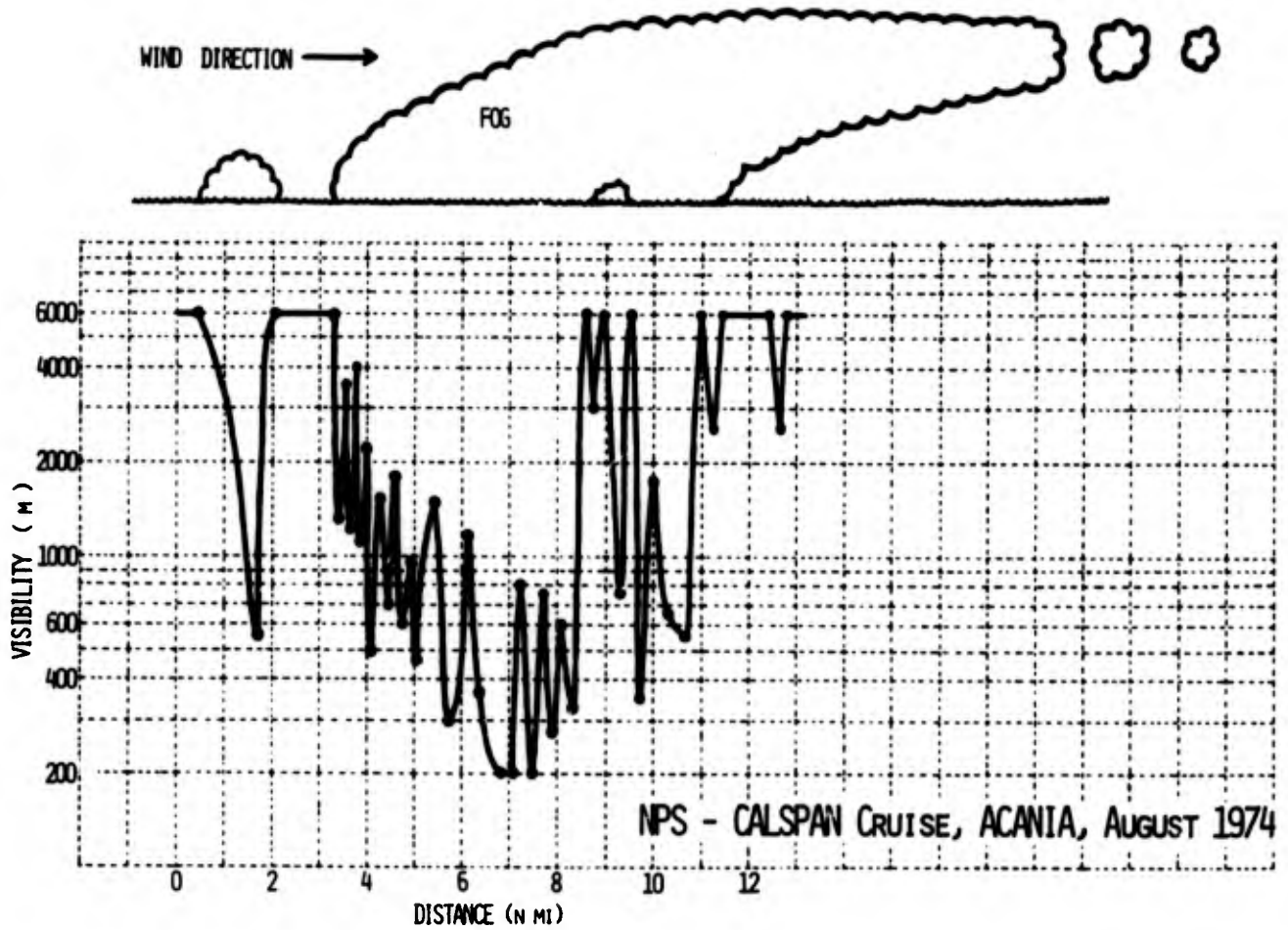


FIGURE 21: VISIBILITY AT 8 M AND SCHEMATIC REPRESENTATION OF THE VERTICAL PROFILE OF A FOG PATCH, 24 AUGUST 1974

Visual observations from the time of initial contact until penetration of the fog was completed were as follows: ACANIA sailed approximately crosswind (heading 270° T) from otherwise clear skies to beneath the trailing, stratus overhang from the fog. After cruising a few moments farther to insure that the ship was closer to the fog centerline, ACANIA was headed upwind (heading 330° T), and fog was encountered at the surface approximately 20 min later at 1831. As the visibility record indicates, visibility fluctuated widely but, in general, degraded to a minimum of 200 m about 4 n mi upwind of initial contact with the fog at the surface. Farther upwind visibility began to improve, and stars became increasingly visible at greater zenith angles. Finally, ACANIA sailed out of the upwind edge at about 2100 PDT; there, skies were as clear (as indicated by the brightness of the moon and stars) as are ever observed. (A spotlight mounted on the bow and used to determine the presence of fog via backscatter below the level of the visibility instrumentation showed that the fog ended as abruptly at the surface as indicated by the visibility record at 8 m.) Slightly farther upwind (at 2132), an additional, small, shallow (stars were visible throughout) fog patch was also encountered.

In an effort to determine the changes in air mass characteristics and the temperature distribution of the sea surface (possibly responsible for fog formation) the cruise was continued in the upwind direction for an additional 11 n mi where another stratus overhang and patchy fog were encountered at 0040 and 0130, respectively. (Data for this second fog upwind were not obtained because an increase in wind speed at that time produced unacceptable levels of sea spray and data acquisition in that direction was terminated.) Air temperature at three levels and surface water temperature, as well as selected vertical profiles, are shown along with the visibility record in Figure 22 for the entire seven-hour portion of the cruise. For clarity, again only temperature data from the 3 m height are drawn because of the similarity of absolute values and rates of change of temperature at all levels. cursory examination of the data presented in Figure 22 reveals two significant features: (1) the position of the fog was correlated with abrupt gradients in sea surface temperature; and (2) the air within the fog

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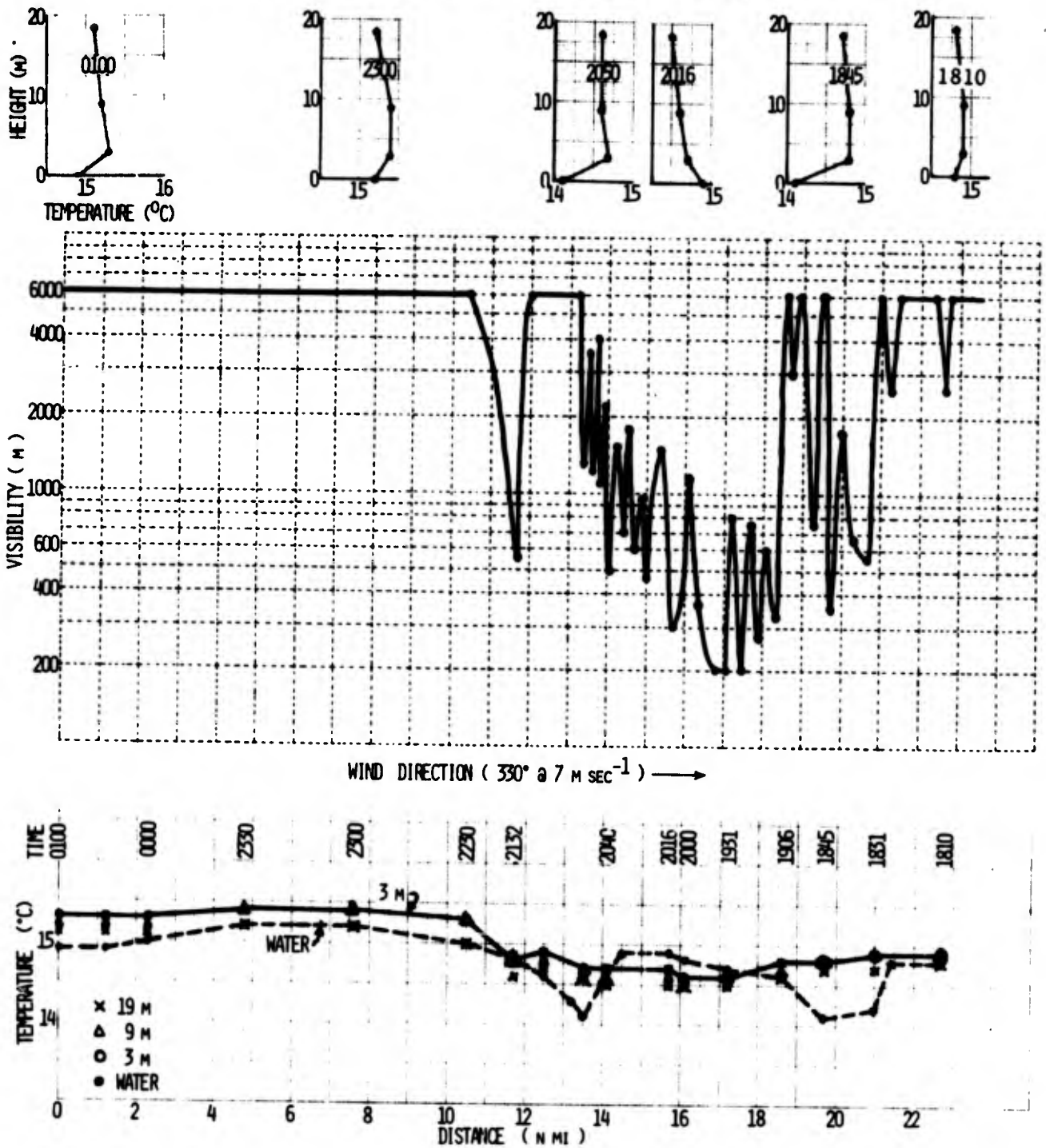


FIGURE 22: VISIBILITY, AIR AND WATER TEMPERATURE AND VERTICAL TEMPERATURE PROFILES IN THE FOG PATCH OF 24 AUGUST 1974

was approximately 0.7°C colder than that upwind of the fog. Similar features have been observed in the past in other marine fogs on this program.

It is apparent from Figure 22 that the most rapid decrease in air temperature occurred within the very small patch of fog (10.5 to 11 n mi in the figure) which was slightly upwind of the first major change in water temperature. The air temperature did not respond to the large temperature variations of the water which existed downwind of this position. In fact, the minor fluctuations in air temperature which did occur seem to be well correlated with the trend of visibility within the fog. Where average fog density increased, air temperature decreased slowly; beyond 17 n mi where the fog began to dissipate, a gradual increase in air temperature occurred. This trend is opposite to that expected from boundary layer exchange with the sea or from latent heat exchange associated with condensation and evaporation.

The cooling that occurred upwind from the 17 n mi point is consistent with continued radiation from the fog. The air warming beyond 17 n mi, which occurred primarily over cold water, seems to be indicative of entrainment of clear air from either side of the fog as the obscuration lifted off of the surface to form the stratus "tail". From existing temperature data there appears to be no other route for heat to enter this area except from the sides.

It is particularly important to note that the air temperature in the clear air downwind from this fog is colder by about 0.5°C than the clear air immediately upwind of the fog patch. The "conditioning" of the air for fog formation, which occurs in clear air only by boundary layer heat exchange with cold underlying water, is accelerated by the presence of the fog patch.

Evidence exists from the data shown in Figure 22 that the air entering this fog patch had been preconditioned by the fog patch observed upstream. Note that the vertical temperature distribution upwind from the 10 n mi point in the figure shows a surface-based inversion in the very lowest levels with a superadiabatic lapse above 3 m. The data show that the low level temperature

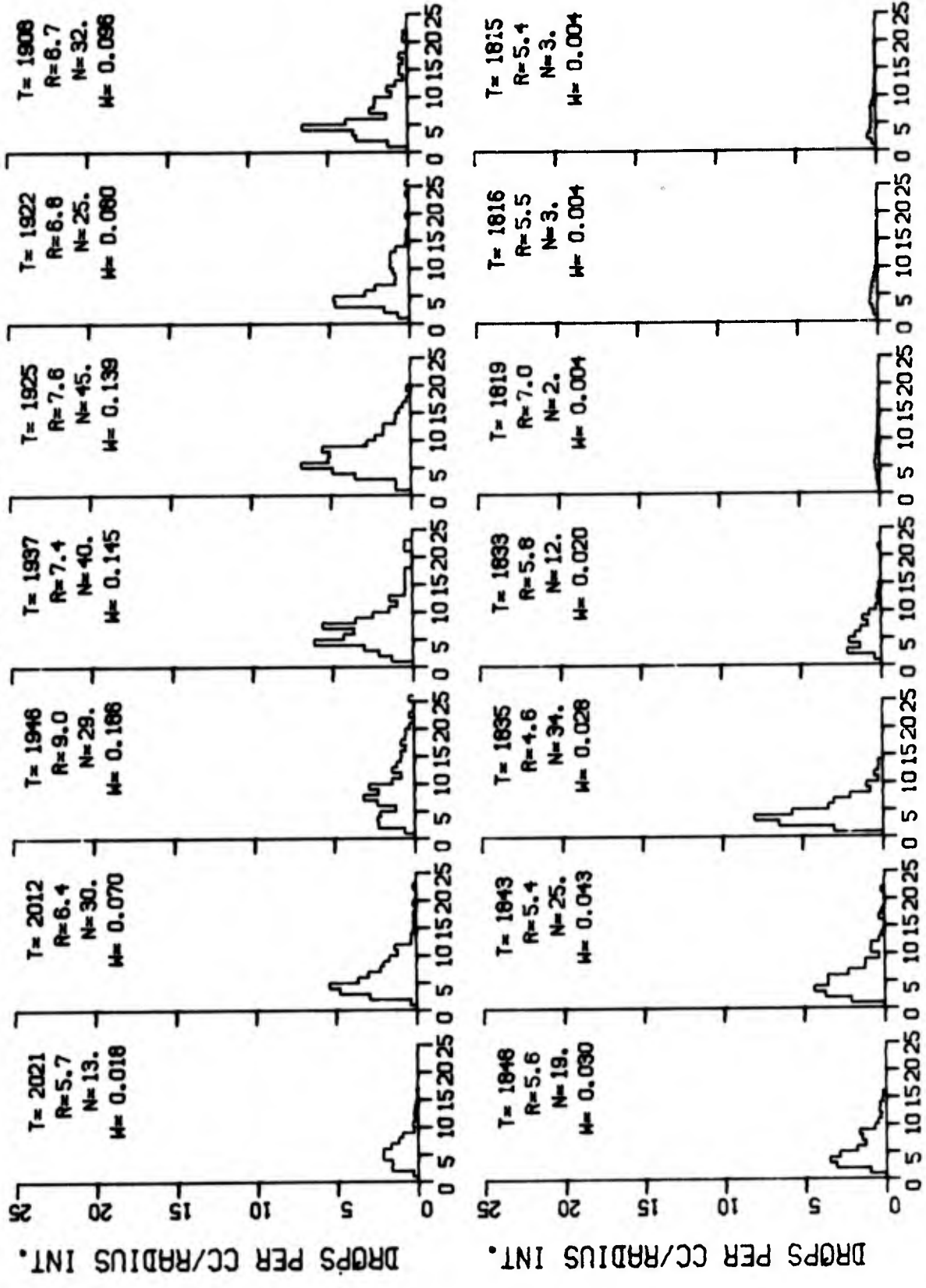
maximum persisted until entering the upwind fog patch. Had heat loss to cold water been the only cooling mechanism operating in the upwind direction, a monotonically inverted lapse would have resulted. Only through cooling from above could the superadiabatic lapse have been produced.

A very important aspect of this fog is that it persisted in a quasi-steady state for at least 2.5 hr (the time it took to sail through it) while nearly 35 n mi of air flowed (at 7 m sec^{-1}) through it. Equally significant is the fact that air flowing out of the downwind edge of the fog was approximately 0.5°C cooler than that entering the fog (see Figure 22). The small fog patch therefore processed a very large volume of air.

The data clearly indicate that the shallow, local fog patches are instrumental in accelerating air mass modification. As air approaching the coast encounters cooler water, local fogs are apparently triggered by boundary layer exchange processes over discontinuities in sea surface temperature. Radiative cooling at upper levels of the shallow fogs establishes a local low-level inversion and promotes local instabilities beneath the inversion which enhance exchange of heat and moisture between the air and sea. The combined results of these phenomena are accelerated cooling of the lowest layer of air, transfer of the inversion base to a slightly elevated level, and addition of moisture to the air mass beneath the low-level inversion. Thus, at the seaward edge of fog-stratus systems, these processes accelerate the conditioning of the air mass for further fog formation.

In addition to the micrometeorological parameters, measurements of drop size distribution were also obtained in this fog patch, and for completeness, these data are presented in Figure 23. In the figure, drop spectra are shown from the upwind edge (starting at the top row, from left to right) to beneath the trailing stratus. For each drop size distribution time (PDT), mean radius (μm), drop concentration (cm^{-3}), and liquid water content (g m^{-3}) are shown. (Drop concentration and liquid water content (LWC) were computed from the normalized drop size distributions and visibility data). These data

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24AUG1974

RADIUS (MICRONS)

FIGURE 23: DROP SIZE DISTRIBUTIONS IN THE FOG PATCH OF 24 AUGUST 1974 FROM THE UPWIND EDGE TO THE DOWNWIND EDGE (TOP-LEFT TO BOTTOM-RIGHT)

are also plotted with the visibility record as functions of distance through the fog in Figure 24.

In general, the microphysical features of the fog followed trends which paralleled the visibility record. In the downwind direction, mean drop size, drop concentration, and LWC increased to maxima in the region of minimum visibility and then gradually decreased as visibility improved farther downwind. A second maximum is also evident in the data for the region of the second visibility minimum.

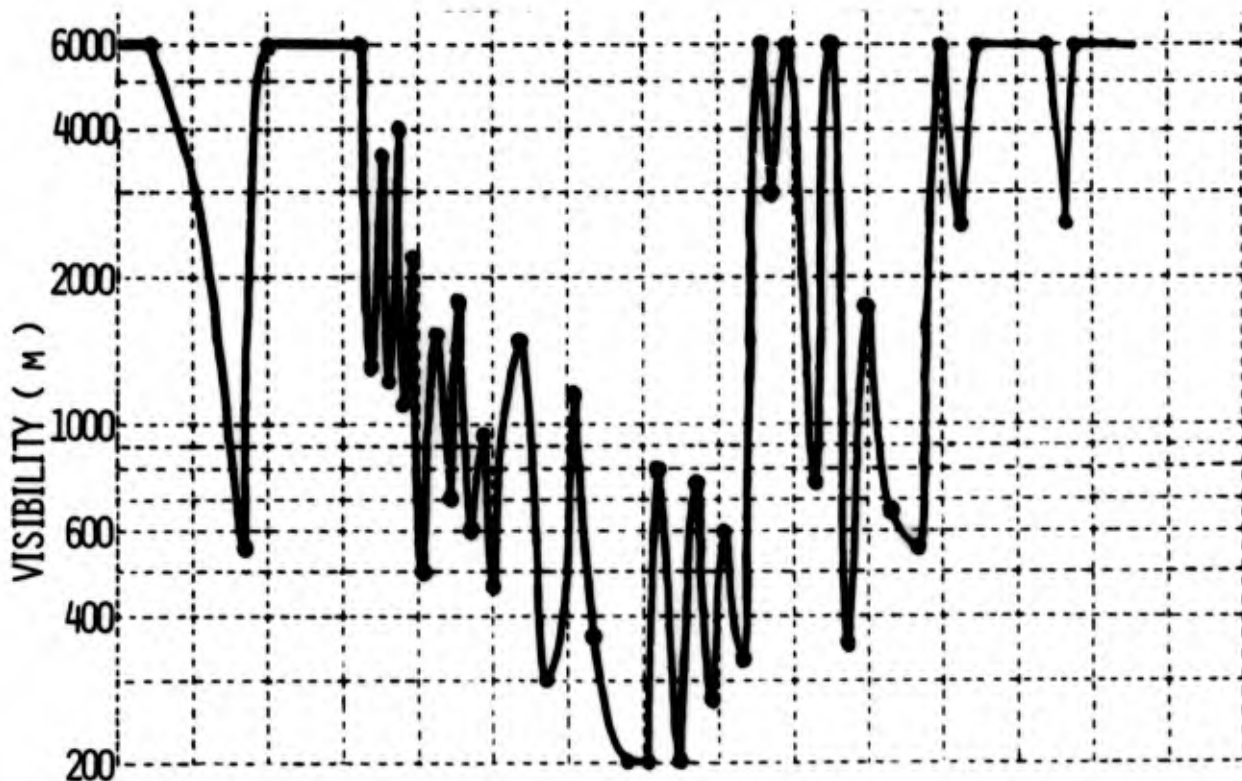
Chemical analysis of fog water samples from this fog revealed no trends in its chemical composition along the wind direction. These data are summarized and listed as "fog patches" in Appendix B.

5.3 A Model of Mesoscale Organization of Fog-Stratus Systems

The data acquired on the east-west cross sections of this fog-stratus system have led us to postulate a preliminary physical model of the mesoscale organization of these systems. Pertinent features are depicted schematically in Figure 25.

As air from far at sea moves coastward, it encounters cold water in the upwelling region and is cooled by turbulent heat exchange with the surface. This heat exchange establishes a surface-based temperature inversion and begins to condition the atmosphere for subsequent fog formation. Offshore winds and subsidence may occur to intensify this inversion aloft, but the inversion base remains at the surface.

Eventually, after prolonged gradual cooling, the air temperature approaches the dew point and initial, local condensation is triggered by sharp, local gradients in sea surface temperature. Radiation from initially condensed moisture very quickly reduces low-level air temperature below sea surface temperature to lift the inversion for the first time above the surface. Simultaneously, the lowest layer of air becomes unstable, which enhances



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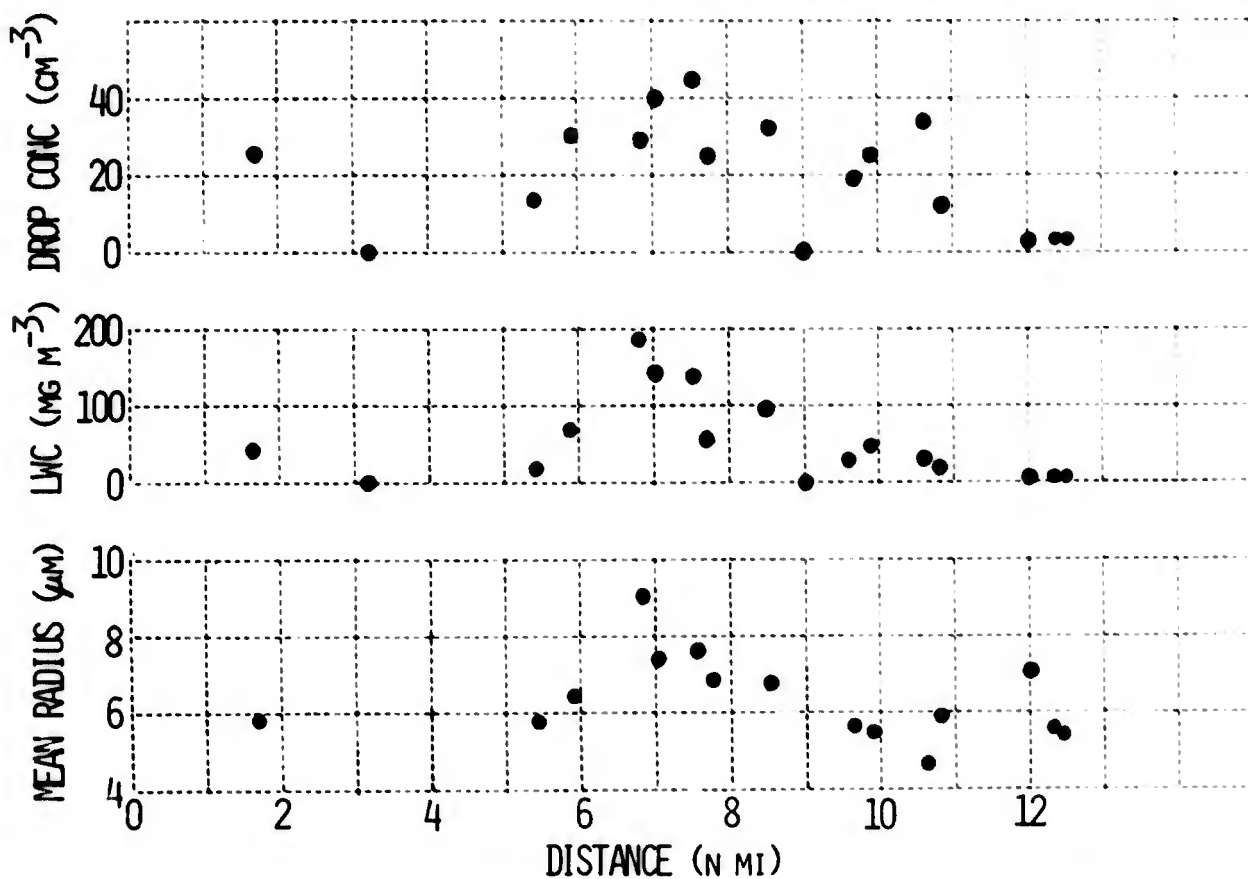


FIGURE 24: FOG MICROPHYSICS AS FUNCTIONS OF DOWNWIND DISTANCE
IN THE FOG PATCH OF 24 AUGUST 1974

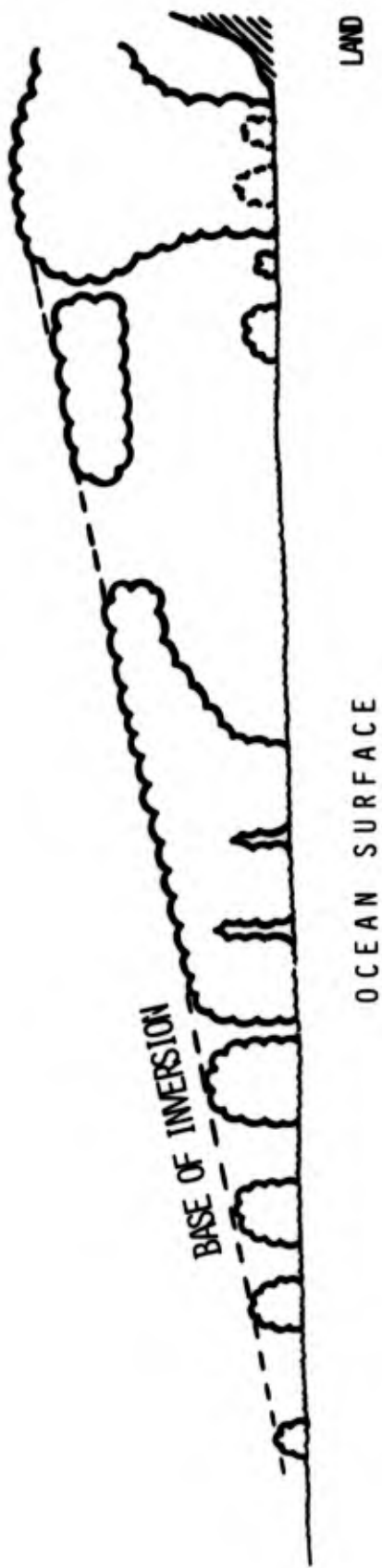


FIGURE 25: SCHEMATIC REPRESENTATION OF THE VERTICAL EXTENT AND CROSSWIND ORGANIZATION OF FOG-STRATUS SYSTEMS OFF THE COAST OF CALIFORNIA

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turbulent exchange with the sea. Now, heat is transferred from the sea to the air; however, radiation from condensed moisture helps to maintain a superadiabatic lapse aloft in spite of heating from below. In addition to a net exchange of heat from surface water to air, a net exchange of water vapor to air begins with the raising of the inversion above the surface. This is the result of cold water droplets providing a sink for evaporation from the sea surface.

Even though dynamic effects cause dissipation of such an initial fog patch, the temporary presence of the fog therefore raised the inversion above the surface, accelerated cooling of the low-level air and caused a net increase in moisture content of the air. The conditions for more significant fog formation have thus been improved.

As air passes over the next sharp sea surface temperature gradient, a new fog is triggered. Under the improved fog-forming conditions, this fog grows larger, persists longer, and raises the inversion to higher levels. Thus, it further accelerates conditioning of the air mass for fog formation. Eventually, as the process is repeated over and over, individual fog patches become so large that they merge to form the band of continuous obscuration shown in Figure 25.

We do not understand the reason for the fog to be lifted off the surface to form stratus downwind from the upwind band of continuous fog. Perhaps it is associated with drizzle which is usually observed in thick fogs and beneath the stratus. Perhaps it is associated with sea surface temperature gradients that we observed in the past to be associated with fog lifting (Mack, 1973a). In any case, the conversion of fog to stratus is a common occurrence along the West Coast and must be included in a descriptive model.

The band of fog that existed near the coast during the investigation may have been caused by any of the variety of mechanisms summarized in Section 2. Experience in all of the ACANIA fog cruises shows that such bands are very

common occurrences. Some of them are undoubtedly produced by the mesoscale phenomena described in Section 3. However, in this discussion we wish to emphasize that such fogs are formed in the air mass that has been thoroughly conditioned for fog formation by the processes described above.

- Comparison of the Model with a Satellite Photograph of June 1973

From the data presented earlier in this section, a few isolated features of the mesoscale organization of California coastal fog-stratus systems were identified. To acquire detailed information on the mesoscale organization of these systems would require simultaneous observations from a number of different locations within and upwind of the system. Additional information relative to the overall organization of the fog-stratus systems can be derived by comparing information acquired from our surface penetrations of the system with satellite photographs of similar systems. We have used two satellite photographs for this purpose. The NOAA II photograph in Figure 19 shows many of the pertinent features of the actual case studied from ACANIA, but reproduced photographic quality is not adequate for examination of some of the details that seem important. The same features are more clearly evident on the larger scale photograph presented in Figure 26, which was taken from SKYLAB II in June 1973. The data acquired from ACANIA in August 1974 and the model presented in the previous subsection will be discussed in terms of this photograph.

It seems from the orientation of the cloud streets along the upwind edge of the June 1973 system that the wind direction was, as usual, between 320° and 330° . These streets appear to be similar in every respect to those described in the previous subsection. Scaling from the length of San Francisco Bay, it appears that upwind fog patches may be less than 0.5 n mi wide and a mile or two long. Obviously they increase in size with downwind distance. From ACANIA data, we suspect that they also increase in depth as the inversion base is gradually lifted higher above the surface. However, from ACANIA data it appeared that the individual patches eventually increased in size until they



Figure 26 SKYLAB II PHOTOGRAPH OF A FOG STRATUS SYSTEM OFF THE CALIFORNIA COAST, 1306 PDT, 2 JUNE 1973.
(Photo courtesy of J. Kaltenbach, NASA Johnson Space Center.)

merged to form a continuous band of fog. From the photograph it is apparent that the banded structure of the system (with bands oriented between the wind direction and the orientation of the shore) begins upwind from the first region of continuous obscuration.

The photograph provides the distinct impression of well-organized stratocumulus cloud tops for the initial band of continuous cloud cover and thus suggests well-organized vertical motions in this region. During the ACANIA cruise the first band of continuous obscuration was definitely in contact with the surface. Evidence of strong vertical motion, combined with the analysis presented in Section 3 of this report, lead us to suspect that a strong convergence zone exists at low levels in this portion of the system. The changes in orientation of the cloud streets upwind of this regions suggest that convergence does exist.

The preceding analyses are based on observations obtained from three cross sections over a 36 hr period through only one such fog-stratus system. Because of the complexity and scale of the phenomena, the analysis is still preliminary in nature and cannot be extended further. It is highly probable that what was observed was but a variation of several possible circumstances in which air approaching the coast is modified to become more conducive to fog formation. The significance of the observation is that a mechanism has been identified which can accelerate the modification or conditioning of the air mass to permit more extensive fog formation.

Section 6

CONCLUSIONS AND RECOMMENDATIONS

The following principal conclusions have been derived as a result of three years of study of marine fog occurring off the California coast:

(1) Within large fog-stratus systems, local fogs form in response to a variety of local influences in a conditioned air mass.

(2) At the seaward edge of fog-stratus systems, organized patterns of shallow fog patches are responsible for accelerated modification or conditioning of the air mass for more extensive fog formation downwind.

(3) While boundary layer exchange processes may be responsible in some instances for triggering fog formation, our data have conclusively shown that radiative flux divergence at the upper levels of embryonic fogs is primarily responsible for continued development and persistence of all marine fogs.

(4) Dynamic effects such as low-level mesoscale convergence patterns, not previously considered important to marine fog occurrence, have been clearly shown to be the major contributing factor (along with radiative cooling) in the formation and persistence of at least one fog. Organized fog streets and cloud wave structure visible in satellite photographs of fog-stratus systems give further evidence of the importance of mesoscale dynamic effects.

It is obvious to us that the West Coast situation consists of a large scale system of interacting influences which gives rise to fog formation through a variety of mechanisms in a gradually conditioned air mass. On a scale such as this, one observation platform is not sufficient. We recommend that future studies include several surface-level observation platforms, aircraft surveillance and coastal observation sites. At the very minimum, the various groups under NASC sponsorship should be observing the same general fog region during simultaneous observation periods.

It is equally clear to us that we've only started to solve the Navy's marine fog problem. What is valid for the West Coast situation (and probably for the west coasts of all major continental areas) may be totally different, for example, from the situation occurring elsewhere, such as in the Aleutians or off the coast of Newfoundland. Similar cooperative efforts involving more than one observation platform will be required for efficient study of such large scale phenomena.

Finally, as has been conclusively demonstrated by our data, dynamic influences, such as low-level convergence patterns, are significant contributing factors in the development and persistence of some--and perhaps most--marine fogs. We therefore recommend that these mechanisms be included in numerical models as soon as practical.

REFERENCES

- Korb, G., and W. Zdunkowski, 1970: Distribution of Radiative Energy in Ground Fog, Tellus, 22, pp. 288-320.
- Leipper, D.F., 1948: Fog Development at San Diego, California, Sears Foundation; Journal of Marine Research, 7, 3, pp. 337-346.
- Mack, E.J., W.J. Eadie, C.W. Rogers, W.C. Kocmond and R.J. Pilié, 1972: A Field Investigation and Numerical Simulation of Coastal Fog, Calspan Report No. CJ-5055-M-1, Calspan Corporation, Buffalo, N.Y. 14221.
- Mack, E.J., R.J. Pilié and W.C. Kocmond, 1973a: An Investigation of the Microphysical and Micrometeorological Properties of Sea Fog, Project SEA FOG: First Annual Summary Report, Rept. No. CJ-5237-M-1, Calspan Corporation, Buffalo, N.Y. 14221.
- Mack, E.J. and R.J. Pilié, 1973b: The Microstructure of Radiation Fog at Travis AFB, Rept. No. CJ-5076-M-2, Calspan Corporation, Buffalo, N.Y. 14221.
- Mack, E.J., U. Katz, C.W. Rogers, and R.J. Pilié, 1974: The Microstructure of California Coastal Stratus and Fog at Sea, Project SEA FOG: Second Annual Summary Report, Calspan Rept. No. CJ-5404-M-1, Calspan Corporation, Buffalo, N.Y. 14221.
- Neiburger, M., 1944: Temperature Changes during Formation and Dissipation of West Coast Stratus, J. of Met., 1, 1 and 2, pp. 29-41.
- Rogers, C.W., Mack, E.J., U. Katz, C.C. Easterbrook and R.J. Pilié, 1974: The Life Cycle of California Coastal Fog On Shore, Rept. No. CJ-5076-M-3, Calspan Corporation, Buffalo, N.Y. 14221.
- Taylor, G.I., 1917: The Formation of Fog and Mist, Quart. J. Royal Meteor. Soc., 43, pp. 241-268.

APPENDIX A

FOG LOG: A LISTING OF FOGS OBSERVED AT SEA TO DATE ON THIS PROGRAM

FOG LOG: A LISTING OF FOGS OBSERVED AT SEA TO DATE ON THIS PROGRAM

| <u>Date</u> | <u>Location</u> | <u>Fog Type</u> | <u>Avg. Min. Visibility</u> |
|---------------|-------------------------------|-------------------------------|-----------------------------|
| 26 Aug '72 | MTY Bay | Stratus Lowering | 1.5 km |
| 29-30 Aug '72 | Farallon Islands | Stratus Lowering | 1.0 km |
| 30 Aug '72 | Farallon Islands | Stratus Lowering | 1.0 km |
| 30 Aug '72 | Farallon Islands | Warm Water | 0.4 km |
| 31 Aug '72 | Coastal near San Francisco | Bay | 1.0 km |
| 9-10 July '73 | Vandenberg | Warm Water | 0.3 km |
| 10 July '73 | Vandenberg | Warm Water | 0.2 km |
| 24 July '73 | MTY Bay | Bay | 0.2 km |
| 25 July '73 | MTY Bay | Bay | 0.2 km |
| 26 July '73 | MTY Bay | Bay | 0.2 km |
| 29 Apr '74 | MTY Bay | Bay | 0.3 km |
| 30 Apr '74 | MTY Bay | Bay | 0.3 km |
| 7 May '74 | MTY Bay | Stratus Lowering | 1.5 km |
| 8 May '74 | MTY Bay | Stratus Lowering | 1.0 km |
| 11 May '74 | MTY Bay | Bay | 0.3 km |
| 22 Aug '74 | Eureka | Coastal (convergence) | 0.1 km |
| 23 Aug '74 | To 40 nmi Offshore Eureka | Fog Patches (numerous) | 0.5 km |
| 24 Aug '74 | Eureka | Shallow Coastal (numerous) | 0.3 km |
| 24 Aug '74 | To 50 nmi Offshore Eureka | Fog Patches (numerous) | 0.5 km |
| 24 Aug '74 | 65 nmi Offshore Eureka | Fog Patch (single) | 0.2 km |
| 25 Aug '74 | 60 nmi Offshore Eureka | Fog Patch (single) | 0.1 km |
| 26 Aug '74 | Cape Mendocino | Coastal (convergence) | 0.2 km |
| 26-27 Aug '74 | Cape Mendocino | Coastal (convergence) | 0.1 km |
| 1 Sept '74 | MTY Bay | Bay | 0.2 km |
| 2 Sept '74 | MTY Bay | Bay | 0.2 km |
| 4 Sept '74 | MTY Bay | Bay | 0.1 km |

APPENDIX B

MICROPHYSICAL AND CHEMICAL CHARACTERISTICS OF WEST COAST MARINE FOG

During the past three years of observation and study of marine fog occurring off the coast of California, a considerable amount of data pertaining to fog microphysics has been accumulated. These data consist of measurements of condensation nucleus concentrations, drop size distributions, drop concentrations and liquid water content, and chemical analyses of discrete samples of fog water. Much of this information has been previously documented (Mack et al., 1973a and 1974) and is summarized and compared in this section, with data obtained on the current investigation.

- Condensation nucleus concentrations

Numerous observations of nucleus concentrations have been obtained at sea off the West Coast. Typically average concentrations are as follows: at 98% RH, 50 cm^{-3} grow to 1μ radius or more; at 0.5% S, 200 cm^{-3} ; and at 1.0% S, 240 cm^{-3} . Typical Aitken nucleus counts in "clean air" were in the range from $600\text{-}1000 \text{ cm}^{-3}$. While it is felt that supersaturation (S) in fogs rarely exceeds a few tenths of a percent, measurements at that low S are, at best, difficult and probably meaningless. Measurements at higher S (e.g., 0.3-1.0% S) are at least indicative of general levels of nucleus concentration. In the past, nucleus concentration at 98% RH (i.e., those which grow to $\sim 1 \mu$ at 98% RH) have been well correlated with drop concentrations in fog.

Nucleus concentration data as functions of supersaturations from the current investigation are presented in Figure B-1. At the top of the figure are data obtained on the nights of 1-2 and 3-4 September 1974 in connection with a study of fog occurring in Monterey Bay (see Section 4). These data exhibit values in good agreement with previously published data.

At the bottom-right of Figure B-1 are data obtained sequentially during a cruise (heading 090°T) from 120 km out to sea into Monterey Bay.

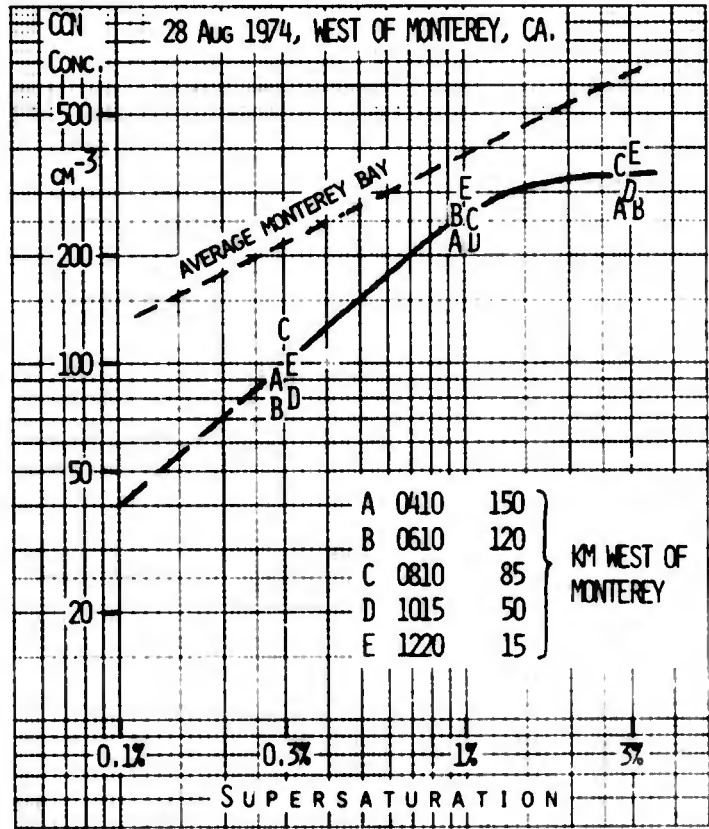
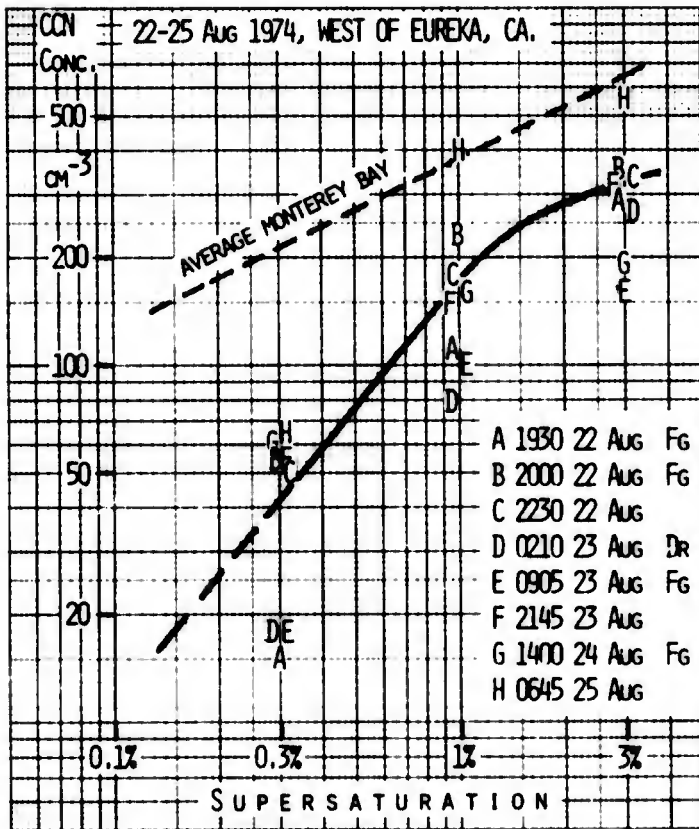
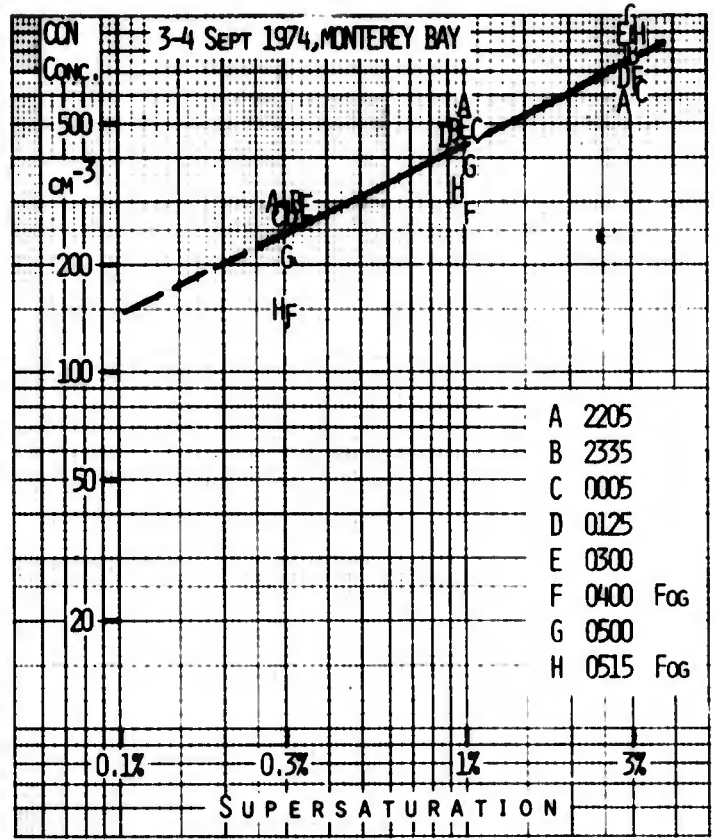
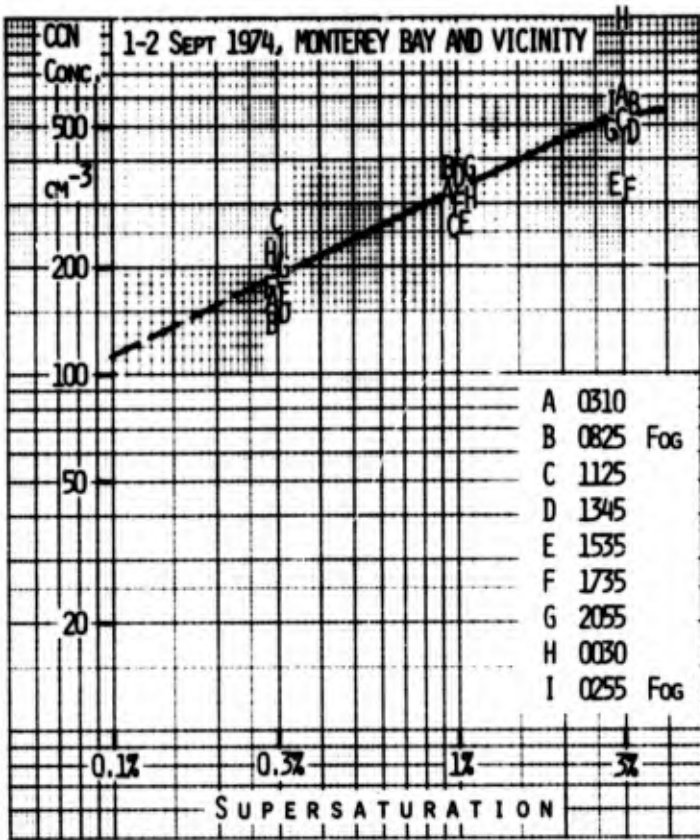


FIGURE B-1: CLOUD CONDENSATION NUCLEUS SPECTRA OBTAINED OFF CALIFORNIA COAST, 22 AUG. - 4 SEPT. 1974

These data show, as expected, that nucleus concentrations increase with proximity to the coastline, probably a result of shipping activity and continental sources. The change in slope of the curve at high supersaturation is interesting, but not surprising, in view of the limited sources for production of smaller particles at sea.

Data shown at the bottom-left of the figure were obtained approximately 10 days earlier off the California coast in the vicinity of Eureka. These data were acquired over a three-day period in the region from 20-100 km offshore but do not exhibit the trend (increasing concentration toward the coast) evident in the data offshore from Monterey. The nucleus activation spectra, however, do exhibit the same change in slope for the smaller particles at higher S. The data also indicate much lower concentrations of the larger nuclei off the coast at Eureka--much lower, in fact, than we have ever measured (at 0.3%S, for example) at sea.

- Fog microphysics

The preceding discussion of nucleus concentration measurements serves to illustrate that considerable variation in the nucleus population (e.g., a factor of 5 at 0.3%S between Monterey and Eureka) upon which marine fogs must form does occur over relatively short distances and time scales. This, combined with the wide variety of fog formation mechanisms, the depths to which fog can grow, and the time span over which fogs persist, gives rise to large differences in the microphysical features of different marine fogs.

Data obtained in various fog types observed off the California coast are summarized in Table B-1. The data shown are numerical averages (with the exception of visibility) of all the data acquired and analyzed during the past three years. In general, fog density is proportional to the depth to which the respective fogs typically grow--which is probably indicative of the strength of the driving mechanisms responsible for fog formation.

TABLE B-I: AVERAGE MICROPHYSICAL CHARACTERISTICS OF MARINE FOGS

| | MEAN RADIUS (μM) | DROP CONC. (CM^{-3}) | AVG MAX LWC (MG M^{-3}) | AVG MIN VSBY (M) |
|---|-------------------------------------|---------------------------------------|--|------------------------|
| COASTAL FOGS (CONVERGENCE) | 10.0 | 25 | 160 | 100 |
| BAY FOGS | 9.5 | 60 | 300 | 100 |
| STRATUS-LOWERING FOGS | 9.0 | 10 | 80 | 300-1000 |
| FOG PATCHES (OVER WATER TEMP. DISCONTINUITIES) | 6.5 | 30 | 80 | 200 |
| SHALLOW COASTAL FOGS | 4.8 | 45 | 30 | 300 |

Note that the shallow fog patches and coastal fogs possessed the smallest droplets, lowest liquid water contents, and greater minimum visibilities. The deep active fogs were the most dense and were comprised of highest liquid water contents and the largest mean drop size; frequently, the deeper fogs were accompanied by near continuous drizzle of drops upwards of 100 μm radius.

- Analyses of fog water samples

In order to gain insight into the origin of marine cloud condensation nuclei, fog water samples were acquired for chemical analyses. The device utilized to obtain discrete samples of fog water (i.e., ~7 ml/5 min) was developed on this program (Mack et al., 1973a), and a brief description of the methodology employed in analyses is given by Mack et al. (1973b).

Analysis of water from individual fogs showed very little temporal or spatial variation in the chemical content of fog water. As was the case in a prior study of continental radiation fog at Travis AFB (Mack et al., 1973b), each marine fog was distinguished by its own particular chemical makeup. The result is not too surprising, since the fog water chemistry must depend on the trajectory and past history of the air parcel in which the fog formed.

The average data from chemical analyses of fog water samples is presented in Table B-II. In the table, data from four types of marine fog are compared with those of the inland fogs and with analyzed sea water (both textbook and a sample from ~80 km off the coast at Eureka). The data are shown in the form of sodium ratios. The comparison strongly suggests that the main inorganic constituent of the fog water was sea salt with some enrichment of Ca^{++} , K^+ , and carbonaceous material.

TABLE B-II: AVERAGE DATA FROM CHEMICAL ANALYSES OF FOG WATER
(SODIUM RATIO $\times 1/\text{Na}^+$)

| | <u>Cl⁻</u> | <u>Mg⁺⁺</u> | <u>Ca⁺⁺</u> | <u>K⁺</u> | <u>TOTAL CARBON</u> |
|-------------------------------|-----------------------|------------------------|------------------------|----------------------|-------------------------|
| BAY FOGS | 1.8 | .08 | .14 | .13 | .60 |
| COASTAL FOGS (CONVERGENCE) | 1.8 | .18 | .15 | .39 | .90 |
| SHALLOW COASTAL FOGS | 1.6 | .12 | .04 | .06 | .05 |
| FOG PATCHES | 2.0 | .16 | .06 | .10 | .18 |
| SEA WATER | | | | | |
| TEXTBOOK | 1.8 | .12 | .04 | .04 | |
| SAMPLE | | .01 | .03 | .09 | .004 |
| INLAND FOGS | 0.9 | 0.1 | .54 | 5.2 | |

APPENDIX C

CALSPAN INSTRUMENTATION INSTALLED ABOARD ACANIA, AUGUST 1974

As in past years, surface-level measurements at sea were acquired from the NPS R/V ACANIA. An 18 m crank-up tower, a specially constructed sampling platform, and the Calspan research van were again installed on the bow to accommodate instrumentation for measuring meteorological and physical characteristics of marine fog. The sampling platform, secured to the bow approximately 5 m above the water surface, was utilized to mount instrumentation for measuring drop concentration, liquid water content (LWC), drop size distribution and air temperature, and for collecting samples of fog water for chemical analysis.

In addition to the instrumentation mounted on the bow platform, sensors to measure wind speed and direction, temperature and dew point were located at various heights on the tower. An additional temperature sensor was placed in the ship's water intake line to provide measurements of surface water temperature. Visibility was measured with an EG&G Forward Scatter Meter secured to the roof of the steering cabin at 8 m and with a Calspan-built 17 m pathlength transmissometer mounted along the railing of the upper deck. Instrumentation for measuring haze and cloud nucleus concentration, and all instrument recorders were housed in the research van located just behind the tower on the bow. A complete list of all instrumentation and locations relative to the water surface is given in Table C-I. Detailed descriptions of individual instruments may be found elsewhere (e.g., see Mack et al., 1972 and 1973a).

Table C-

CALSPAN INSTRUMENTATION INSTALLED ON R/V ACANIA, AUGUST 1974

| <u>Instrument</u> | <u>Height Above Sea Surface</u> |
|---|-------------------------------------|
| Temperature Sensors (Foxboro) | sea surface, 3, 9, 18.5 m |
| Dew Point Sensors (Foxboro) | 9, 18.5 m |
| Wind Speed and Direction (Skyvane) | 19 m |
| Visibility (EG&G Forward Scatter) | 8 m |
| Transmissometer (Calspan) | 7 m |
| Cloud Nuclei (Calspan, thermal diffusion chamber) | 5 m |
| Haze Nuclei (Calspan, thermal diffusion chamber) | 5 m |
| Drop Samples (Calspan, gelatin replication) | 5 m |
| Liquid Water Content (computed) | 5 m |
| Drop Concentration (computed) | 5 m |
| Fog Water Collector (Calspan) | 5 m |