FOG ON THE CENTRAL CALIFORNIA COAST FOR 1973: ANALYSIS OF TRENDS

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THESIS

FOG ON THE CENTRAL CALIFORNIA COAST
FOR 1973:
ANALYSIS OF TRENDS

by

John William Beardsley

March 1976

Advisor: D. F. Leipper

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20. (continued)

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Four Oakland soundings are compared with four radiosondes taken at NPS Monterey, and the Oakland soundings are found to closely approximate coastal conditions on these days.

Fog on the Central California Coast for 1973:

Analysis of Trends

by

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TABLE OF SYMBOLS AND ABBREVIATIONS

BI	Base of the temperature inversion
FAA	Federal Aviation Agency
MI	Moisture Index
NAS	Naval Air Station
NOAA	National Oceanic and Atmospheric Administration
NPS	Naval Postgraduate School
T_a	Surface air temperature
T_s	Sea-surface temperature
T_T	Temperature at the top of the temperature inversion
TI	Temperature Index
UI	Upwelling Index

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I. INTRODUCTION

A great deal of data and documentation is available on advection fog for the central west coast of North America. However, on closer examination of the available references, a gap appears in the sequence of studies carried out to date. Byers [1930] and Patton [1956] conducted extensive investigations of central California summer marine fog on the coast and in the San Francisco Bay area. McClure [1974] examined the relation between temperature inversions and marine fog, based on ten months of data, but he used Oakland as his only central California station rather than an actual coastal station. Peterson's and Leipper's 1975 study extended Leipper's 1948 fog prediction model to cover the central California coast during the period May through September. Most of the effort which has gone into the above papers has been limited to the summer months.

Therefore, considering the well-documented hazards imposed by marine fog to military and civilian operations and also the deficiency of information on fog development for the winter season on the central California coast, it was determined that a study of this nature was appropriate and should be undertaken.

Specifically, a statement of the problem is to conduct an examination of air mass fog formation on the central California coast, utilizing a full year of data.

In this study, upper-air radiosonde data will be plotted with visibility data from coastal stations. Non-diurnal indices will be computed, and these data will be used to examine actual fog sequences and determine a sequential model. This model will be compared to actual fog developments for 1973.

II. OBJECTIVES

A. To examine one full year of meteorological data on the central California coast, in order to determine which parameters could be used as fog forecasting aids.

B. To observe the seasonal and daily variation of the parameters in A.

C. To examine the individual cases of fog, in order to formulate a standard fog development model for each season.

D. To estimate the accuracy of the Oakland radiosonde in reflecting upper-air conditions over the central California coast.

III. BACKGROUND

In order to study marine fog along a length of coastline one must consider the effect which topography has on various meteorological parameters. Also, the synoptic weather picture must be understood, and the interaction between the ocean and atmosphere examined. Only after each of these basic yet indispensable areas is understood can one proceed to study the formation and characteristics of marine fog in the area of interest.

In this section, selected factors which affect coastal fog are reviewed:

A. RELIEF FEATURES
B. ATMOSPHERIC CIRCULATION
C. SEA-SURFACE TEMPERATURE
D. TEMPERATURE INVERSION
E. FOG FORMATION
F. FOG DISSIPATION
G. SUMMARY

A. RELIEF FEATURES

Topography has a major effect on local fog and stratus. Coastal mountains tend to contain the atmospheric marine layer [Rosenthal 1972]. Schroeder, et al [1967] discuss the role of terrain features in controlling the interaction between the cool, moist marine air mass and the warm, dry continental air mass. They state that a steep, mountainous coastline will restrict sea breeze penetration to only a few kilometers, whereas a flat, unobstructed coastline will allow penetration of up to 300 km.

The coast of California between San Francisco and Monterey is oriented northwest-southeast. The continental shelf south of

San Francisco narrows to less than five miles wide and coastal mountains rise abruptly from most of the shoreline to heights of over 1220m (4000 ft) [Patton 1956]. The Santa Cruz range forms the coastal chain, running from half-way down the San Francisco Peninsula to an area ten miles inland from the northern shore of Monterey Bay. The Santa Lucia range commences at the southern shore of Monterey Bay and continues southeastward along the coast at altitudes exceeding 1220m.

Significant features of the coastal mountains are the gaps which allow marine air into the flat inland areas. In addition to the Golden Gate, there are three gaps in the coastal Santa Cruz mountain range between San Francisco and Monterey Bay; the San Bruno Gap (61m elevation) and the higher and narrower Crystal Springs Gap, both in the Bay Area, and the Pajaro River Gap. The latter is the low wide valley along the eastern shore of Monterey Bay which separates the Santa Cruz and Santa Lucia mountains and forms the mouth of the Salinas Valley.

Topography is an important feature which greatly affects the general atmospheric circulation of the region, as will be shown in the next section [Patton 1956].

Figure 1 shows the locations of the land stations from which data was collected for the present study. Station heights above mean sea level are:

Oakland	1.9 m	Monterey Airport	49.2 m
Pillar Point	40.0 m	Hidden Hills	262.0 m
Pigeon Point	9.2 m	R/V Acania	2.0 m
Point Pinos	8.6 m		

Pillar Point and Pigeon Point are located on the coast and are directly exposed to marine atmospheric conditions. Point Pinos is protected from southerly winds, but is exposed to prevailing northwesterly winds.

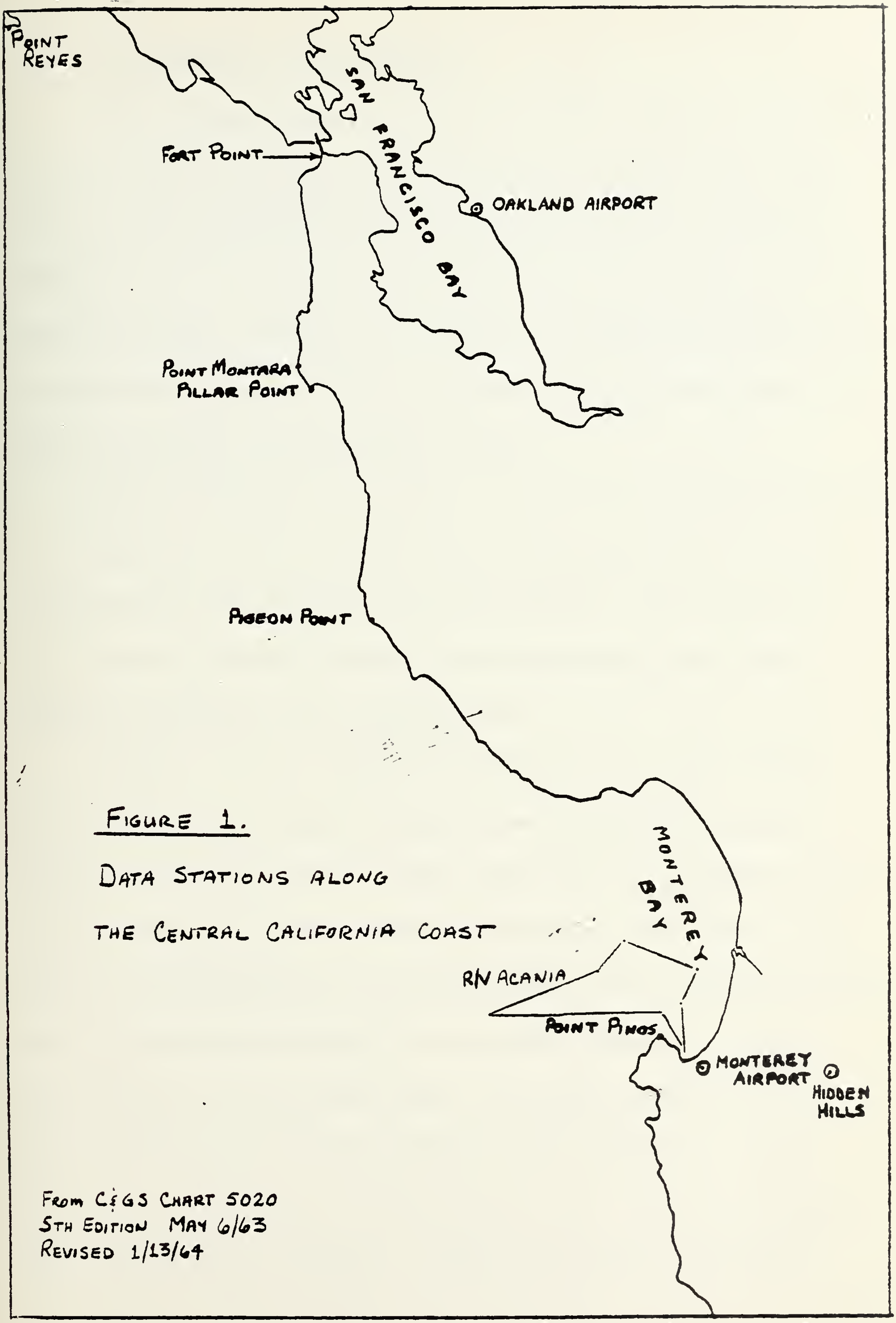


FIGURE 1.

DATA STATIONS ALONG THE CENTRAL CALIFORNIA COAST

B. ATMOSPHERIC CIRCULATION

The circulation of air over the San Francisco Bay area is controlled by the position of the North Pacific anticyclone [Patton 1956]. In the winter months, the North Pacific high center lies to the southwest of California where it assumes the configuration of a less dominant high without the shape, gradient or circulation of a well defined anticyclone. In the summer, the anticyclone strengthens and it moves to the northwest, centering itself around 40°N, 140°W.

Also developing in the summer over the central valley of California is an intense low pressure system extending from Mexico to Oregon, formed by the radiant heating of the flat terrain. This summertime low is usually separated from the North Pacific high by the inland mountain chain [Byers 1938, Patton 1956].

Together, the strengthened North Pacific anticyclone and the inland low pressure trough combine so that the isobars run approximately parallel to the Pacific coast. The clockwise circulation around the high, along with surface friction, causes the surface winds to blow from the northwesterly or westerly direction. These imposing pressure features completely override the diurnal land-sea-breeze system characteristic of many coastal areas. According to Byers [1938], surface wind from the land is very rare in the summer and usually results only in a decrease of the on-shore winds. However, drainage wind from the land is common by night at Monterey in the summer. [R. J. Renard, NPS, personal communication].

The following table, based on 31 years of data, shows the dominance of the northwest surface winds, especially in summer:

TABLE I

Average Hourly Wind Movement at Point Reyes [from Patton 1956]

Month	J	F	M	A	M	J	J	A	S	O	N	D	Year
Prevailing direction	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW
Velocity (km/hr)	28.2	31.4	33.7	38.0	42.4	43.4	36.2	32.2	29.3	27.5	26.7	28.3	33.0

When the North Pacific anticyclone moves eastward and its isobaric patterns overlap the Pacific coast, the inland low pressure system is forced southward, resulting in a transport of continental air toward the San Francisco Bay area from the east and producing high temperatures. If the anticyclone moves south, as it does in the winter, cyclonic storms may pass and produce rainfall and fog along the coast [Patton 1956].

Tables II and III illustrate the difference in monthly air temperatures between Point Reyes, which is directly impinged upon by the California current and atmospheric marine layer, and Oakland, which is partially shielded from direct ocean influence by the Santa Cruz and other mountains. The greatest difference occurs during the summer months as a result of the increased solar radiation inland, as well as the North Pacific high causing inland subsidence and heating of the upper air.

TABLE II

Mean Air Temperature at Point Reyes (34 years) [from Byers 1938]

Month	J	F	M	A	M	J	J	A	S	O	N	D	Year
Temperature (C)	9.7	9.9	10.2	10.3	10.7	11.3	12.0	12.5	13.6	13.0	12.1	10.4	11.3

TABLE III

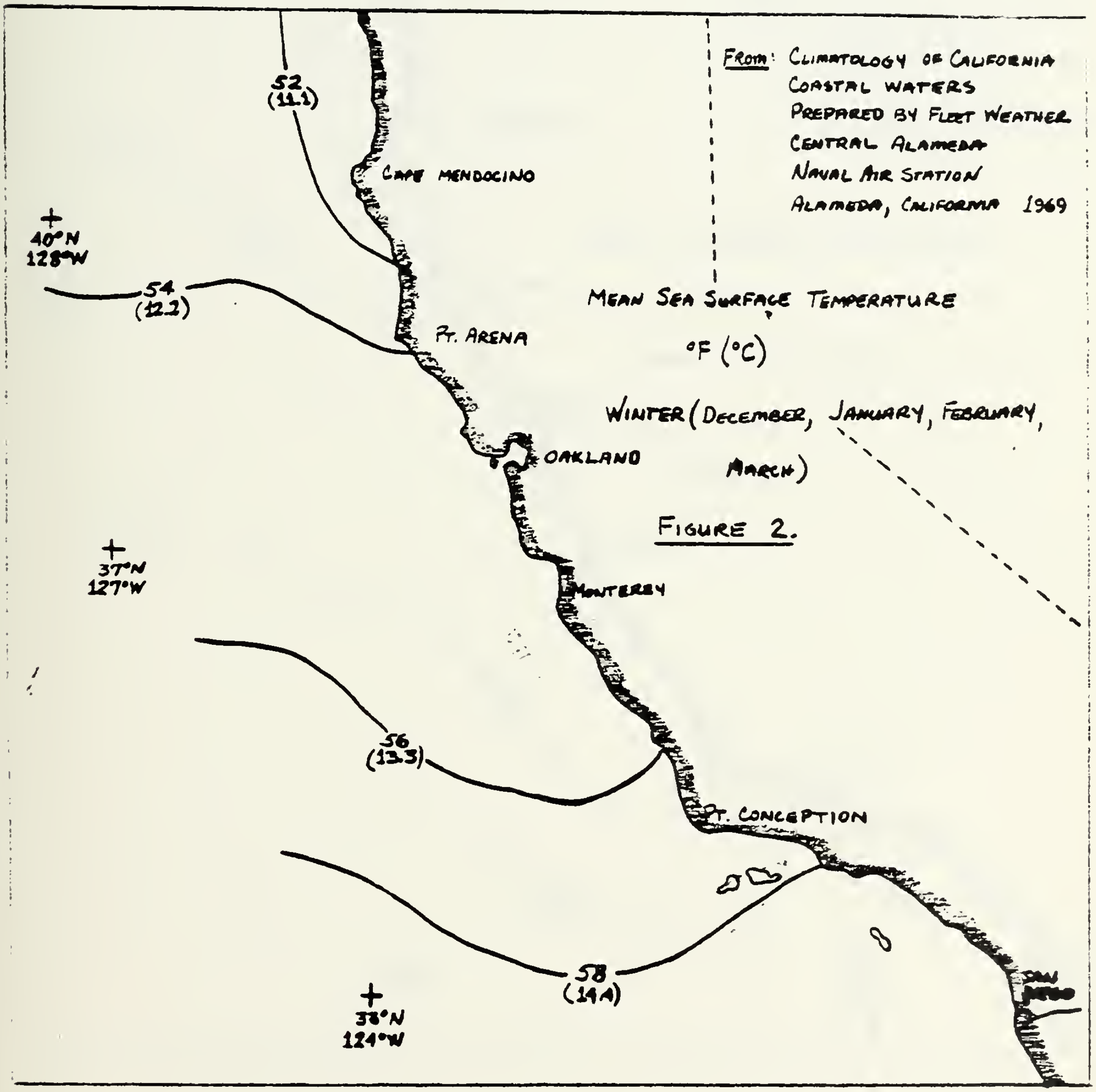
Daily Average Air Temperature at Alameda Naval Air Station
[from NAS Alameda Forecasters Handbook, 1972]

Month	J	F	M	A	M	J	J	A	S	O	N	D
Temperature (C)	9.8	11.9	13.1	14.6	15.7	17.3	17.9	17.9	18.9	16.6	14.2	10.7

In its normal summertime position, the Pacific anticyclone serves to insulate the Pacific coast from the intrusion of the few weak summer low pressure systems [Patton 1956].

C. SEA-SURFACE TEMPERATURE

Two factors cause the Central and Northern California coastal waters to be colder than normal during the summer and fall: 1) the California current and 2) coastal upwelling. According to Sverdrup et al [1942], the California current is a sluggish continuation of the Aleutian current, approximately 700 km wide which flows adjacent to the coast in a southeasterly direction. Figures 2 - 5 show the sea-surface temperature pattern resulting from the combined effects of


From: Climatology of California
Coastal Waters
Prepared by Fleet Weather
Central Alameda
Naval Air Station
Alameda, California 1969
Mean Sea Surface Temperature
°F (°C)
Winter (December, January, February,
March)
Figure 2.
52
(11.1)
54
(12.2)
56
(13.3)
58
(14.4)
Cape Mendocino
Pt. Arena
Oakland
Monterey
Pt. Conception
40°N
128°W
37°N
127°W
33°N
124°W

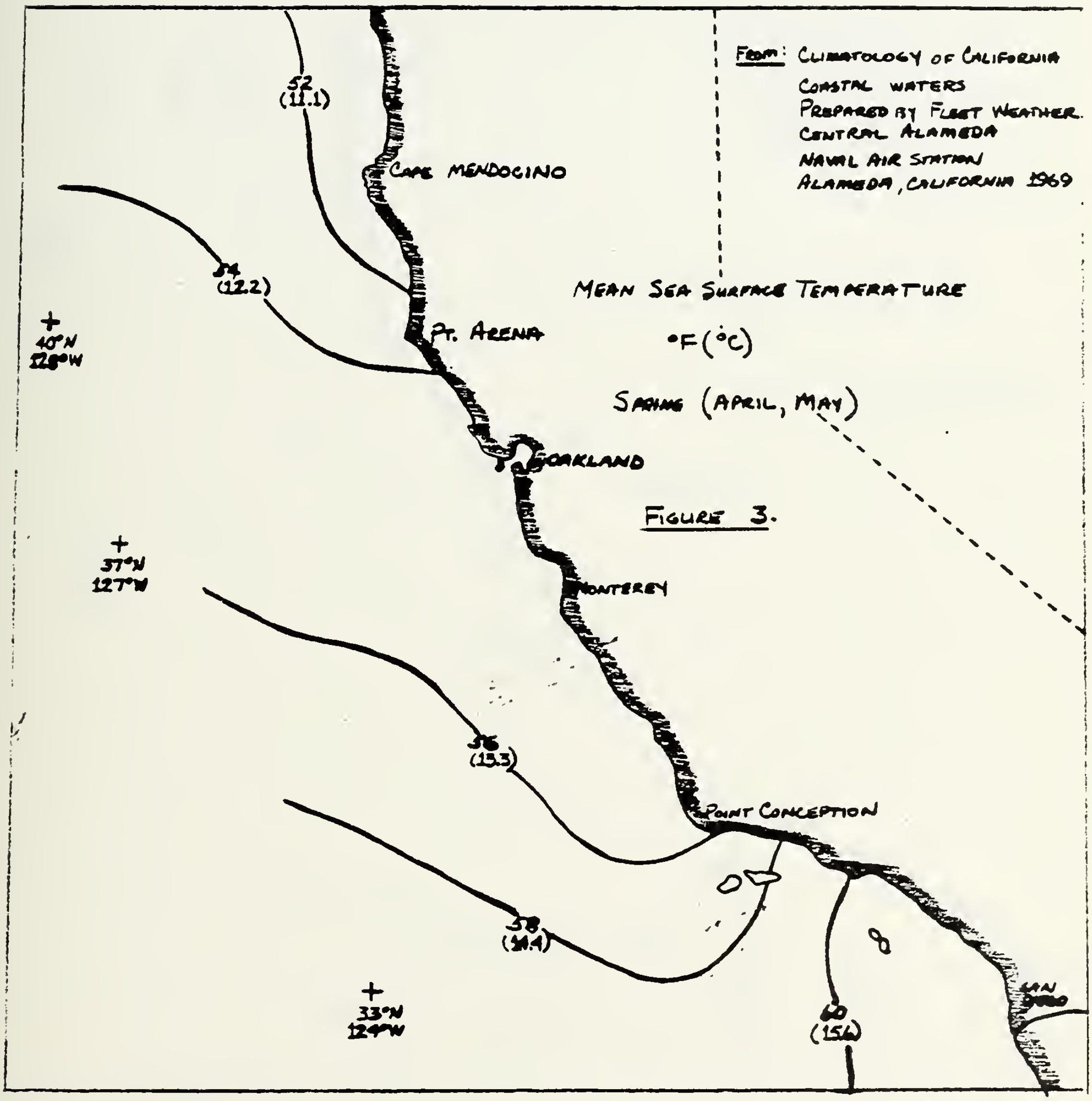

From: Climatology of California Coastal Waters
Prepared by Fleet Weather Central Alameda
Naval Air Station
Alameda, California 1969
Mean Sea Surface Temperature
°F (°C)
Spring (April, May)
Cape Mendocino
Pt. Arena
Oakland
Monterey
Point Conception
52 (11.1)
54 (12.2)
56 (13.3)
58 (14.4)
60 (15.6)
40°N 128°W
37°N 127°W
33°N 124°W

Figure 3.

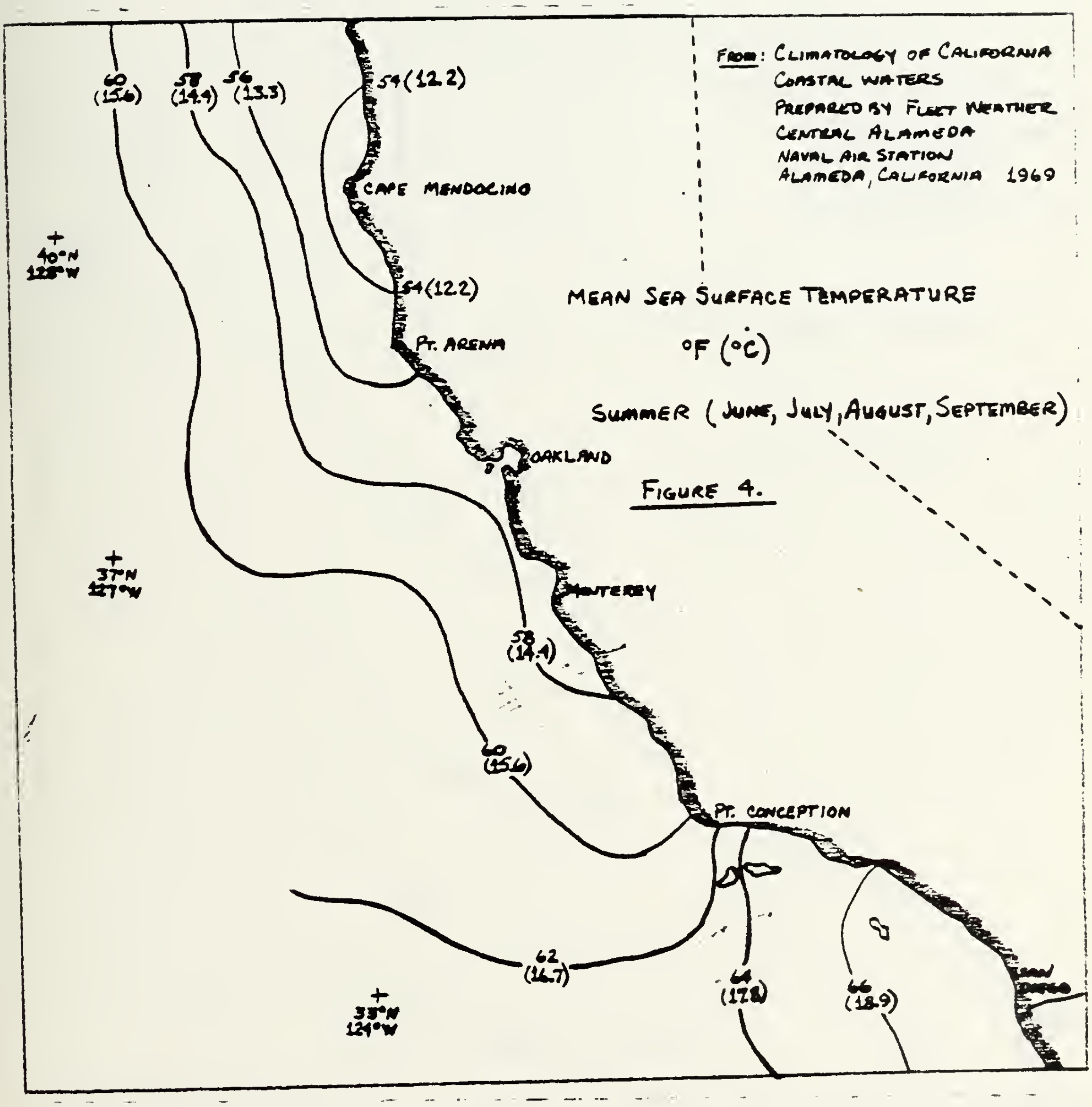
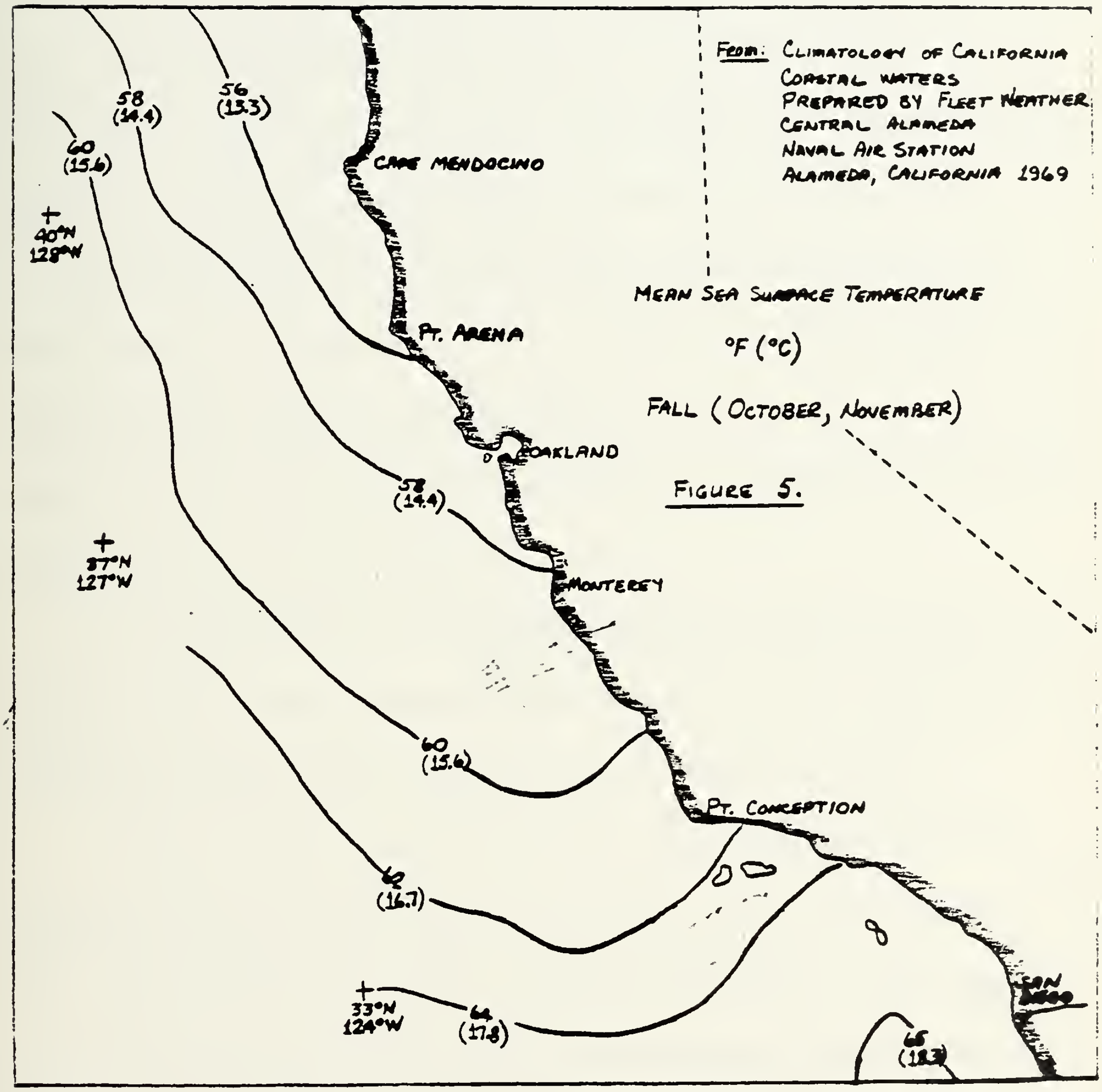

From: Climatology of California
Coastal Waters
Prepared by Fleet Weather
Central Alameda
Naval Air Station
Alameda, California 1969
Mean Sea Surface Temperature
°F (°C)
Summer (June, July, August, September)
60 (15.6)
58 (14.4)
56 (13.3)
54 (12.2)
Cape Mendocino
54 (12.2)
Pt. Arena
Oakland
Monterey
58 (14.4)
60 (15.6)
Pt. Conception
62 (16.7)
64 (17.8)
66 (18.9)
San Diego
40°N 125°W
37°N 127°W
33°N 124°W

Figure 4.


From: Climatology of California Coastal Waters Prepared by Fleet Weather Central Alameda Naval Air Station Alameda, California 1969
Mean Sea Surface Temperature
°F (°C)
Fall (October, November)
Figure 5.
Cape Mendocino
Pt. Arena
Oakland
Monterey
Pt. Conception
56 (13.3)
58 (14.4)
60 (15.6)
58 (14.4)
60 (15.6)
62 (16.7)
64 (17.8)
65 (18.3)
40°N 128°W
37°N 127°W
33°N 124°W

these two mechanisms. Figure 4 shows a crescent of cold water centered on Cape Mendocino. Byers [1938] explains this anomaly as due to upwelling of colder water during the period April-August. Bakun [1974] however, shows conclusively, using seven years of data (1967-1973), that upwelling at Cape Mendocino occurs from March to mid-September, and that as one moves further south to the tip of the Baja Peninsula, upwelling is prolonged for the entire year.

By June-July, the cold sea surface area has spread south to San Francisco. In August, the sea-surface temperature off of San Francisco has reached a minimum, and from this period, the temperature rises until temperatures offshore and alongshore are nearly equalized in March [Patton 1956].

As will be shown, the upwelled tongue of cold water plays an indispensable role in influencing the formation of the atmospheric inversion, which in turn controls fog and stratus formation.

Table IV shows the difference in sea-surface temperature between San Francisco, Alameda (on the continent side of San Francisco Bay) and Pacific Grove on the Monterey Peninsula. It illustrates graphically how much sea-surface temperatures differ at coastal locations having various degrees of exposure.

TABLE IV

Mean Surface-Water Temperatures for Selected Central California Stations (C)
[from NOAA, U. S. Coast Pilot 7, 1975]

Month	J	F	M	A	M	J	J	A	S	O	N	D	Mean
San Francisco (Fort Point)	10.4	10.9	11.6	12.4	13.1	13.9	14.7	15.2	15.5	14.8	13.0	11.2	13.1
Alameda	10.3	11.9	13.9	16.1	17.8	19.4	20.5	20.5	20.2	17.7	14.4	11.4	16.2
Pacific Grove	11.8	12.0	12.2	12.4	12.8	13.4	13.8	13.9	14.2	13.7	12.9	12.4	13.0

D. TEMPERATURE INVERSION

Leipper, in his 1948 paper on winter fog development in San Diego, stated that the first stage of fog development is the presence of warm air over colder water, which guarantees the formation of a surface temperature inversion. The inversion serves to restrict the vertical movement of moisture and causes the thin lower layer to approach saturation [Leipper 1948].

A crucial question arises - where does the warm air come from? There have been a number of different explanations advanced. Byers [1930] stated that the warm air in the upper layer is a permanent condition, and the cooler marine layer simply flows underneath. Bowie [1928] identified two separate air masses, with a warm continental air mass being on top. Leipper [1948], Patton [1956], Petterssen [1938] and Schroeder [1967] offered the most valid explanation; namely, that the warm air is the result of upper air that has subsided and warmed

adiabatically. Leipper [1948] pinpointed the cause of subsidence by specifying that the North Pacific high moves inland, resulting in a general easterly flow which progresses downslope along the mountains east of San Diego and is heated adiabatically. As the warm air comes in contact with the colder surface water a temperature inversion is formed. Patton [1956] contended that the subsiding air mass, more than any other factor, affects the height of the base of the inversion.

The Forecasters Handbook for Naval Air Stations Alameda [1972] and Moffett Field [1974] acknowledged subsidence as the factor which warms the air and, combined with cooling from below, forms the inversion in the San Francisco area.

E. FORMATION OF FOG

Byers [1930] attributed the formation of advection fog at sea to the passage of saturated air over the colder upwelled coastal waters. Formation is greatly facilitated by the presence of hygroscopic salt particles which act as nuclei around which fog droplets form.

Petterssen [1938] refuted the contention that fog is formed by cooling from below. He proposed that the observed unstable conditions beneath the inversion were the result of convection and turbulent mixing.

Patton [1956] agreed with Byers, but clarified his position: "Stratus cannot occur without cooling of the surface layers by contact with upwelling water, but the original temperature of the air mass

determines whether such cooling is sufficient to produce minimum temperatures at the base of the inversion low enough to cause condensation."

Leipper [1948] described the formation of fog in stages, the first of which is the advection of warm continental air over colder water with the consequent development of a temperature inversion. Following this, the dry air aloft permits increased radiational cooling of the moist surface layer and consequent initiation and/or intensification of the fog.

Goodman [1975] in her examination of the microstructure of San Francisco Bay area fog, demonstrated that cooling from above by radiation was responsible for a 1-2 C night time drop in temperature in the marine layer.

The Forecasters Handbook for Naval Air Station Moffett Field [1974] describes the two types of California fog as advection (as noted by Byers, Patton, and Leipper above) and radiation. Advection fog can form over land or water, but radiation fog, at least according to the Forecasters Handbook, can form only over land when the earth, cooled by radiation, cools the air to its dewpoint. However, radiation fog can be advected for short distances over a body of water.

By virtue of the almost constant northwesterly prevailing winds in the marine layer, advection fog appears to compose the major share of fog occurring on the exposed California coast. The moist marine air passing eastward over the water is several degrees warmer than

the cold tongue of upwelled surface water along the coast. This marine air causes the inversion base to lift off of the surface. Beneath the inversion, the marine air continues to cool, and as the dewpoint is passed, fog forms. The fog is then advected toward the shore by the prevailing winds. The top of the fog or stratus layer normally coincides with the base of the inversion [Byers 1938, Patton 1956].

F. DISSIPATION OF FOG

Dissipation of fog is caused by heating of the cool, moist marine layer, so that the air temperature is raised above the dewpoint, causing evaporation of the fog.

Leipper [1948] observed that after marine fog forms at sea, it becomes thicker due to radiation cooling from the top and mixing, thereby decreasing the air temperature to below that of the sea surface. Sea surface evaporation continues. As the fog layer initially invades the coastal area, it may be dissipated by the daytime heat of the land. However, eventually the fog layer becomes deep enough to maintain itself further inland over the warm land.

In the San Francisco Bay area, Byers [1930] found that inflowing afternoon fog seldom passed beyond the Golden Gate, due to mixing with the warmer turbulent land air and subsequent evaporation. Only after the air inside the Golden Gate had cooled sufficiently, usually shortly before sunset, would the fog be able to maintain itself. Although Byers found that the maximum fog thickness may be in excess

of 600 m, he observed that the average thickness was about 400 m. Leipper, in his 1948 San Diego study, recorded a maximum thickness of 400 m. Byers [1938] also noted that as fog flowed over hills surrounding the Bay area, adiabatic heating on the leeward slopes caused dissipation about 100 m below the crest.

Dissipation of fog also can be caused indirectly by the eastward movement of the North Pacific high. As it overlaps the northwestern states, the anti-cyclonic circulation initiates an easterly flow of warm, subsiding air which forces the inversion base nearly to the ground and along with mixing dissipates any fog or stratus which may exist. These occasions of inland movement of the high are known for extremely clear weather, usually lasting several days [Forecasters Handbook, Naval Air Station Alameda 1972].

G. SUMMARY

From the discussion of the various parameters which affect west coast marine fog formation and movement, it is seen that:

1. Relatively warm air, circulating over the cold tongue of water caused by coastal upwelling, is cooled and an inversion is created.

2. In the summer, when the North Pacific high has migrated to the northeast and a ridge extends over land, subsidence strengthens the inversion, and this very stable layer serves effectively to separate the cool moist marine air in the lower levels from the warm dry air at higher levels.

3. Beneath the inversion, the air over the areas of upwelled water continues to cool to the dewpoint, and condensation of water particles in the air occurs. This process could not exist without the presence of cloud condensation nuclei.

4. The return of the prevailing winds from the northwest drives the fog across the coast and against the slope of the coastal mountains.

5. If the fog is shallow and the inversion is low, dissipation will occur shortly after the fog crosses the coast.

6. The low pressure area over the central valley, caused by intensive heating, serves to reinforce the difference in pressure across the coastline and to draw the modified marine air inland through the mountain gaps.

7. The orientation of the mountains and valleys in the direction of flow of the prevailing wind channels the inflowing fog to the low areas inland of the coastal range.

8. The fog remains until heating from above and below causes evaporation.

Crouch [1973] presents a graphic picture of the way in which he has observed marine fog crossing the Pajaro River-Monterey Bay gap and spreading to the inland valleys during the summer months:

> "As the heated air of the [Salinas] valley rises during the day, a layer of cool air from the ocean begins to move inland, carrying masses of fog into the valley of the Salinas and pressing

it against the Aromas hills and the low ridges near San Juan Bautista that mark the northern limits of the valley .... Salinas may be a chilly 50° while 40 miles away in King City the thermometer will stand at 90°, and in the side valleys the heat will go up past the 100° mark ..... Long exploratory streamers of fog begin to move slowly southward. The white tentacles become patches and the patches become billows, moving past Salinas and Spreckles and Chualar .... At the same time another stream of fog moves up Carmel Valley, borne inland by a steady wind. It climbs the ridges of the Aguajito and Jacks Peak, curling up over Los Laureles and down into Corral de Tierra. Slowly the fog piles higher against the western slopes of Mount Toro and Palo Escrito ridge until, bursting over the top in a graceful banner, it flows downward to join the white river moving silently up the Salinas Valley."

IV. APPROACH

A. SELECTION OF DATA

After the initial decision was made to examine an annual fog cycle on the Central California coast, it was necessary to specify the location and time frame for the study. The coast between San Francisco and Monterey was chosen because of the close proximity to the Oakland International Airport, one of the very few locations where daily upper-air soundings were observed. Also, there was good coverage of this area provided by coastal stations at Pillar Point, Pigeon Point, Point Pinos and the Monterey Airport.

The period 1973 was chosen because of data availability. Data provided by McConnell [1975] listed Oakland soundings from 1968 through June 1973. The soundings for the remainder of 1973 were obtained from the National Weather Records Center through the Naval Weather Service Detachment, Asheville, North Carolina. Surface weather observations from Point Pinos and Pigeon Point were available commencing October 1972, but Pillar Point records were not available prior to January 1973. Additionally, FAA observations from Monterey Peninsula Airport were available for 1972 and later, as well as Hidden Hills temperature and relative humidity records. Also, surface weather observations from the deck log of R/V Acania were on file for 1973. Consequently,

1973 was chosen as the year with the most complete observations on hand.

The 0400 (PST)[1] radiosonde was chosen over the 1600 sounding because 1) the continental air is best represented by the early morning flow which exists at 0400, 2) more fog occurred in the early morning hours than in the afternoon, thereby enabling more frequent observation of upper-air conditions during periods of fog, and 3) the 0400 sounding is the one used by forecasters for predicting the day's weather.

Sea-surface temperature exerts a controlling influence on fog formation. A significant problem which arose in the selection of data was the choice of which sea-surface temperature to use for computation of the Temperature Index and Moisture Index. Data from four sources were available: 1) A supplement to Fishing Information, published by the National Marine Fisheries Services at 15-day intervals, contained sea-surface temperature charts contoured at 2°F, based on data from merchant vessels, fishing vessels, and airborne infra-red surveys; 2) A diagram from Bakun, et al [1974] showed sea-surface temperatures for the Pacific coast, based on 20 years of data; 3) A graph of monthly mean surface-water temperatures (and densities) for San Francisco (Fort Point) based on 51 years of data, appeared in NOAA United States Coast Pilot 7 [1975]; 4) Monthly mean sea-surface temperature measurements at Fort Point for 1973 were unpublished data obtained from

[1] Due to the important diurnal ramifications of fog development, all times are PST unless otherwise designated.

National Oceanic and Atmospheric Administration.

Table V compares the data from these sources. From Table V, the general conclusions can be drawn that

1) 1973 open ocean surface temperatures were lower than average for that area.

2) 1973 Fort Point sea surface temperatures were higher than the Fort Point average

3) In 1973, the open ocean surface temperatures were lower than those at Fort Point, except during December-March.

It was decided not to utilize the Fort Point data since that station is situated at the southern base of the Golden Gate bridge. It was felt that those measurements were not representative of more exposed, deep water locations, where upwelling waters interact to form fog.

The mean monthly measurements for 1973 (column (1)) were chosen because:

1) Fishing Information is a publication readily available to anyone requiring such data,

2) The isotherm charts allow the selection of a representative temperature for the ocean surface over which the prevailing northwesterly winds actually blew, and

3) These data represent the period of study and are not modified by data from other years as in long term averages.

TABLE V

Comparison of Sea-Surface Temperature (T_s) Measurements for the Coastal Area off San Francisco (^oC)

	(1) Open Ocean T_s, 1973	(2) Open Ocean T_s, 20 years	(2a) difference (1)-(2)*	(3) Fort Point T_s, 51 years	(4) Fort Point T_s, 1973	(4a) difference (4)-(3)*	(5) difference (1)-(4)**
January	12.2	12.5	-0.3	10.4	11.3	+0.9	+0.9
February	12.7	12.3	+0.4	10.9	12.2	+1.3	+0.5
March	12.4	12.1	+0.3	11.6	12.3	+0.7	+0.1
April	11.3	12.0	-0.7	12.4	12.1	-0.3	-0.8
May	11.4	12.3	-0.9	13.1	13.2	+0.1	-1.8
June	12.0	13.1	-1.1	13.9	15.0	+1.1	-3.0
July	12.3	14.0	-1.7	14.7	15.0	+0.3	-2.7
August	11.8	14.8	-3.0	15.2	15.6	+0.4	-3.8
September	13.4	15.3	-1.9	15.5	15.7	+0.2	-2.3
October	13.2	15.2	-2.0	14.8	14.8	0.0	-1.6
November	12.4	14.4	-2.0	13.0	13.1	+0.1	-0.7
December	12.8	13.5	-0.7	11.2	11.3	+0.1	+1.5

* a(+) difference indicates that 1973 was warmer; (-) means colder.

** a(+) difference indicates that the ocean was warmer than Fort Point; (-) means colder.

Column (1) from Fishing Information Supplement, bi-weekly January-December 1973.
Column (2) from Bakun, et al [1975].
Column (3) from United States Coast Pilot 7 [1975].
Column (4) from telephone conversation with Mr. Miller, National Oceanic and Atmospheric Administration, Rockville, Maryland, January 1976 (unpublished data).

In the calculation of the Moisture Index and Temperature Index (see page 37), the monthly mean data shown in column (1) of Table V were not used; instead bi-weekly mean values were used, from which the monthly means of column (1) were computed.

It should be noted here that throughout 1973, overcast conditions were never reported at Pigeon Point, even when all other stations reported low stratus. Additional comments will be made concerning Pigeon Point data in the analysis section.

B. TREATMENT OF DATA

1. Annual Data

The data are organized into two Appendices, the first of which is 1973 Annual Data. The following graphs, spanning the entire year, are included:

Height of the inversion base (BI)

Fog days for Monterey Airport, Point Pinos, Pigeon Point, Pillar Point

Temperature at the top of the inversion (T_T)

Moisture index (MI)

Temperature index (TI)

Hidden Hills maximum daily temperature

Hidden Hills minimum daily relative humidity

Upwelling Index (UI)

The height of the inversion base has been noted by numerous authors as being of prime importance in fog formation. In Leipper's 1948 paper, it was listed as one of three non-diurnal indices which characterized fog, and one which could be used to predict fog on a day-by-day basis. On the graph depicting the height of the inversion base (Figures A-1 and A-2), a tick mark along the horizontal axis indicates that there was no inversion at Oakland.

The temperature at the top of the inversion (T_T), based on the 0400 Oakland sounding, was used in calculating the temperature index, and varied directly with it. T_T by itself gives an indication of the strength of the inversion gradient because sea-surface temperature varies only by a few degrees.

The moisture index (MI) was cited by Leipper [1948] as a critical index in describing fog development. The moisture index is the 1600 surface dewpoint temperature at Oakland minus the sea-surface temperature. The sea-surface temperature used in this calculation was described in the previous section. The time of 1600 was chosen as the time closest to the maximum on-shore flow of marine air. One can think of a high positive moisture index as indicating a high degree of saturation in the surface air, and a condition favorable to fog formation.

The temperature index (TI) is the third important descriptive index in fog development. The temperature index is the 0400 temperature at the top of the inversion minus the sea-surface temperature. TI is a

measure of the strength of the inversion gradient and of overall atmospheric stability. A high TI means relatively warm conditions aloft and a strong gradient, which is favorable to fog formation.

Since upper-air observations are few, it was decided to use those taken at a nearby inland location. Hidden Hills provided an established, convenient location for recording 24-hour continuous temperature and relative humidity at a substantial elevation above sea level. Hidden Hills is located about five miles inland from Monterey Bay, at a height of 262 m. By monitoring the parameters of maximum daily temperature and minimum daily relative humidity, it was possible to determine whether a continental regime or the marine layer was enveloping Hidden Hills. High temperatures and low relative humidities were indicative of warm, dry continental air, while a reversal of the parameters indicated cool, moist marine air at this intermediate altitude.

Bakun's [1974] upwelling index (UI) was calculated using six-hourly synoptic surface atmospheric pressure fields. The greater the northerly wind component, the greater was the degree of upwelling, and the cooler the sea-surface temperature; hence the more favorable were conditions for fog. An index value greater than zero indicates upwelling, while less than zero signifies downwelling. In cases of only slight upwelling, there may have been no effect on sea-surface temperature if the mixed layer were of moderate depth.

2. Daily Data

Appendix B, 1973 Daily Data includes the following:

Oakland radiosonde - 0400 (local)

Continuous surface visibilities for Monterey Airport, Point Pinos, Pigeon Point, and Pillar Point.

These data are presented with the Oakland soundings across the top of each page. The visibilities at the coastal stations for the same dates are aligned beneath each sounding plot. The visibilities are plotted in a bar graph format, allowing comparison on an hourly basis and a direct comparison of one day to other days.

Each bar graph represents a 24-hour period (1600-1559 PST) for each station. Each 0400 sounding can be correlated with the daily bar graphs directly, and the visibilities at any time can be compared between stations.

The visibility data for the Monterey Airport were recorded as conditions changed, often several times an hour. The Monterey Airport data were considered highly reliable. The data from the three coastal stations consisted of observations entered every three hours. Using persistence, the conditions between observations were assumed to be the same as at the observation times. For cases in which the conditions were different for subsequent observations, the period between observations was divided in half and the appropriate visibility conditions assigned to each period.

The visibility graphs show four ranges of surface visibility:

- heavy fog, $0 \leq$ visibility $\leq 1/2$ mile
- light fog, $1/2 <$ visibility ≤ 3 miles
- haze, $3 <$ visibility ≤ 7 miles
- clear, visibility 7 miles

A vertical line (|) was used together with one of the above symbols to indicate any occasion when overcast was reported on the surface weather observation sheets.

Although visibility less than one kilometer is the internationally accepted definition for fog, visibility of one-half mile was used as the cut-off criterion in this paper because all stations reported visibility in units of miles vice kilometers.

Visibility data are presented for all fog sequences which occurred in 1973, and the 0400 Oakland radiosonde is plotted for every day of the year.

V. DATA ANALYSIS

A. YEARLY ANALYSIS

From figures A-1 and A-2, it is seen that 1973 can be divided into two fog-related periods. The summer fog period is taken to be late April through October and the winter fog season November through mid-April. The fog-related periods are designated based on the number and distribution of fog days throughout the year, as shown in Figures A-1 and A-2 and in Table VI.

As used in this analysis, the term "fog" and "fog-day" refer to visibility conditions less than one-half mile. When the term "light fog" is used, it refers to visibility conditions greater than one-half mile and equal to or less than three miles.

TABLE VI

1973 Marine Fog Occurrence at Central California Coastal Stations

	Summer fog days*	Winter fog days	Summer fog hours	Winter fog hours	Summer average daily duration(hr)	Winter average daily duration(hr)
Monterey Airport	47	9	207	29	4.0	3.7
Point Pinos	62	11	485	73	7.8	6.6
Pigeon Point**	48	4	265	21	5.5	5.2
Pillar Point***	91	17	784	167	8.6	9.8

* Days on which fog was reported

** Missing 20 days of data in summer and 52 days in winter

*** Missing 4 days of data in summer and 58 days in winter.

To check on the validity of the 1973 data, the percentage of hours with fog for the stations at Point Pinos, Pigeon Point, and Pillar Point were calculated and compared with mean data presented by Patton [1956] based on figures supplied by the Coast Guard. (Pillar Point was not listed by Patton; however, since Point Montara is in the immediate vicinity, Pillar Point was compared to Point Montara). Table VII compares the results.

TABLE VII

Percentage of Hours with Fog at Coastal Stations

	1973	Mean year (USCG data)
Point Pinos	6.4	9.0
Pigeon Point	3.3	11.8
Pillar Point	10.9	10.6 (Point Montara)

It should be recalled that the 1973 data were not complete; most notably, Pigeon Point was missing almost 20 days in the summer fog period. However, even assuming that Pigeon Point experienced the average daily fog duration of 5.5 hours for the 20 days for which data are missing, this would raise the yearly total hours to 395, or only 4.5%. This figure appears unreasonably low, especially with the higher figures for Point Pinos and Pillar Point. These observations serve to reinforce the author's opinion that the surface observations for Pigeon Point are incomplete and probably inaccurate.

Based on the location of Pigeon Point and on the daily record of visibility at the two adjacent stations, it is estimated that Pigeon Point probably experienced an additional 25 days of fog, that is, 14 in the summer period and 11 in the winter. It is impossible to estimate accurately the additional fog in hours that may have occurred at Pigeon Point. However, by using a daily average duration of 8.0 hours for the summer and 7.5 hours for the winter and multiplying by the estimated number of additional days, a rough figure can be determined (the values of 8.0 and 7.5 hours were obtained by choosing a representative figure intermediate between the durations of Point Pinos and Pillar Point). The above estimations and computations yield the revised figures for Pigeon Point:

	Summer fog days	Winter fog days	Summer fog hours	Winter fog hours	Summer average daily duration(hr)	Winter average daily duration (hr)
Pigeon Point	62	15	377	104	6.0	6.9

This compares more favorably with the two adjacent stations, although the values given for the summer remain somewhat low.

It is seen from Table VI that the summer period had many more days on which fog occurred and many more total hours of fog at all stations than did the winter period. Additionally, the data indicate a generally longer average daily duration of fog during the summer. Using this adjusted Pigeon Point data, it may be shown that the average

daily duration of fog at each station increases with distance north except at Pigeon Point, in the summer period.

The greatly decreased daily duration of fog at Monterey Airport is undoubtedly due to the diurnal heating of the land causing accelerated dissipation of the fog. This illustrates the difference which may occur between a station with a complex environment only 1.5 miles from the water, and a true coastal station.

Several compilations of parameters from Figures A-1 and A-2 have been made to show the difference between summer and winter, and are presented in Tables VIII-XI.

Table VIII compares inversion base (BI) statistics for the two fog-related seasons.

TABLE VIII

Inversion Base Statistics - Oakland, 1973

	Summer	Winter
$400\ m < BI < 1500\ m$	78 days (41.0%)	20 days (11.5%)
$0 < BI \leq 400\ m$	39 days (20.5%)	8 days (4.6%)
$BI = 0$	67 days (35.3%)	113 days (64.9%)
No inversion at Oakland	6 days (3.2%)	33 days (19.0%)
Total days*	190 days	174 days

*Total days = 364 due to one missing radiosonde

It must be recognized, however, that Oakland exhibits meteorological features more characteristic of a land station than a coastal station. Because Oakland's location is inside the mountain range that separates most of San Francisco Bay from the ocean, the Oakland radiosonde is not indicative of the low level atmospheric conditions over the open ocean where advection fog is formed. It has therefore been assumed that if a no-inversion condition is shown by the 0400 Oakland sounding and the surface air temperature at Oakland ($T_{a_{oak}}$) is greater than the ocean surface temperature (T_s), an inversion must exist over the open ocean due to the cooling of the air by the surface waters. If, however, $T_{a_{oak}} < T_s$, then a "no-inversion" situation exists over the ocean as well.

The days of no inversion at Oakland are indicated on Figures A-1 and A-2 on the graph entitled "Height of the Base of the Inversion" by a tick mark below the horizontal axis. These cases were adjusted, where necessary, to open ocean conditions and are shown in Table IX.

In 1973 there were 39 days of no inversion at Oakland, but as seen from Table IX, 12 of these were cases in which $T_s < T_{a_{oak}}$, or an open ocean inversion was assumed to exist. There were seven reported fog days which occurred during the 39 days of no inversion at Oakland. Of these seven fog days, five occurred on days of assumed open ocean inversions. In other words, during the days of no-inversion at Oakland, 71% of the fog occurred in 31% of the time. The remaining

TABLE IX

Distribution of Cases in which the 0400 (Local) Oakland Radiosonde showed no inversion to exist

Total days of no inversion at Oakland, 1973 →	39			
Distribution by season →	Summer 6		Winter 33	
Distribution by inversion condition over ocean: $T_{a_{oak}} < T_s$ = no inversion over ocean $T_s < T_{a_{oak}}$ = open ocean inversion	No inversion over ocean 2	Open ocean inversion 4	No inversion over ocean 25	Open ocean inversion 8
Number of fog days →	1	1	1	4

two fog days, occurring during conditions of $T_{a_{oak}} < T_s$, appear to have been the result of frontal effects, since cold fronts were in the near vicinity of the San Francisco Bay area on both occasions [Weatherwise 1974].

Based on data which have been adjusted in Table IX, Table VIII can be revised to reflect the assumed conditions for the open ocean off the Golden Gate, as follows (Table X)

TABLE X

Inversion Statistics - Open Ocean off San Francisco 1973

	Summer	Winter
400 m < BI < 1500 m	78 days (41.0%)	20 days (11.5%)
0 < BI ≤ 400 m	39 days (20.5%)	8 days (4.6%)
BI = 0	71 days (37.5%)	121 days (69.5%)
No inversion	2 days (1.0%)	25 days (14.4%)
Total days *	190 days	174 days

* Total days = 364 due to one missing radiosonde

During the winter, either a surface inversion (BI=0) or no inversion existed 83.9% of the time (146 days) at Oakland. For only 4.6% of the winter season (8 days) was the inversion base between 0 and 400 m. According to Leipper [1948] a surface inversion represents the phase of the fog sequence immediately prior to the actual formation of fog.

Once fog forms, the mixed layer should cool due to radiation and subsequent mixing and the inversion should lift off of the surface. Except for the eight days during which the inversion base was between the surface and 400 m, conditions in the winter season were generally unfavorable for fog formation. In other words, if fog formed at sea during the the winter fog period, it was shallow (because the inversion base rarely rose above the surface) and undoubtedly dissipated before being advected ashore.

Conversely, the summer shows conditions much more evenly distributed. The important requirement, noted by Leipper [1948], that the inversion lift off of the surface in order that fog may be formed and advected, occurred almost five times as frequently in the summer as in the winter. Additionally, the no inversion condition, which is not conducive to fog formation, occurred only 1.0% of the time in the summer against 14.4% in the winter. The overall picture, based on the height of the inversion base, is one of a far more favorable environment for advective fog formation at the coast in the summer than in the winter.

Referring to Figures A-1 and A-2, the mean temperature at the top of the inversion (T_T) was 18.8° C for the summer and 10.2° C for the winter. Since the sea surface temperature (T_s) tends to equal the air temperature directly above it, and since the seasonal variation of T_s is more stable than the variation of T_T, then the higher T_T indicates a stronger inversion gradient, which serves to prevent mixing of the marine layer with the upper air.

The mean moisture index was +0.3° C for the summer and -3.3° C for the winter. This index, calculated daily at the radiosonde time of maximum onshore sea breeze, indicates the relative amount of moisture in the surface air layer offshore. Leipper [1948] cited a moisture index favorable to fog at San Diego in winter as any positive value or any negative value between 0.0 and -5.0° C.

When the daily temperature indices were averaged, the mean temperature index was 7.8° C for the summer and -1.4° C for the winter. The temperature index, calculated at the radiosonde time closest to the time of maximum off shore land breeze, points out the influence of the warm, dry continental upper air in strengthening the inversion. Leipper [1948] listed any positive (+) value of the temperature index as a favorable condition for marine fog at San Diego. A summary of the parameters listed above is presented in Table XI.

Table XI supports the contention that one must observe trends, rather than absolute values when dealing with fog formation. The mean temperature at the top of the inversion was 18.8°C for the entire summer, and 19.5°C for the summer days with fog; only 0.7°C difference. Yet, as seen in Figures A-1 and A-2, large and definite upward and downward trends are obvious. The same may be said for the other indices.

With coastal upwelling linked so closely to marine fog formation, it would be expected that maximum upwelling would occur during the

TABLE XI

Comparison of Fog Parameters Between Summer and Winter, 1973

	Summer (190 days)	Summer fog days (111 days)	Winter (174 days)	Winter fog days (26 days)
$0 < BI \leq 400$ m at Oakland	39 days	36 days	8 days	2 days
Mean temperature at top of inversion*	18.8°C(190 days)	19.5°C(111 days)	10.2°C(174 days)	10.0°C(26 days)
Mean moisture index	0.3°C	0.8°C	-3.3°C	-2.2°C
Mean temperature index	7.8°C	8.8°C	-1.4°C	-0.2°C

*If no inversion existed, the surface temperature was used.

summer fog season. As seen from Figures A-3 and A-4, this was the case, with upwelling in 1973 beginning in March and lasting through October, with intermittent bursts into November. Upwelling overlapped the summer fog season on both ends by at least one month. However, there was only very limited fog during these periods of winter upwelling, due to the decreased moisture index and temperature index. This demonstrates the point that all of the fog parameters must achieve the proper relative balance before advection fog will form.

Figures A-3 and A-4 present the variation of the Hidden Hills maximum daily temperature and minimum daily relative humidity for 1973. During the summer, the maximum daily temperature was higher and the minimum daily relative humidity was lower, in general than during the winter. Since three months of data were missing from the winter season, the mean values of these parameters were not calculated. Hidden Hills data were usefully employed in analyzing individual fog sequences, especially during periods between the times of the Oakland soundings.

B. DAILY ANALYSIS

1. <u>General Comments</u>

In the description of central California coastal advection fog development, <u>relative</u> values are important: the lower level air must be warmer than the sea surface; the air dewpoint temperature must be greater than, or near the sea surface temperature (moisture

index); the temperature at the top of the inversion must be greater than the sea-surface temperature (temperature index).

Exactly when, or if fog forms depends on many interrelated conditions: the temperature of the air; the sea surface temperature; the temperature above the inversion; the height of the inversion; the amount of moisture in the air; the density, size, and type (hygroscopic or non-hygroscopic) of cloud condensation nuclei; wind and turbulence; and coastal topography, to cite an incomplete list. The difficulty of setting an absolute critical value on any parameter, be it a direct measurement or a relative quantity, can be readily seen.

In the analysis of the daily data, it seemed important to examine trends, rather than to rely on absolute values. Absolute values can change from year to year as climatic conditions change, whereas the trends which describe an event are more likely to remain consistent. As an example, the 1973 sea-surface temperature close to the Golden Gate was about 2^{o}C colder than the mean.

For the above reasons, the data trends were examined, rather than absolute values, with the intention that the results will be applicable to general cases of fog development, and not just to 1973 cases.

In examining the data for trends and patterns, it became apparent that certain conditions did exist prior to, during, and following the formation of marine fog. The indices graphed in Appendix A

behaved in a generally predictable fashion; in other words, given the trends of the indices for a given period, one could come close to describing the visibility conditions. The reverse is also true: by knowing the visibility conditions, one could probably predict the trends which the indices were following.

When a specific case of fog development was isolated the behavior of the various indices was noted. By examining the indices for trends in a number of cases, a typical case of fog development for the summer was derived and described in terms of the trends of the various indices. Hereafter, a fog development case shall be called a sequence. As defined here, a full fog development sequence includes haze, light fog, dense fog, and low overcast. Such a sequence usually covers several days. A fog sequence may be divided into several periods; for example, the period before the fog, the fog period, and the period following the fog. These components of the sequence, or phases, are defined in terms of the indices and are utilized in the ideal sequence for the summer period.

2. Summer

a. Ideal Sequence

The initial synoptic conditions for the ideal summer fog sequence are: the North Pacific high has moved partially inland from its normal summer position, so that the isobars are roughly perpendicular to the coast. Further south, an inland low has developed

over the central valley due to the high insolational heating. The orientation of the surface isobars and the anticyclonic circulation about the high pressure area results in the subsidence of dry continental air from upper levels as it moves from inland toward the coast; this air is heated adiabatically and becomes warm and dry as it flows seaward.

The phase one conditions encountered at Oakland are: A 0400 sounding shows no inversion, although some warming in the lower level may be evident. Coastal visibility conditions are clear.

Phase two reflects the warming of the air column by dynamical heating. The sounding shows a heated air column with a surface inversion. The moisture index decreases due to the dryness of the descending air, and the temperature index increases. Hidden Hills observations begin to show an increasing difference between temperature and relative humidity, as the former rises and the latter falls. As the offshore winds increase, the upwelling index decreases. It is during this phase that the lower level air over the sea becomes almost saturated. Haze may be present.

In phase three, the North Pacific high begins to withdraw to its normal offshore position. Northeasterly winds begin to decrease, and the prevailing northwesterlies begin to return, lowering the surface air temperature and strengthening the inversion. As the air cools, fog forms, the inversion base lifts off of the surface, the surface air temperature decreases, and additional cooling takes place

at the top of the inversion due to radiational cooling. The moisture index increases and the temperature index may decrease somewhat. The Hidden Hills temperature decreases and the relative humidity increases. The upwelling index begins to increase, due to the increasing northerly wind component. As the northwesterly sea breeze strengthens, the fog is advected toward the coast.

Phase four commences as the inversion base rises above 400 m. The fog lifts off of the surface to become low overcast. The values of the indices return to approximately their pre-sequence values. This phase continues as long as the high level inversion and overcast remain. When the inversion is wiped out due to upper-air cooling, both this phase and the entire fog sequence end.

Summarizing, the behavior of the indices during the ideal summer sequence should be as follows:

1) Before and during phase one, the upwelling index should be high due to the northerly/northwesterly winds causing offshore surface transport.

2) As easterly winds flow offshore and warm the air column (phase two), the temperature index increases, and the upwelling index decreases, as does the moisture index.

3) Phase three conditions take over, and the marine layer pushes inland from the northwest. The moisture index increases, the upwelling index starts to increase, and the temperature index decreases.

4) During phase four, the inversion lifts above 400 m as the marine layer thickens. The indices continue their phase three trends, and return to their approximate pre-sequence values.

b. Actual Summer Fog Sequences

Following the review of the ideal pattern for summer marine fog development off the central California coast, four actual fog cases now are examined. The first sequence, 26-31 May, is one which closely parallels the ideal sequence. The second case, 19-28 April, demonstrates that a passing frontal system can delay a specific phase up to several days, but may not substantially alter the order within a sequence. The third case, 6-19 May, shows that there are times when a passing front may cause complex changes and reversals in the sequential development of marine fog. The last sequence examined, 23-30 September, was chosen because pertinent supplementary data were available which enabled correlation between stations. The following discussion can be followed on the appropriate figures in Appendices A and B.

1) The period 26-31 May 1973 is an example of a six-day, uninterrupted sequence of fog development. On 26 May, there existed a long narrow tongue of high pressure paralleling and slightly overlapping the coast from southern California to Vancouver Island. The 0400 Oakland sounding showed no surface inversion, a phase one condition (although there did exist a weak upper inversion with a base

at 600 m). All stations reported clear conditions. Examination of the synoptic situation for 27 May revealed that a lobe of the anticyclone had detached itself and at 0400 was located over portions of British Columbia, Washington and Oregon. The 27 May Oakland sounding showed warming along the entire air column, which created a surface inversion and lowered the upper inversion base to 525 m. The three southern stations were clear, while Pillar Point experienced haze and fog in the afternoon. These conditions all indicated phase two. On 28 May, the inland high merged with the coastal high and pushed deeper inland. Continued warming brought the inversion to the ground and strengthened it. Haze was observed at three of the four stations. Phase two was still in effect on 28 May. The sounding for 29 May revealed continued warming with the inversion base still on the surface (phase two). The high along the coast was weakening, which allowed the prevailing northwesterlies to push the marine layer onto the coast; by the morning sounding of 30 May, the inversion base had lifted to 150 m (phase three). Fog was present at all four stations on the evening of the 29th and on the morning of the 30th. Pillar Point and Point Pinos also reported fog on the evening of 30 May. The synoptic picture for 31 May showed that the high had retreated offshore. The inversion base at Oakland had risen to 750 m, well into phase four. Haze with overcast was observed at all stations, except for three hours of fog which occurred at Point Pinos at midnight on 31 May. This completed the sequence.

During this sequence, the moisture index increased on the first day (26 May) and reached a local maximum on the 28th. It began decreasing during phase two as the dry easterly winds forced the marine layer out to sea. The temperature index increased during the warming trend of phase two to a maximum on the 29th. The upwelling index registered a local maximum on 25 May, one day before the sequence began. As the easterly winds arrived, the upwelling index decreased to a minimum on the 28th. With the formation of fog and return of the prevailing northwesterly winds, the upwelling index turned upward.

Hidden Hills data, although not available for most of the sequence, seemed to indicate a maximum temperature and minimum relative humidity on the first day of fog at the coast.

(2) The second sequence examined was a ten-day period from 19-28 April 1973. This was the first fog sequence of the summer period, and, as seen from Figure A-1, it could be identified easily by the absence of fog preceding or following it.

Phase one commenced on 19 April. The morning sounding at Oakland showed no surface inversion, with a mild upper-air inversion which disappeared later in the day due to heating. The surface isobars were parallel to the coast. Conditions were clear at all coastal stations, with haze on that evening at Monterey Airport. Phase two was evident in the sounding for 20 April. Warming of the air

caused a slight surface inversion, as the surface isobars began to push inland. Phase two continued over the next two days, until 22 April, as increased warming deepened the surface inversion. On 23 April, the sequence was interrupted by a passing cold front. The presence of the front was reflected on the sounding by abrupt cooling of the lower 1000 m of the air column. Light scattered haze and overcast were reported at the stations. On 24 and 25 April, phase two continued as warming returned. Haze interspersed with fog was prevalent at all stations.

On 26 April, the anticyclone retreated westward from the coast. The inversion lifted from the surface, commencing phase three. Heavy fog occurred at all stations. The sounding for 27 April showed an inversion base of 475 m, indicating that phase four had commenced sometime between the 26th and 27th. There were patches of fog, haze, and overcast at the three southern stations, and heavy fog lasted almost all day at Pillar Point. (The fog was probably due to frontal activity, since a cold front extended across the coast of central California on the morning of 27 April). The sequence ended on the 28th as the inversion lifted to almost 1000 m, resulting in overcast but no fog at all stations.

The behavior of the moisture and temperature indices was generally as expected in the ideal sequence. The MI decreased sharply on the 20th (phase two) and the TI began an upward trend, both reflecting the presence of warm, dry subsiding continental air. (Figure A-1) On the 21st and 22nd, an approaching cold front caused

warm, moist low-latitude air to circulate over the coast, which resulted in an increase in the MI and TI. Both indices experienced a sudden dip as a result of the frontal passage on 23 April. By the 24th, the first day of fog, both indices were trending upward again, and both peaked on the 25th. By the 28th, the final day of the sequence, both indices had fallen to a value near their pre-sequence value.

The upwelling index was a high value on 19 April, the first day of the sequence. As warming and offshore winds commenced, the UI decreased to a minimum on the 21st (Figure A-3). On the 22nd and 23rd, the UI increased, although the winds were southwesterly ahead of the approaching cold front. The maximum UI on the 23rd and the decrease thereafter was the result of the frontal passage and the return of offshore winds and phase two conditions. The 25th saw the return of the marine layer and the prevailing northwesterlies, and an increase in the UI.

The Hidden Hills data for this sequence showed that, from phase one on 19 April, the daily maximum temperature increased and the daily relative humidity decreased, indicating strong subsidence. The curves peaked/bottomed on the 22nd, indicating the maximum influence of continental air. The dip in temperature and the spike on the relative humidity curves on the 23rd reflect the marine air influx from the frontal passage. By the 25th, both parameters had continued their previous trends, so that by 28 April, Hidden Hills was again

enveloped in the marine air regime.

This case demonstrates that a passing front could delay the development of a phase, in this case phase two, without necessarily altering or reversing the order of phases.

(3) May 6-19 1973 serves as a typical example of summer fog development along the central California coast. The manner in which the development shifts from one phase to another, forward and backward, and the effect of frontal passages is clearly seen.

On 6 May, a condition of no inversion existed at Oakland, with an upper air inversion at 550 m. This was phase four. Overcast was reported at three of the four stations. On 7 May, a cold front passed through central California which resulted in an almost isothermal sounding below 1050 m. All stations reported scattered haze and overcast. On 8 May, the sounding indicated a weak phase two, with a mild surface inversion and conditions starting to warm aloft. Haze was reported at Pillar Point. On 9 May, phase three was in evidence as the inversion base rose to 290 m, with fog occurring at Monterey Airport and Point Pinos, and haze at Pillar Point. On 10 May, conditions reverted to between phases two and three, with surface warming causing a weak surface inversion with an upper inversion at 210 m. Only haze was reported at three of the stations. The 11 May sounding disclosed that increased warming had strengthened the surface inversion, resulting in phase two conditions of haze and light

fog at all stations. On 12 May, an inflowing marine layer combined with warm continental upper air to lift the inversion base to 220 m (phase three). Heavy or light fog was observed at all stations, along with some overcast. On 13 May, continued warming forced the inversion base to 100 m, but with a strong increase in the gradient at 540 m. Various combinations of intermittent heavy fog, light fog, haze and overcase were present at all stations, indicative of phases three and four. On 14 May, conditions remained about the same. The upper gradient had weakened and lowered to 350 m, and the primary inversion base was at 100 m. Light fog was reported at Pillar Point, with haze and overcast at Monterey. On 15 May, cooling of the upper air with warming of the marine layer raised the inversion base to 350 m. Phase three was evident with heavy fog reported at Pillar Point, and light fog and haze at Monterey. For the next three days (16-18 May), the inversion base remained close to 200 m and heavy fog occurred at all stations. This was a continuation of phase three. On 19 May, the inversion base lifted to 510 m, which characterized phase four, and overcast became prevalent. It had taken 13 days for this sequence to run to completion.

From Figures A-1 and A-2 it is evident from the density of fog in the summer that most fog occurrences follow this irregular pattern of development. It is still possible, as shown above, to identify the individual phases of fog development, but it becomes

difficult, in the light of the available data, to know where one sequence terminates and the next one starts.

The final summer fog sequence examined, that of 23-30 September 1973, is especially interesting due to supplementary fog observations from R/V Acania.

The sequence began with a no inversion condition on the 0400 23 September Oakland sounding (Appendix B). Some haze and overcast was reported, probably due to a passing cold front. The upwelling index was high at 100 m^3/sec. Phase one continued into the next day, with another no inversion sounding on 24 September (although a mild upper air inversion did exist). On 25 September, phase two began as the sounding showed a surface inversion with warming of the air column. The upwelling index began to dip, and the temperature index began a steep climb. The moisture index began to decrease as a result of the warm, dry offshore airflow. The soundings for 26 and 27 September showed continued surface inversions (phase two) with increased warming. The upwelling index and moisture index continued to fall, and the temperature index continued to climb. The 28 September sounding showed the unusual situation of a very shallow yet intense surface inversion beneath an isothermal layer. The author feels that due to the cooling which is evident in the following day's sounding, the conditions on 28 September must have developed into phase three.

This is borne out by Figure 6 which shows the results of a one day data-gathering cruise by R/V Acania on 28 September 1973. When the Acania got underway at 0935, visibility conditions were clear. On entering the offshore fog bank at 1155 (PDT), the air temperature was 14.4°C, and the bucket sea-surface temperature was over 15°C. Therefore, the base of the inversion base had risen off of the surface. (It is of interest to note that the surface temperature recorded at Monterey Airport at 1150 (PDT) was 25°C, emphasizing the difference between a station on the water and one slightly inland.) As seen from Figure 6, it was noted that at 1700 (PDT), the fog line had advanced toward shore past Point Pinos, but had not yet enveloped Monterey Harbor. From Appendix B Point Pinos reported heavy fog commencing at 1430. The fog advected inland, and was recorded as light fog at 1915 and heavy fog at 2015 at Monterey Airport. (The airport surface temperature had dropped to 12.8°C by this time). Farther north, Pigeon Point reported heavy fog at about 1930, and Pillar Point at 1800. As further evidence that the marine layer was established over the ocean, the moisture index rose sharply, and the temperature index peaked and began to fall off.

The sounding on 29September reflected surface cooling at Oakland, which meant phase three conditions over the ocean. Fog was evident in the morning hours at all stations. The upwelling index had begun to rise. By 30 September, the Oakland radiosonde showed an inversion with a base at 425 m, which means that phase four

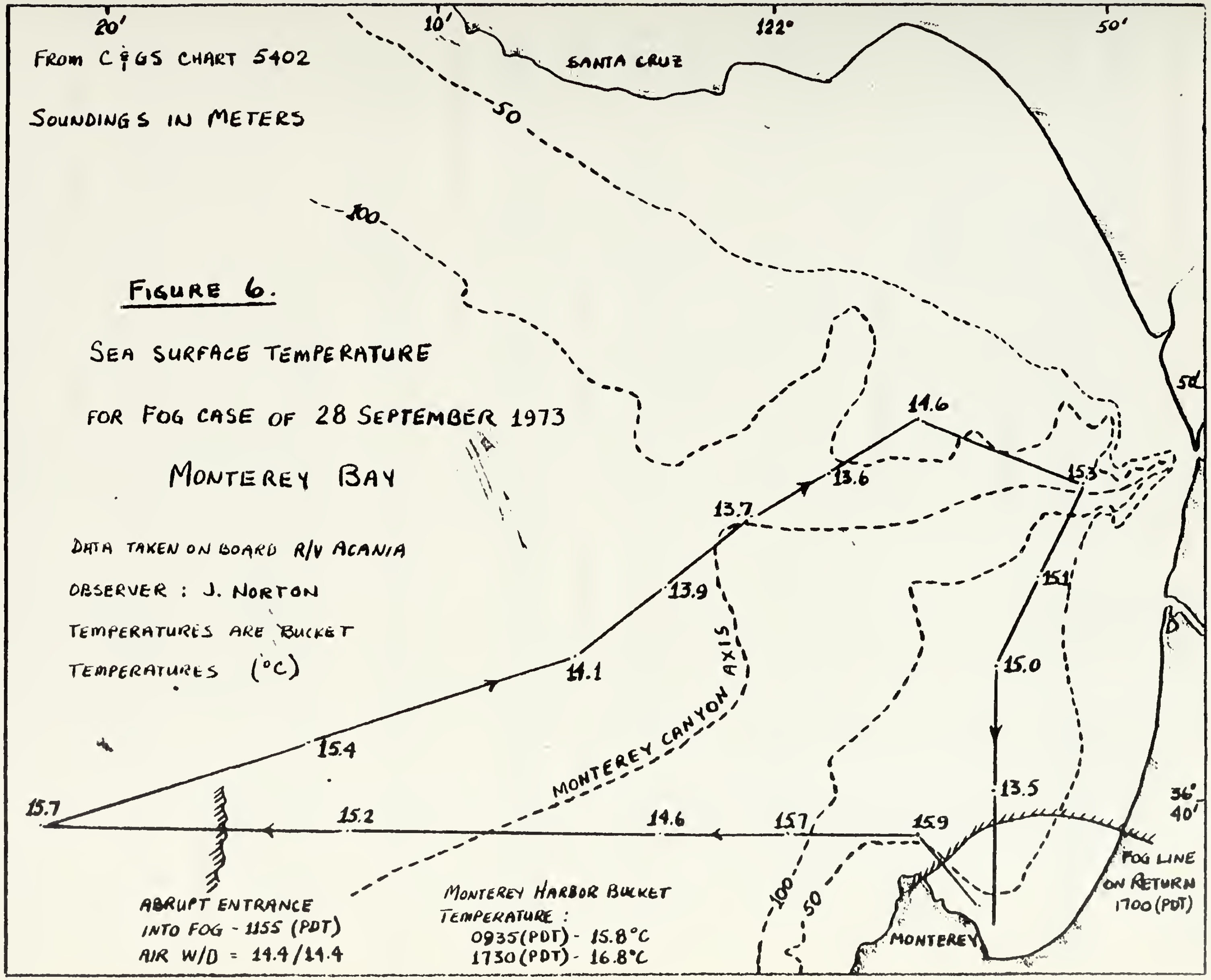


Figure 6.

Sea Surface Temperature for Fog Case of 28 September 1973

Monterey Bay

had been entered. Haze and overcase was evident at all stations. Phase four continued into the next day as the inversion base continued to lift, with resulting overcast. The phase and sequence terminated on 1 October. This sequence was valuable because it provided data which could be correlated between stations.

3. Winter

a. General Comments

There were four coastal fog sequences during the winter period. All four were either initiated or modified by frontal activity. Therefore, it appears that, with only four cases as a data base and the degree of variation which existed among the cases, it would not be possible to construct a representative ideal sequence for the winter season. However, it is considered worthwhile to list the similarities of the four winter cases.

b. Similarities Among Winter Fog Cases, With An Actual Sequence Described.

The synoptic situation in the winter was decidedly different from the summer. The North Pacific high was displaced to the southwest which allowed the frequent passage of cyclonic depressions from the Gulf of Alaska across the central Pacific coast. This usually involved the movement of the low from the northwest. Additionally, an inland anticyclone, initially situated over Oregon or Washington moved southward as the low approached the coast. The isobaric

patterns were generally perpendicular to the coast. Depending on the relative position of the two air masses, the winds were mostly from the southwest quadrant.

On the days of fog, the 0400 Oakland sounding usually indicated either a surface inversion or no inversion. As shown by Table VIII, there were only eight days during the winter when the Oakland inversion was between the surface and 400 m. The moisture index, in three of the four cases, increased noticeably above the average for the winter.

The same effect was noted for the temperature index. However, when a day by day analysis was attempted, it was found that patterns which existed in the summer sequences were not apparent in winter. The main similarity of the four winter sequences was the occurrence of at least one frontal passage sometime during the sequence. However, the effect of the passage was to confuse conditions so that no consistent pattern could be observed.

As an example of a case of winter fog development, the period 8-15 December 1973 is described. On 8 December, a high pressure area centered over Vancouver Island caused the surface isobars to be oriented normal to the coast, with an offshore air flow, causing a modest degree of upper-air warming. The sounding for 8 December showed a surface temperature several degrees lower than the sea-surface temperature, with a slight inversion base at 400 m.

Visibility at all three stations (Pigeon Point data was not available) was clear or light haze, except that Pillar Point had fog from 1700-2000. This fog probably resulted when the anticyclone to the north began its southward movement, causing warming and creating a surface inversion with the air reaching the coastline from the southeast and south. Such conditions were reflected the following day, when the sounding showed such an inversion. Additionally, the moisture index decreased and the temperature index increased. The Hidden Hills maximum daily temperature increased while the minimum relative humidity decreased. December 9 was a clear day at all stations, as would be expected from the high degree of heating.

On 10 December, the anticyclonic circulation drove the upper-air temperature to the highest value for the month, although the surface air temperature decreased due to the influence of an approaching cold front from the northwest. Pillar Point experienced haze most of the day, while Point Pinos and Monterey Airport had scattered haze, fog, and overcast during that night and into the next day.

On the 11 December sounding, a surface inversion existed, as well as an upper inversion with a base at 550m. Frontal influence became evident over the next three days with the cooling of the air column. The surface inversion gradually weakened on the 12th and 13th as the front passed through the area, so that by 14 December it had disappeared completely. During this period, the MI peaked on

the 13th, as the effects of the continental high were felt on the 14th and 15th. The TI decreased as marine air invaded the area, then increased on the 15th. Visibility conditions on the 12th and 13th were primarily haze and overcast; however, on 13 December fog appeared at Pillar Point for nine hours in the morning.

On 14 December a high pressure area was taking shape over Nevada with the isobars extending to the California coast. The warming at the coast resulting from this high began during the 14th when a surface inversion undoubtedly formed over the ocean. Heavy fog was observed at both coastal stations. The Hidden Hills maximum daily temperature was climbing and the relative humidity was decreasing. The sounding for the 15th showed a surface inversion with upper-air warming. The low moisture index kept conditions clear or hazy that day. For the next two days, the central Pacific coast came under the influence of a frontal depression; therefore, 15 December is considered the end of this sequence.

C. COMPARISON OF OAKLAND AND NPS RADIOSONDES

The Oakland International Airport was the only location near the central California coast where upper-air data were collected every day, twice daily during the period of interest. The radiosonde data are still being taken and the data are available. The only unfavorable aspect of using Oakland upper air soundings for the present purposes was the location. As previously noted, Oakland is

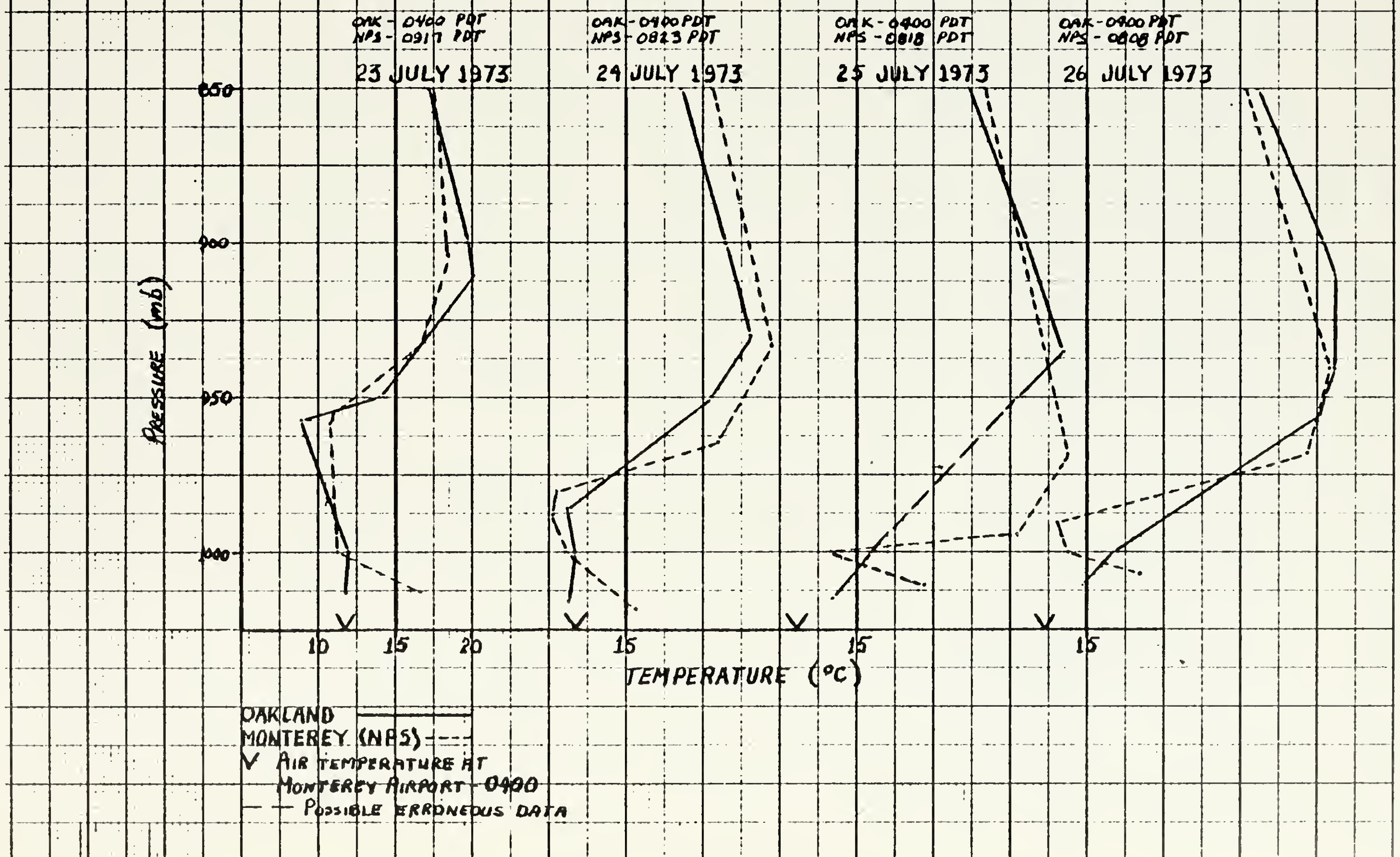
separated from the ocean by a mountain range, and it lies on a bay where the surface and air temperatures are generally higher than those at sea. Since this paper uses the Oakland sounding as an indicator of the inversion characteristics for the central California coast, it is pertinent to consider how accurately that sounding reflects actual coastal conditions.

The only other 1973 soundings available to compare to Oakland data were four radiosondes taken at the U. S. Naval Postgraduate School in July. The NPS launch site was located one-half mile from Monterey Bay. Figure 7 shows the soundings from the two locations compared on the same axis. It should be noted that the NPS data were acquired between four and five hours later in the day than the Oakland data; therefore, allowances must be made for diurnal heating. The air temperature at Monterey Airport at the approximate time of the Oakland sounding is indicated by a caret on the temperature axis.

The diurnal effects are readily seen at the surface, where the NPS temperature was greater than Oakland in all cases. The air temperature at Monterey Airport was less than or equal to the Oakland temperature on three of the four occasions, and only slightly greater than Oakland in the fourth case. Both curves had the same general shape and would undoubtedly have been much closer had the data been taken simultaneously. Due to the large discrepancy between Monterey and Oakland on the 25 July curves and the fact that vertical

FIGURE 7.

UPPER AIR TEMPERATURE ~ OAKLAND AND MONTEREY ~ JULY 1973



points were widely spread at Oakland, it is believed that an error may exist or that data may be lacking in the Oakland curve. The Monterey sounding for 25 July was rechecked and found to be correct. All the curves were in closer agreement above 900 mb than they were below.

It can be said, based on the very limited data of Figure 7, that the Oakland sounding appears to be a good approximation of conditions over at least a portion of the central California coast, especially above 900 mb.

VI. CONCLUSIONS

From the data in Appendix A, it is seen that 1973 can be divided into two distinct fog-related seasons along the central California coast. The summer season (late April through October) had a much greater incidence of fog than did the winter season (November through mid-April). During the summer, surface conditions were milder due to the insulating effect of the North Pacific anticyclone. Only infrequently did cold fronts pass across the coast, and the disrupting effect on a fog sequence lasted in terms of hours only. During the winter, frontal passages were a common occurrence, with cold fronts disrupting and delaying fog sequences for periods of days.

The strong gradient of the summer inversion was generally not present in the winter, due to the much reduced upper-air warming. Although supporting data are not available, it is possible that some of the winter fog observed along the coast was actually radiation fog formed over land and advected out to sea.

Data trends of the indices presented in Appendix A were analyzed and applied to the sequences of daily fog development. The moisture index and temperature index were found to be accurate indicators of the presence of continental and marine air. Also, the Hidden Hills temperature and relative humidity measurements were valuable in

providing intermediate-level air descriptions. The upwelling index varied seasonably as one might predict, but the value of this index declined when applied on a daily basis to fog sequences.

A development model of summer fog was formulated based on the variation of visibility and the trends of the non-diurnal indices. The model proceeds from clear conditions to haze, and then to the formation and advection of fog, ending with the lifting of the fog to form overcast. The formulation of such a model for the winter was not possible due to the small number of fog cases and the disruption caused by frontal activity.

Finally, it can be concluded that the Oakland radiosonde provided a good approximation of upper-air conditions over the coast of central California.

Based on the development model presented herein, it is believed that this study should aid the central California coastal fog forecaster in his work. By maintaining a continuous plot of the fog indices, the forecaster should be able to observe phase development and to foresee advective fog conditions before they occur, especially in the summer.

VII. RECOMMENDATIONS

As stated previously, the Oakland radiosonde proved to be a satisfactory representative for actual coastal soundings. However, it would be desirable to have on hand further upper-air data for the points of interest. The Naval Postgraduate School in 1975 acquired an acoustic sounder, which can output continuous readings of the height of the base of the inversion. This instrument has been operating on shore and on board R/V Acania, collecting valuable data for fog analysis. In the future, acoustic sounding data, if available, should be used in conjunction with Oakland sounding data.

The data which are presented in Appendices A and B were calculated manually, after a previous computer program produced results which did not show the true picture. It was found that a certain degree of analysis was necessary on many of the soundings, in order that the proper values were used for computing the indices. As an example, in the determination of the temperature index, the computer sometimes used the wrong T_T if there happened to be two inversions. The computer can be an invaluable asset, but the program must be written carefully by an individual aware of the manner in which the parameters fluctuate.

The daily radiosondes were plotted by hand. This proved to be a tedious task, which has since become unnecessary due to a computer

subroutine using the CALCOMP plotter, developed by R. Schwarz, then of the Meteorology Department of the Naval Postgraduate School. This subroutine will plot the sounding, using data available from Oakland or elsewhere.

As mentioned previously, the upwelling index was useful in the seasonal description of fog. However, it would be interesting to be able to compare daily sea-surface temperature fluctuations to the daily upwelling index, to determine if the sea-surface temperature varied as predicted.

In this paper, data which were readily available were utilized to analyze fog development. As in many research ventures, it is realized that the data available were not the most descriptive for the task at hand. What is needed is surface and upper-air data in the area of advective fog formation, i. e., over the open ocean to the west or northwest of the Golden Gate. An ideal location for a data collection station would appear to be North Farallon Island. Such a station could collect radiosonde data, surface visibility and temperature, and sea-surface temperature -- all at the same time and for given periods of fog. If such a station proves unfeasible for future studies, possibly an unmanned data buoy, as recommended by Peterson and Leipper [1975], could be considered.

APPENDIX A

YEARLY DATA

FIGURE A-1

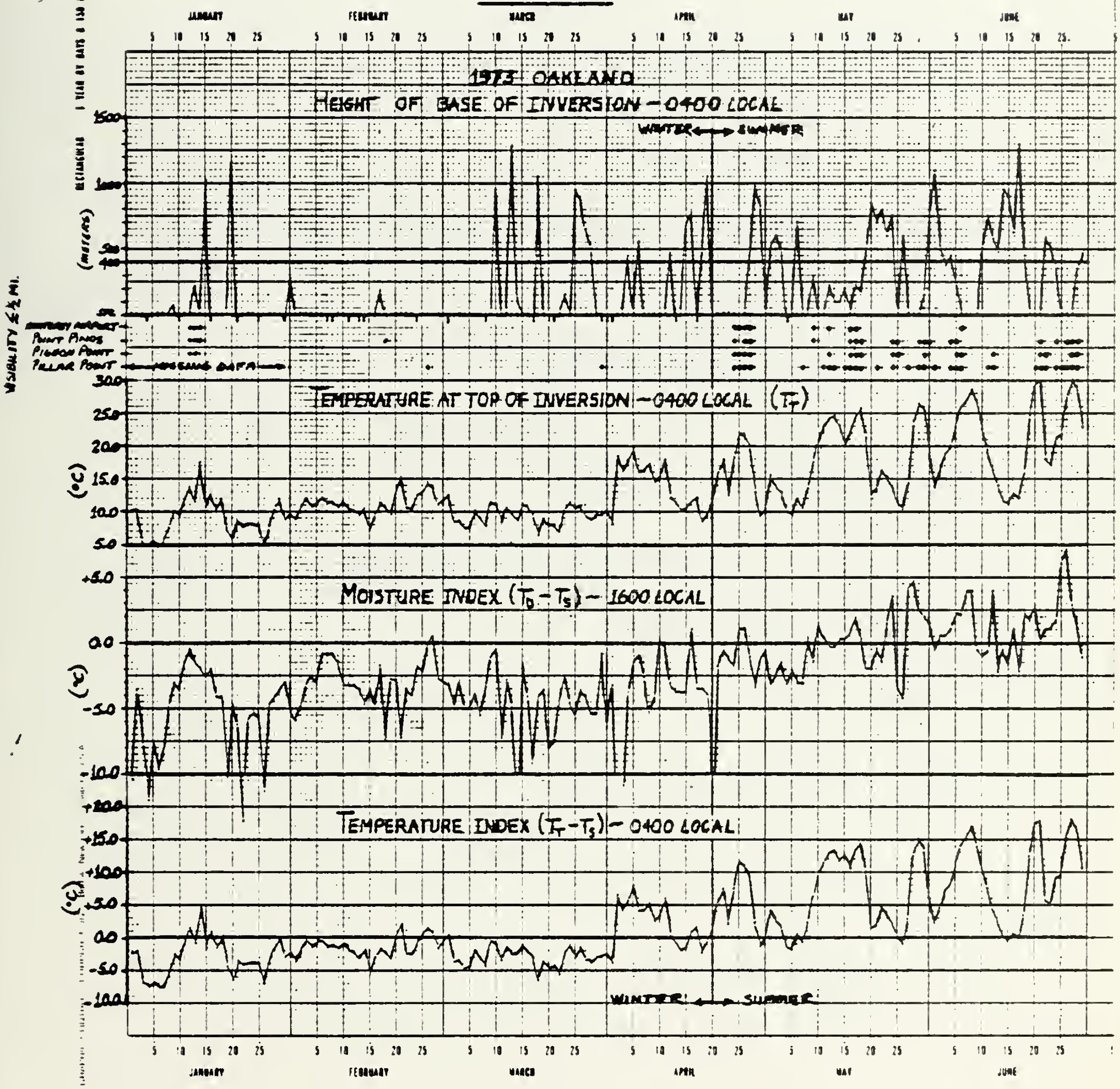
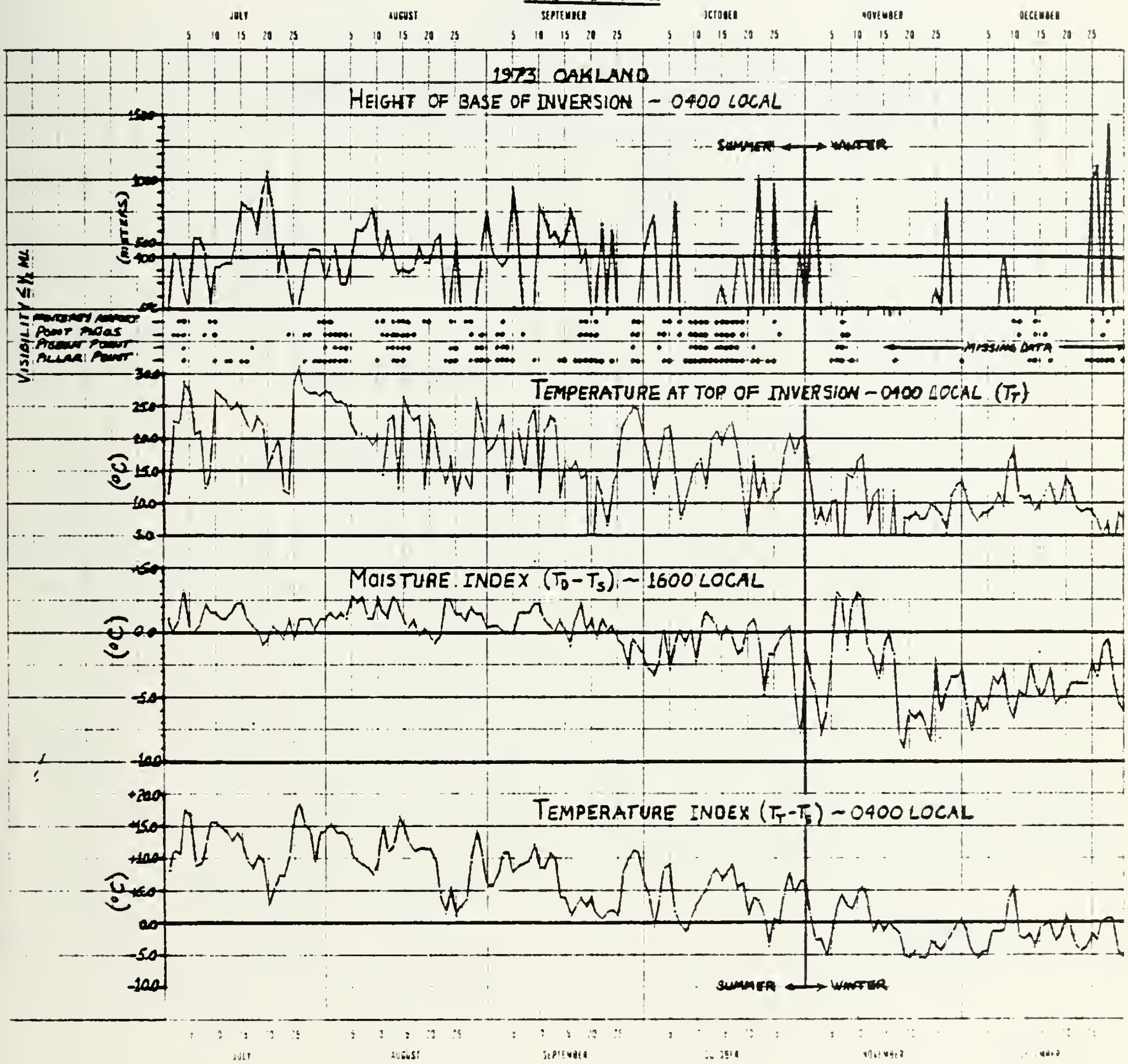

1973 OAKLAND
HEIGHT OF BASE OF INVERSION — 0400 LOCAL
WINTER ⟷ SUMMER
(METERS)
VISIBILITY ≤ ½ MI.
POINT PINOS
PIGEON POINT
PILLAR POINT
MISSING DATA
TEMPERATURE AT TOP OF INVERSION — 0400 LOCAL (T_T)
MOISTURE INDEX ($T_D - T_S$) — 1600 LOCAL
TEMPERATURE INDEX ($T_T - T_S$) — 0400 LOCAL
(°C)
WINTER ⟷ SUMMER
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE

FIGURE A-2


1973 OAKLAND
HEIGHT OF BASE OF INVERSION ~ 0400 LOCAL
SUMMER ← → WINTER
(METERS)
VISIBILITY ≤ ½ MI
MISSING DATA
TEMPERATURE AT TOP OF INVERSION ~ 0400 LOCAL (T_T)
MOISTURE INDEX (T_D-T_S) ~ 1600 LOCAL
TEMPERATURE INDEX (T_T-T_S) ~ 0400 LOCAL
SUMMER ← → WINTER
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

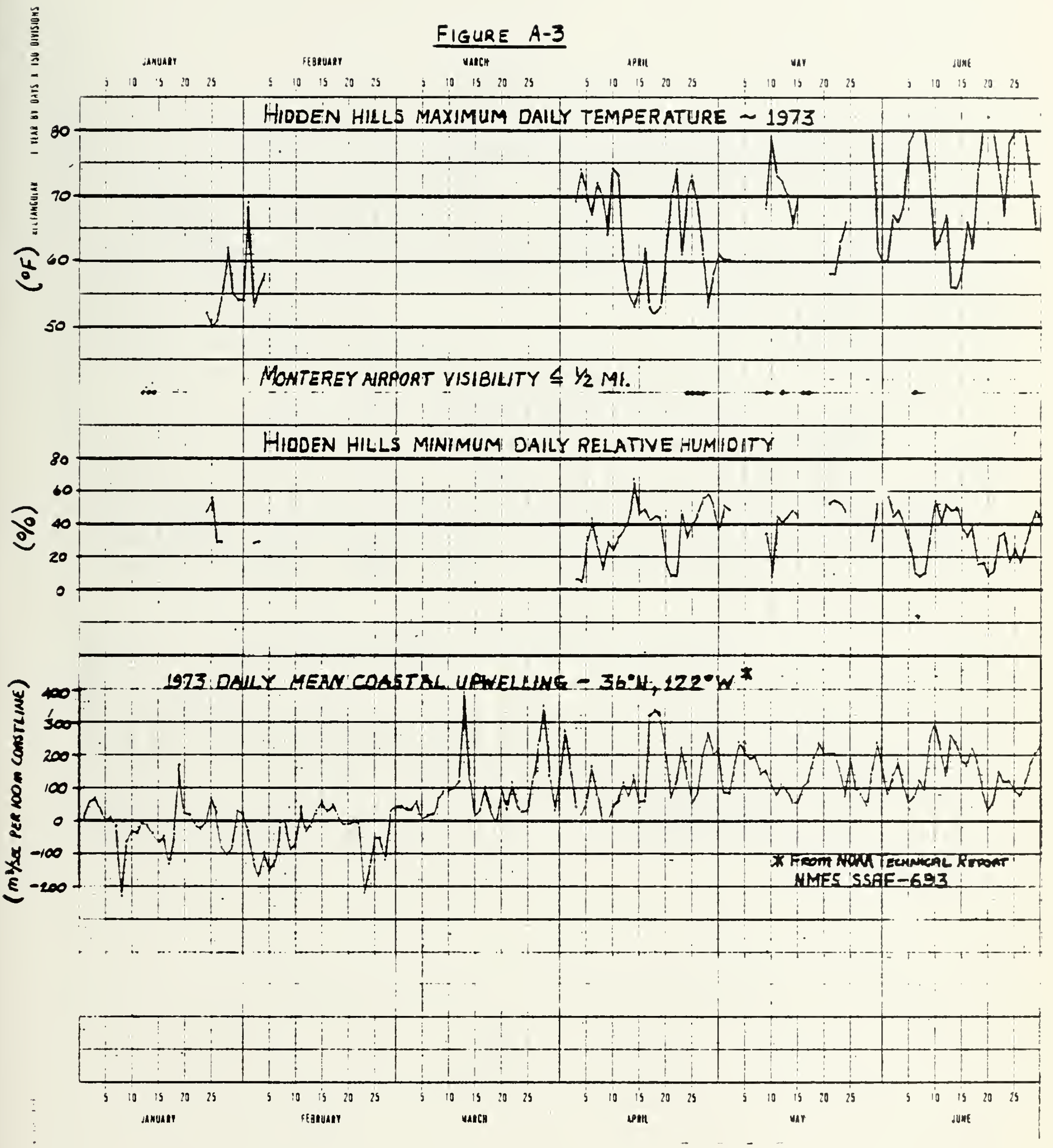
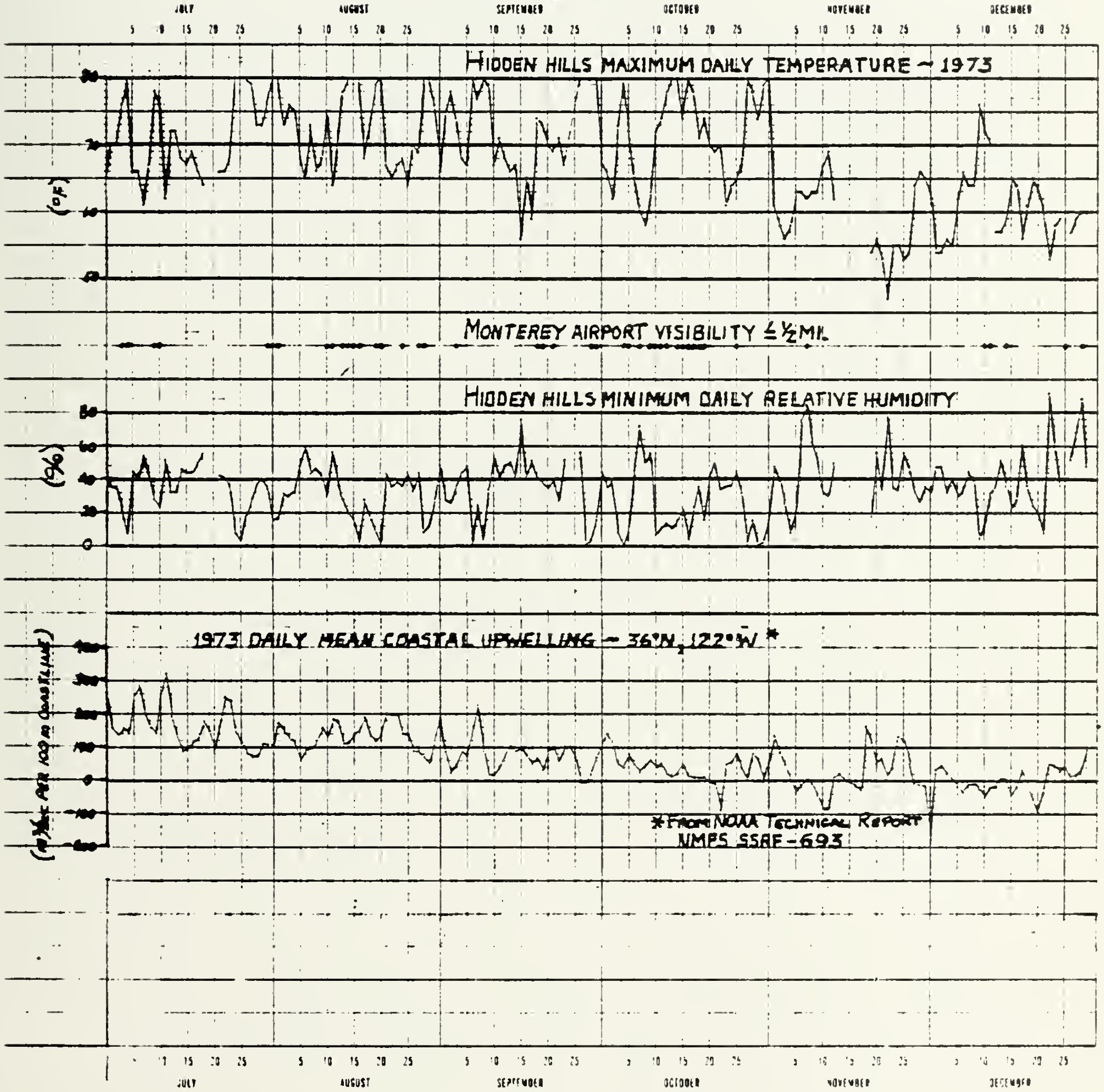


FIGURE A-3
HIDDEN HILLS MAXIMUM DAILY TEMPERATURE ~ 1973
(°F)
MONTEREY AIRPORT VISIBILITY ≤ ½ MI.
HIDDEN HILLS MINIMUM DAILY RELATIVE HUMIDITY
(%)
1973 DAILY MEAN COASTAL UPWELLING - 36°N, 122°W *
(m³/sec PER 100m COASTLINE)
* FROM NOAA TECHNICAL REPORT NMFS SSRF-693
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE

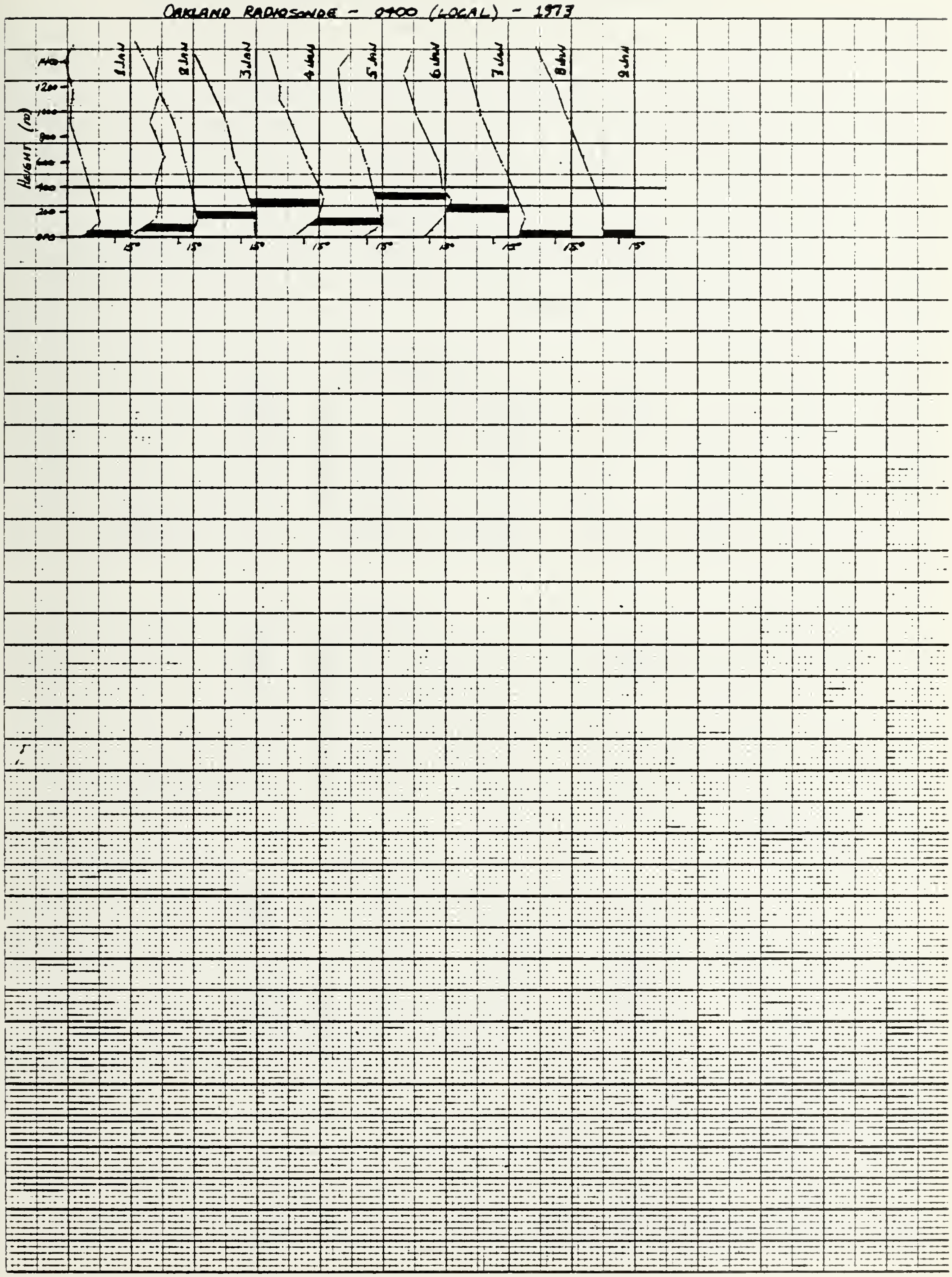
FIGURE A-4

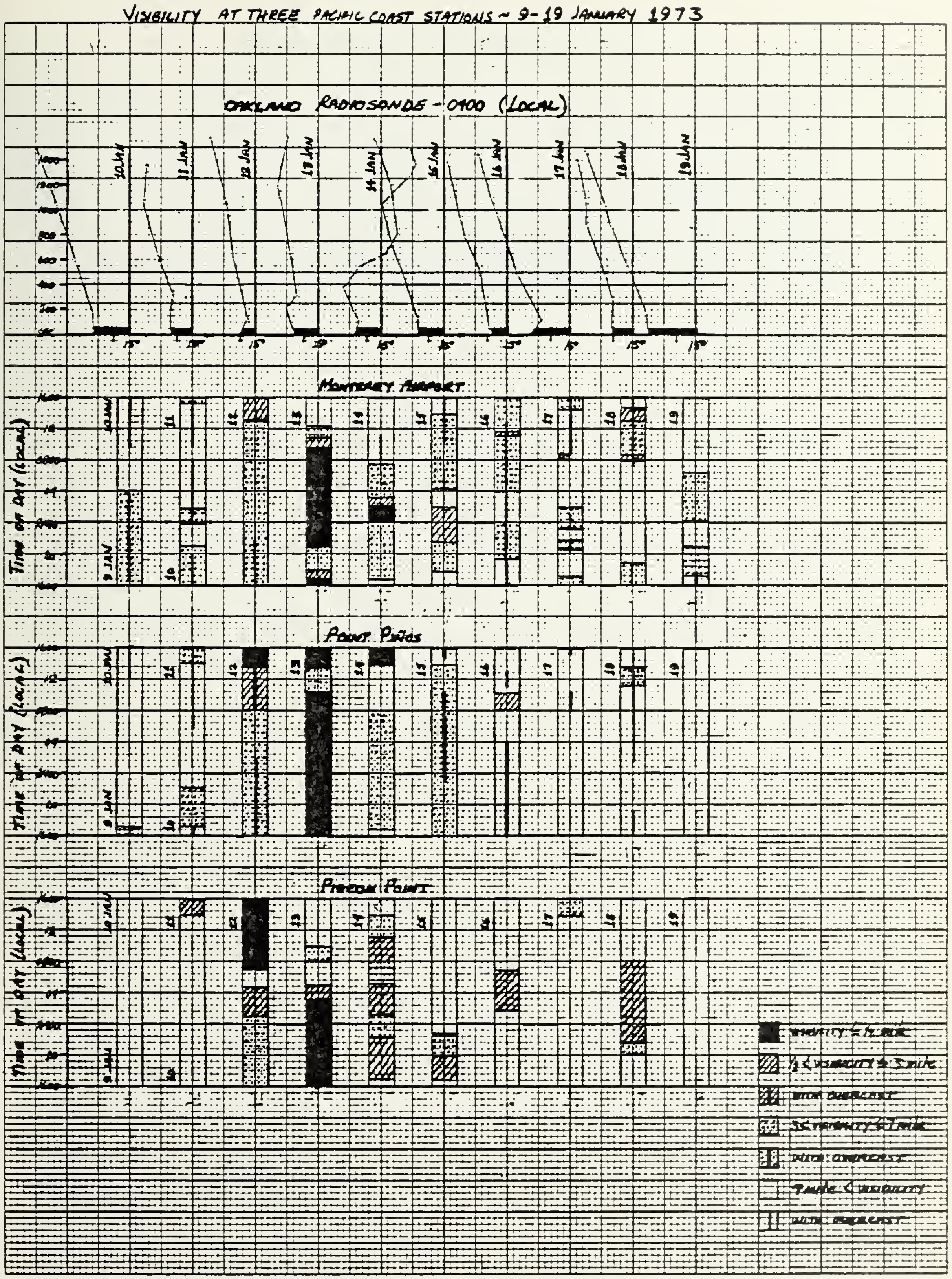


JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
HIDDEN HILLS MAXIMUM DAILY TEMPERATURE ~ 1973
(°F)
MONTEREY AIRPORT VISIBILITY ≤ ½ MI.
HIDDEN HILLS MINIMUM DAILY RELATIVE HUMIDITY
(%)
1973 DAILY MEAN COASTAL UPWELLING ~ 36°N, 122°W *
*FROM NOAA TECHNICAL REPORT
NMFS SSRF-693

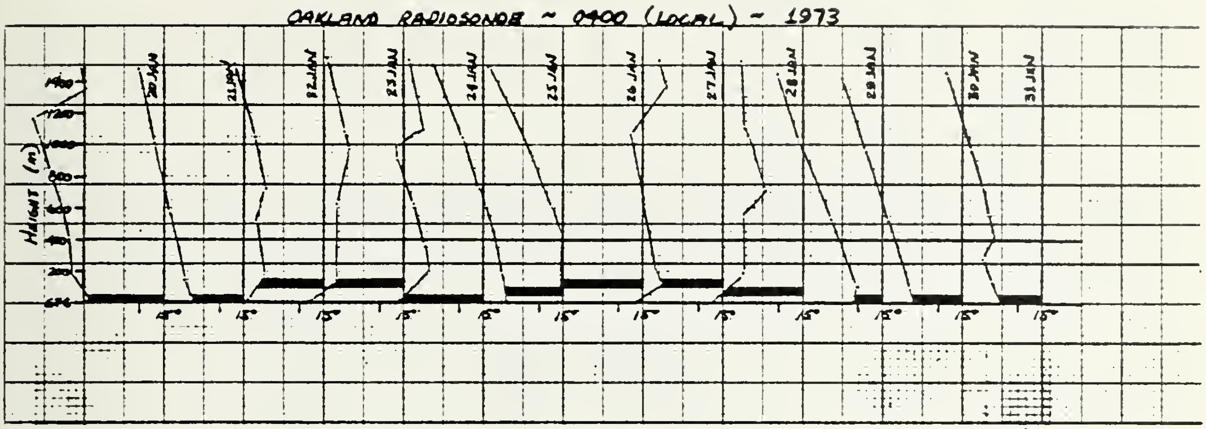
APPENDIX B

DAILY DATA

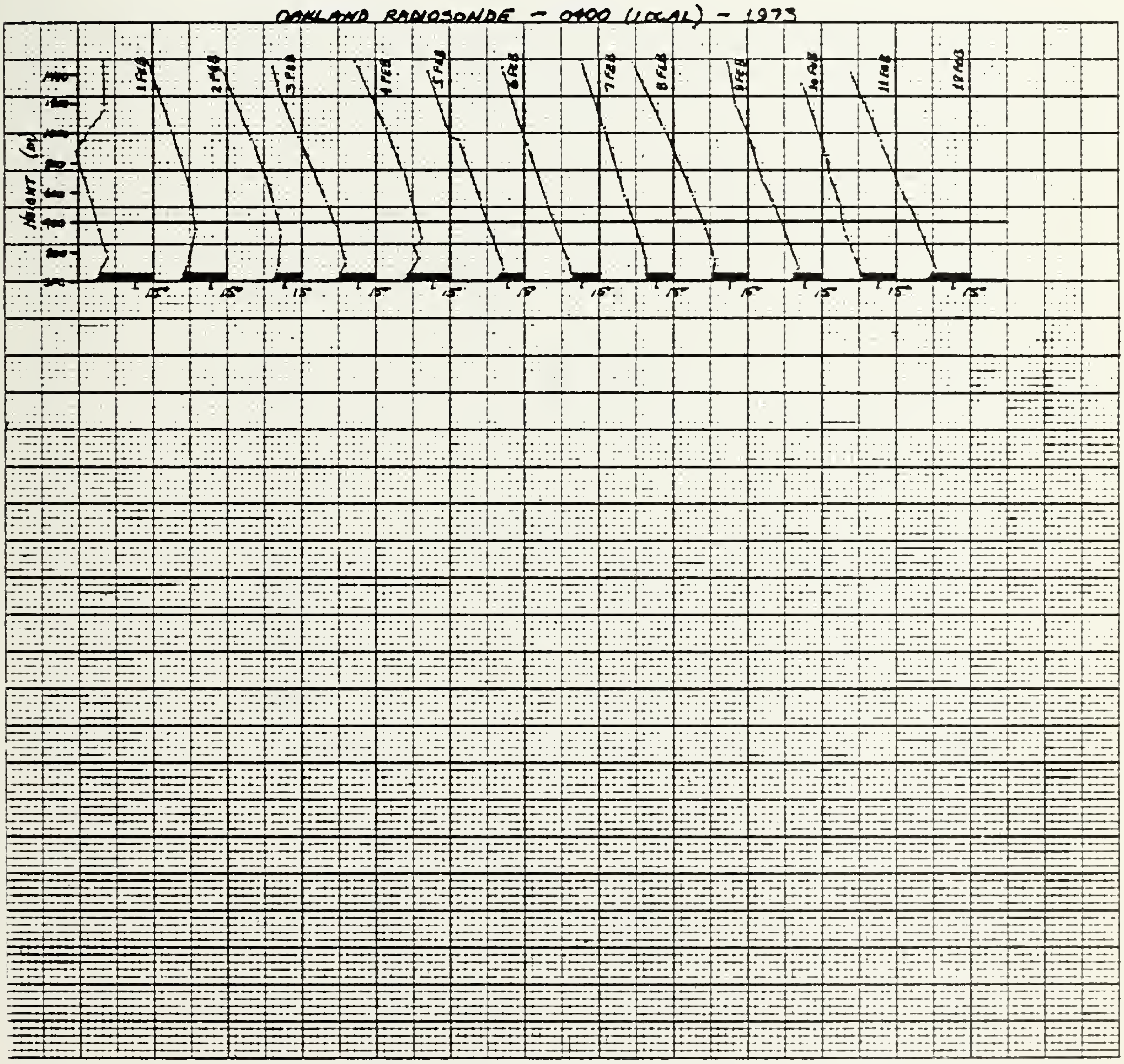

OAKLAND RADIOSONDE - 0400 (LOCAL) - 1973
HEIGHT (m)
1200
200
1 JAN
2 JAN
3 JAN
4 JAN
5 JAN
6 JAN
7 JAN
8 JAN
9 JAN
15°


VISIBILITY AT THREE PACIFIC COAST STATIONS ~ 9-19 JANUARY 1973
OAKLAND RADIOSONDE - 0400 (LOCAL)
MONTEREY AIRPORT
POINT PIÑOS
PIGEON POINT
TIME OF DAY (LOCAL)
1/2 < VISIBILITY ≤ 3 mile
WITH OVERCAST
3 ≤ VISIBILITY ≤ 7 mile
WITH OVERCAST
7 mile < VISIBILITY
WITH OVERCAST

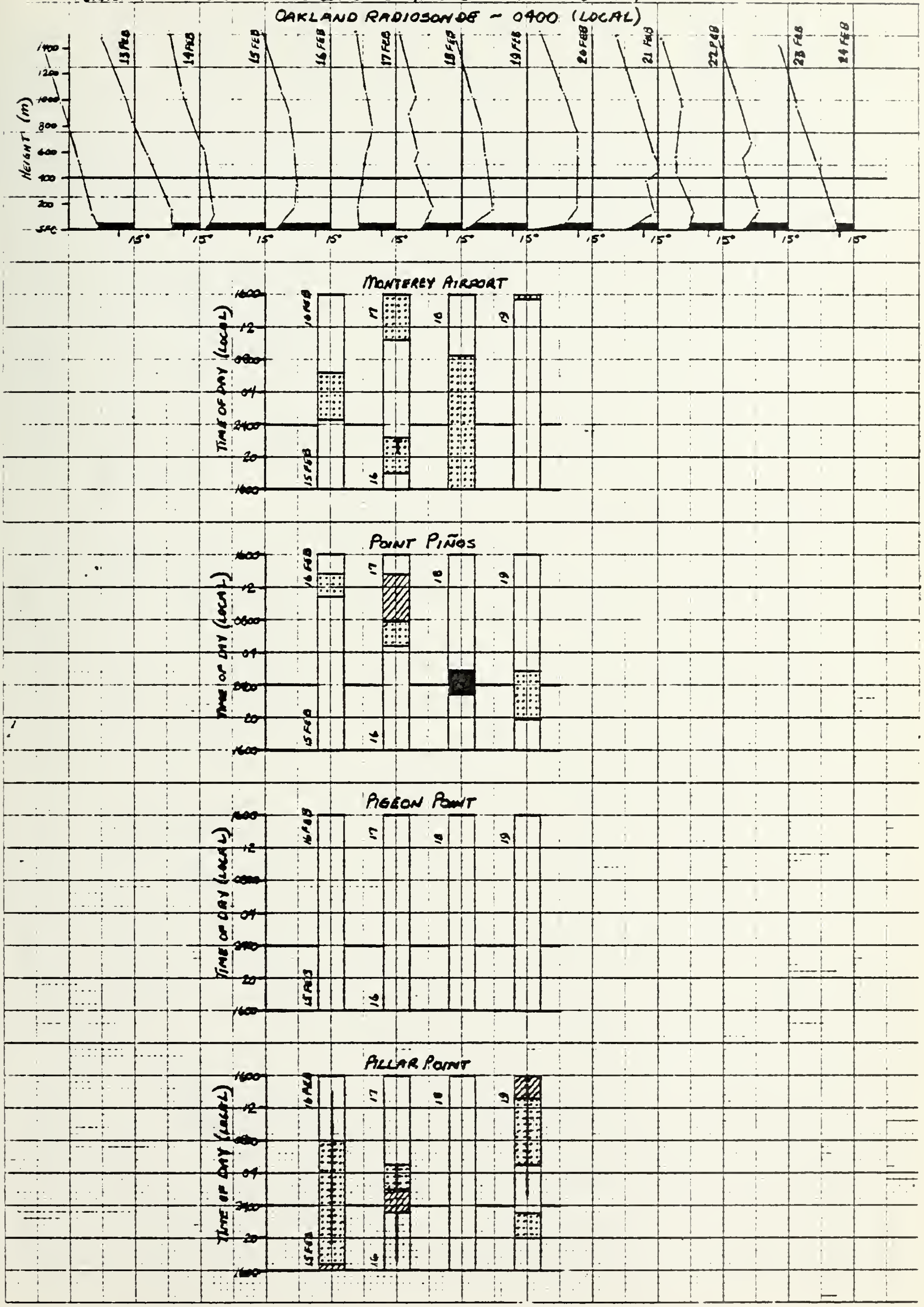
OAKLAND RADIOSONDE ~ 0400 (LOCAL) ~ 1973



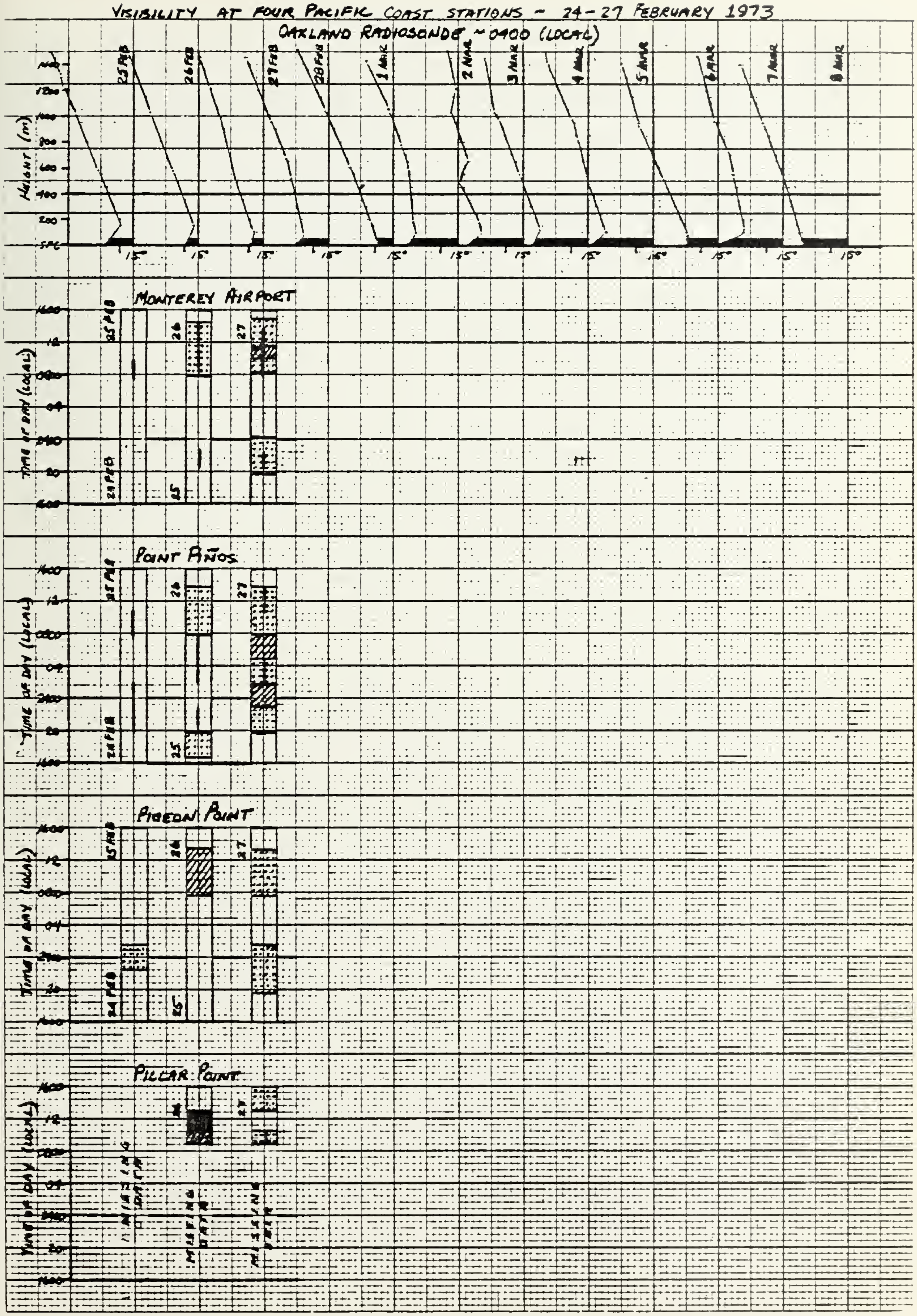
OAKLAND RADIOSONDE ~ 0400 (LOCAL) ~ 1973



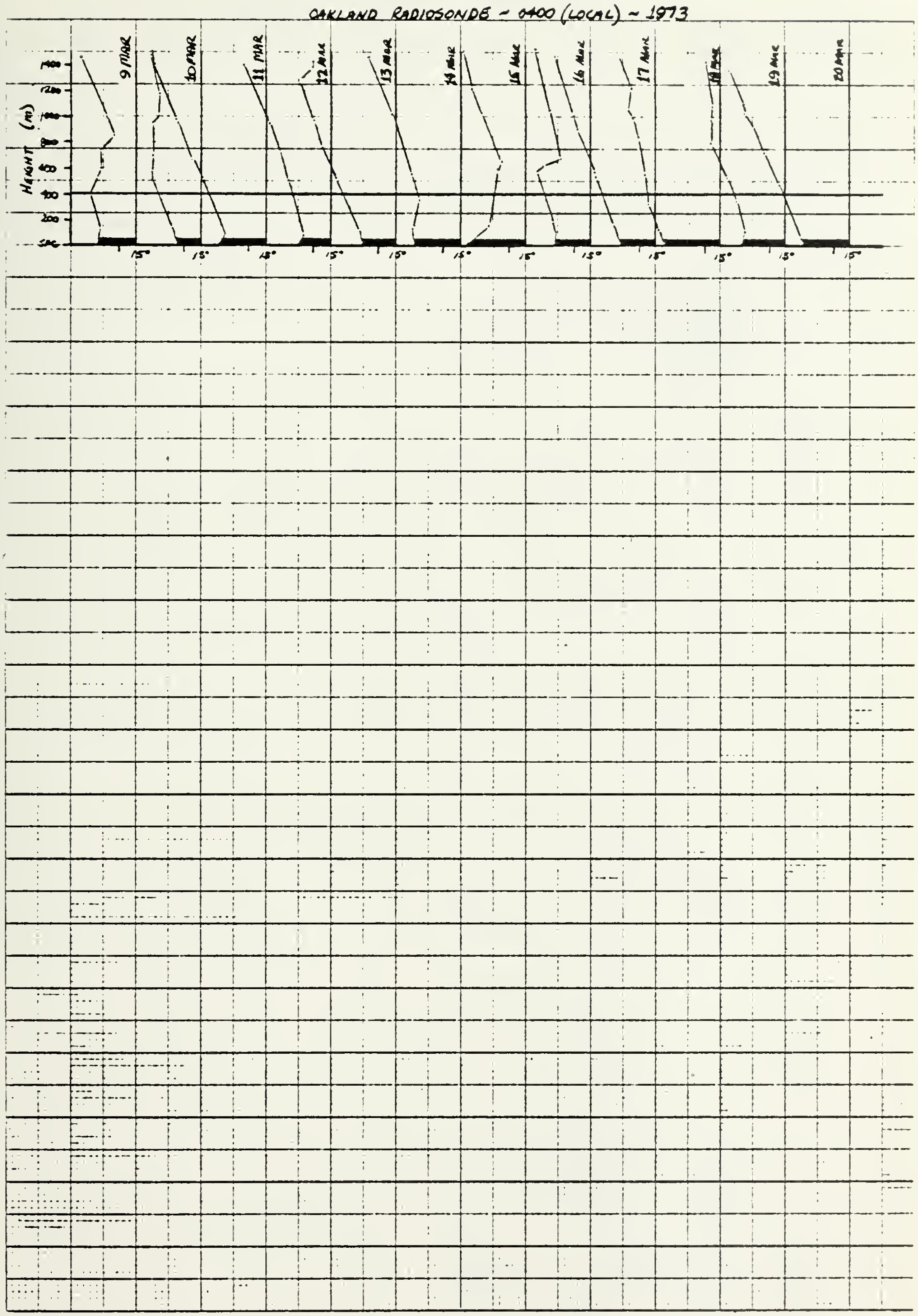
VISIBILITY AT FOUR PACIFIC COAST STATIONS ~ 15-19 FEBRUARY 1973



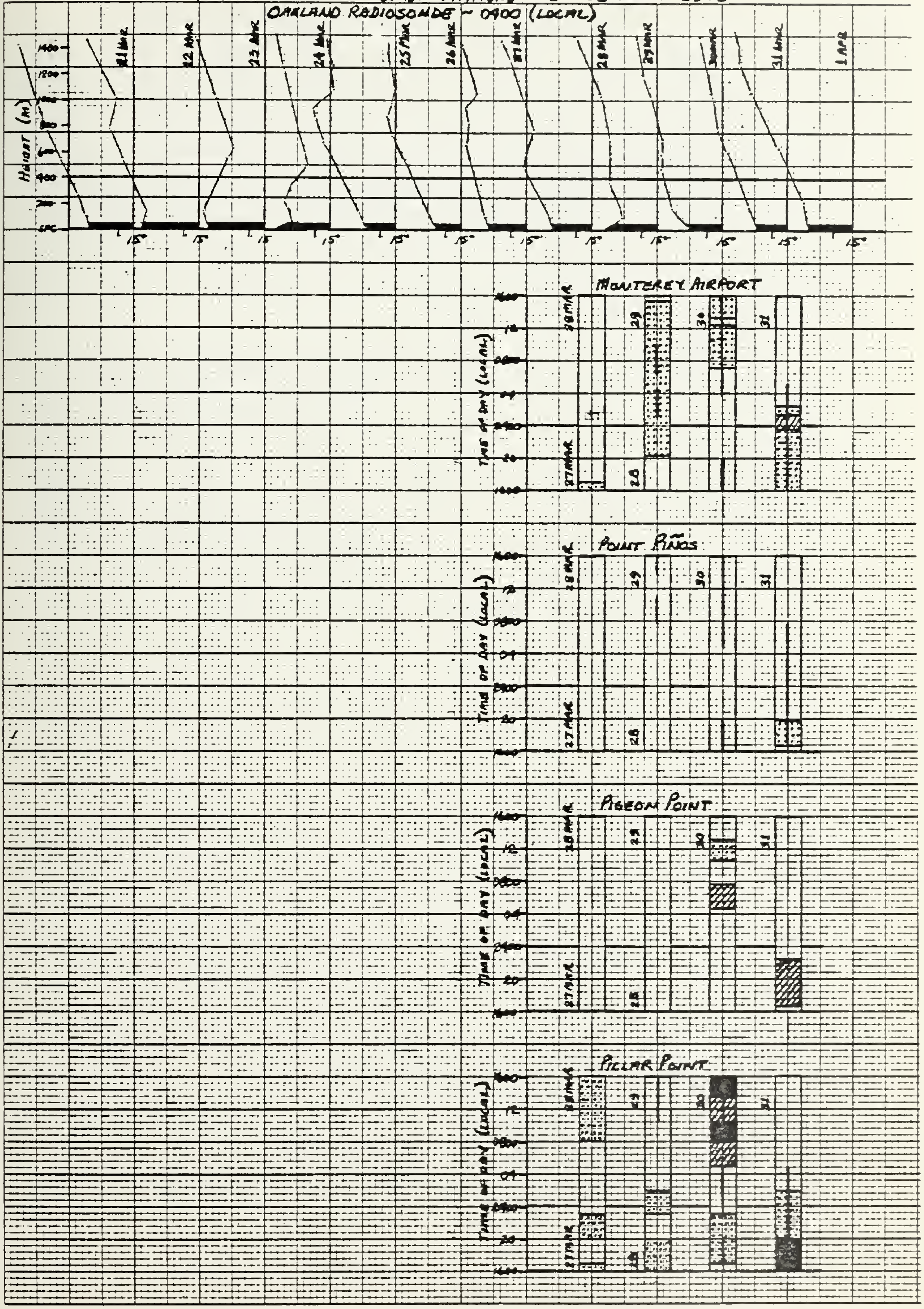
VISIBILITY AT FOUR PACIFIC COAST STATIONS - 24-27 FEBRUARY 1973

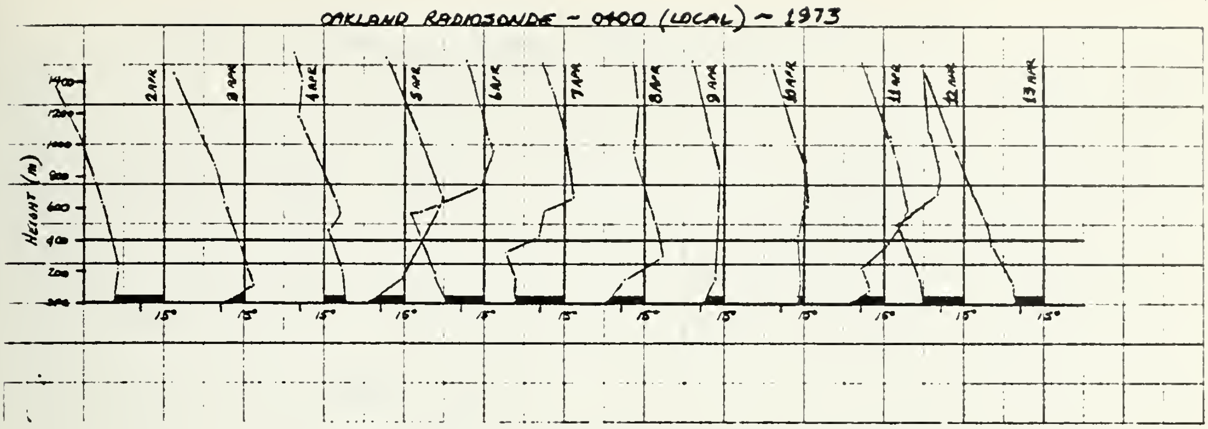


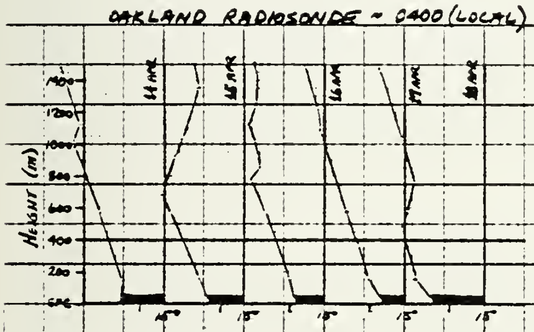
OAKLAND RADIOSONDE ~ 0400 (LOCAL) ~ 1973



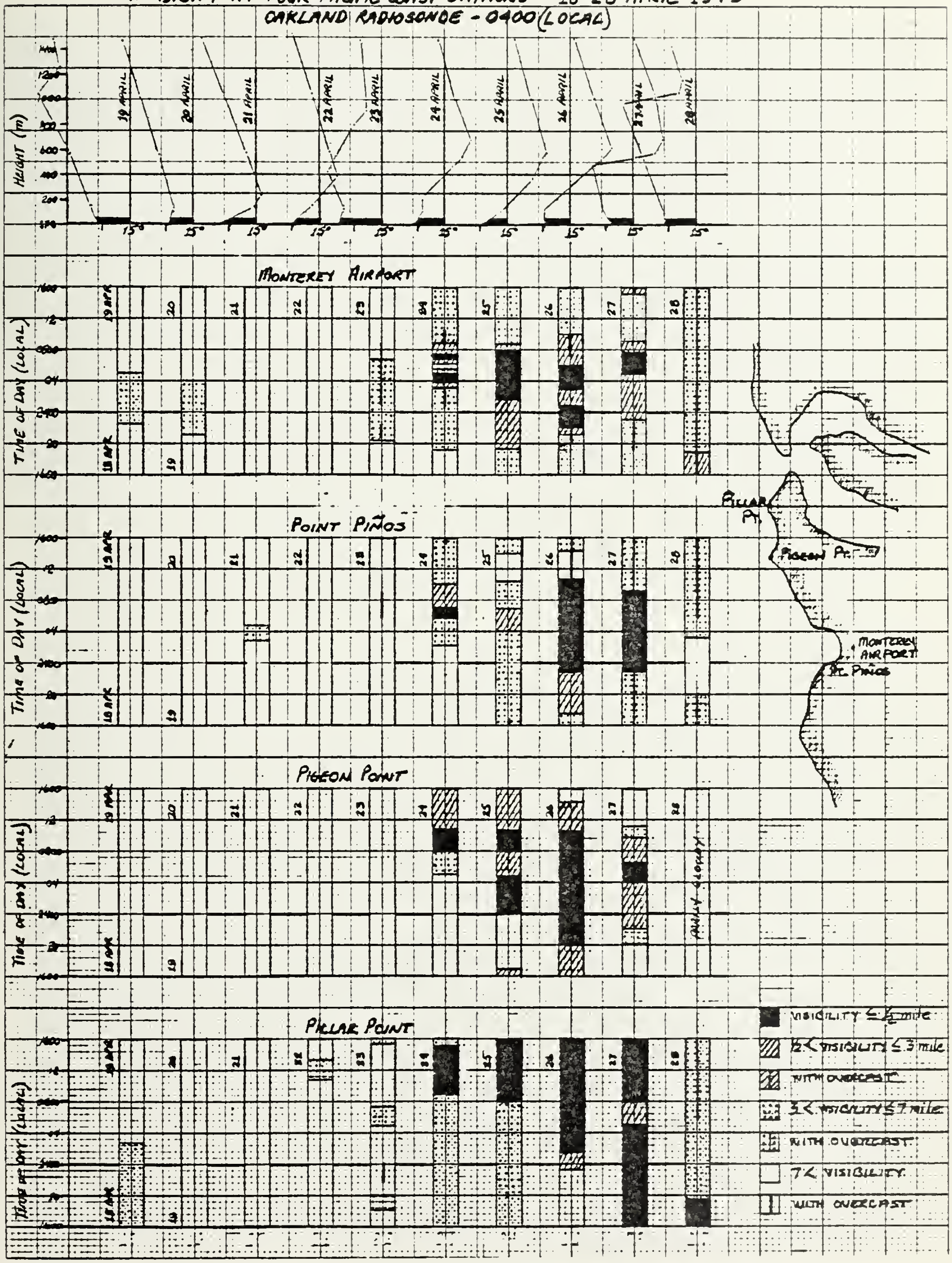
VISIBILITY AT FOUR PACIFIC COAST STATIONS ~ 27-31 MARCH 1973



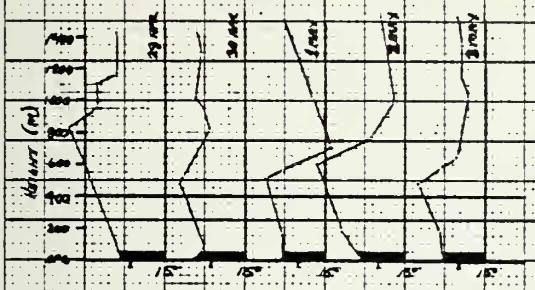

OAKLAND RADIOSONDE ~ 0400 (LOCAL) ~ 1973
HEIGHT (m)
2 APR
3 APR
4 APR
5 APR
6 APR
7 APR
8 APR
9 APR
10 APR
11 APR
12 APR
13 APR

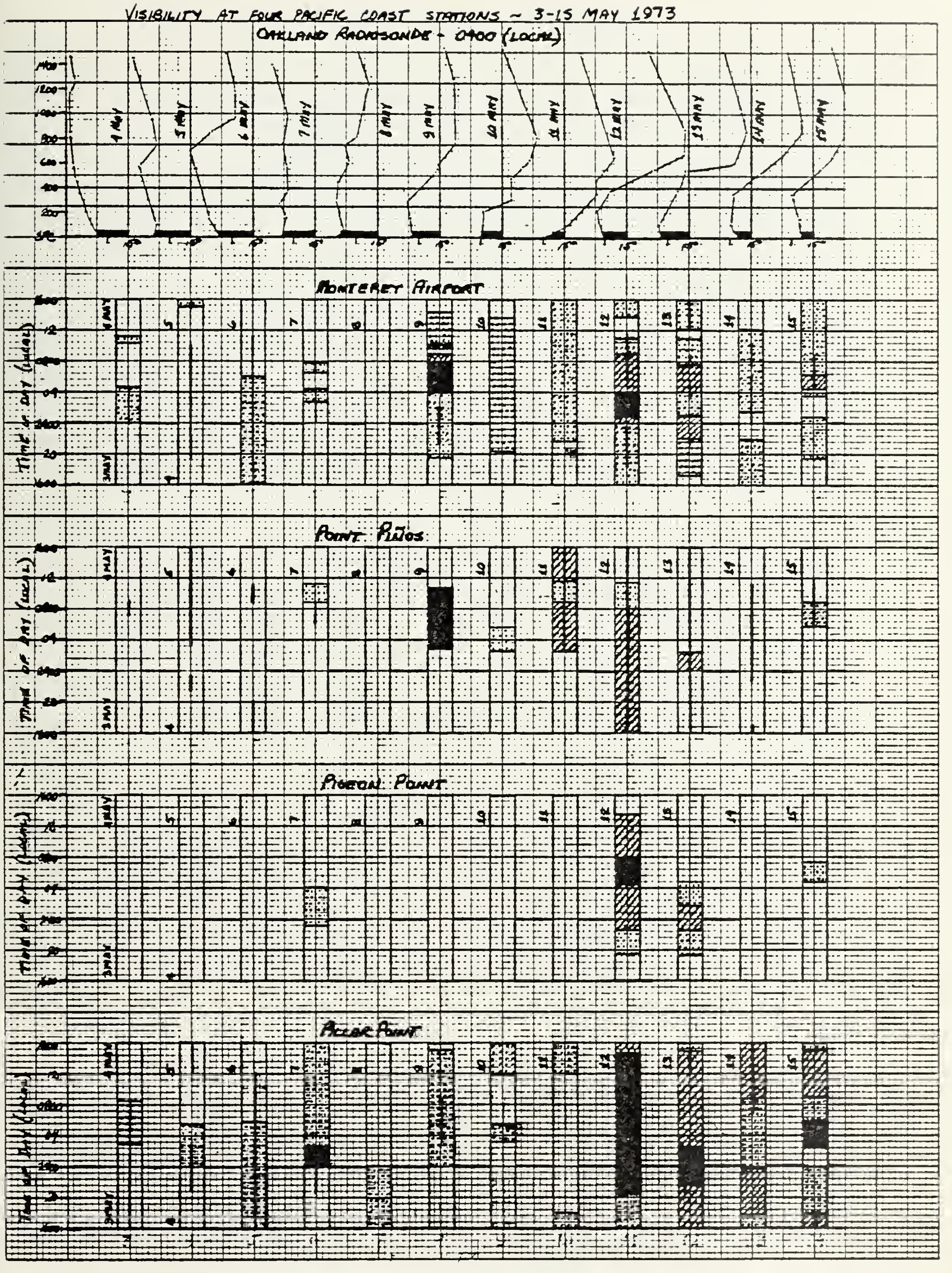

OAKLAND RADIOSONDE ~ 0400 (LOCAL) ~ 1973
HEIGHT (m)

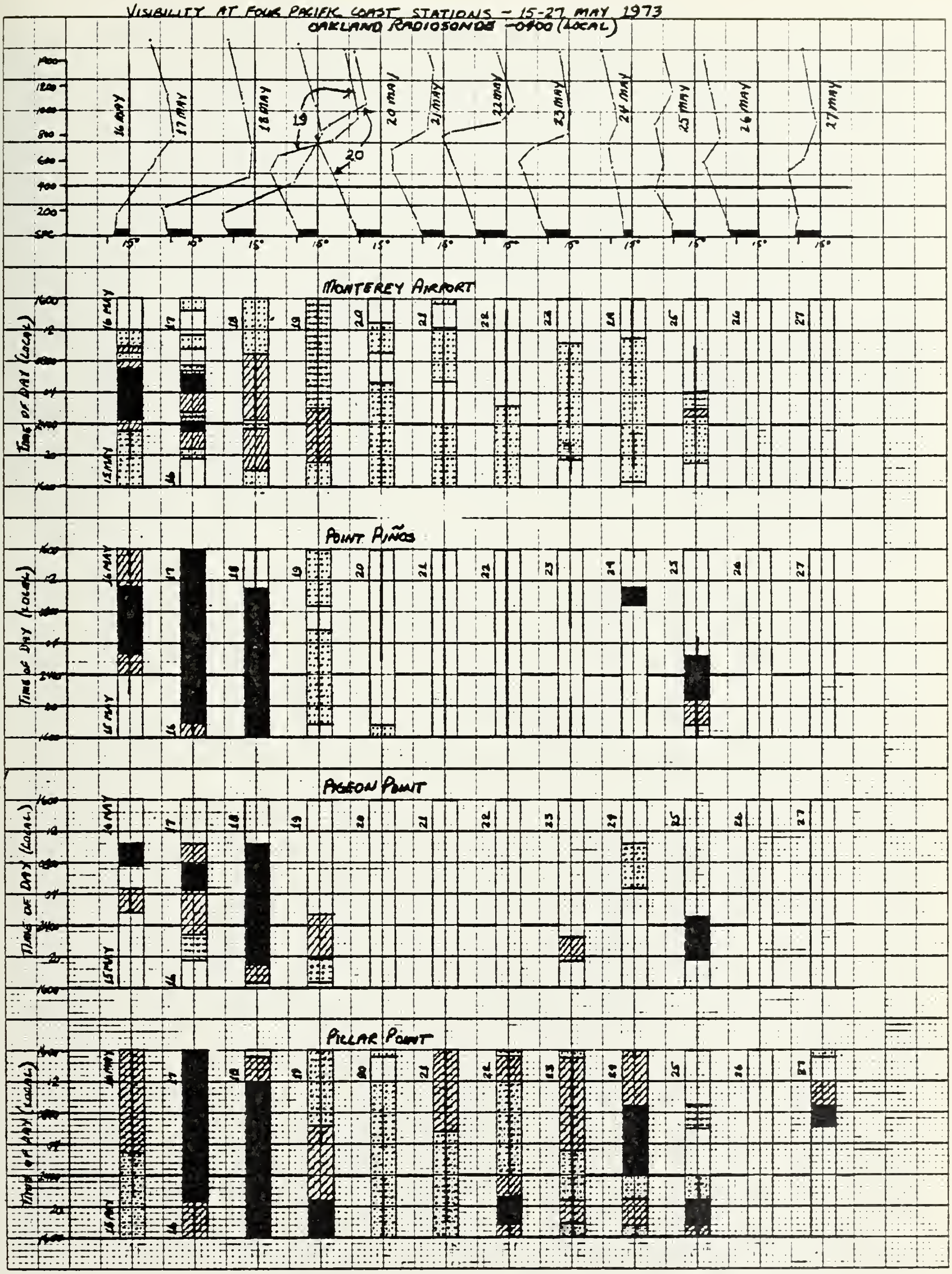
VISIBILITY AT FOUR PACIFIC COAST STATIONS - 18-28 APRIL 1973

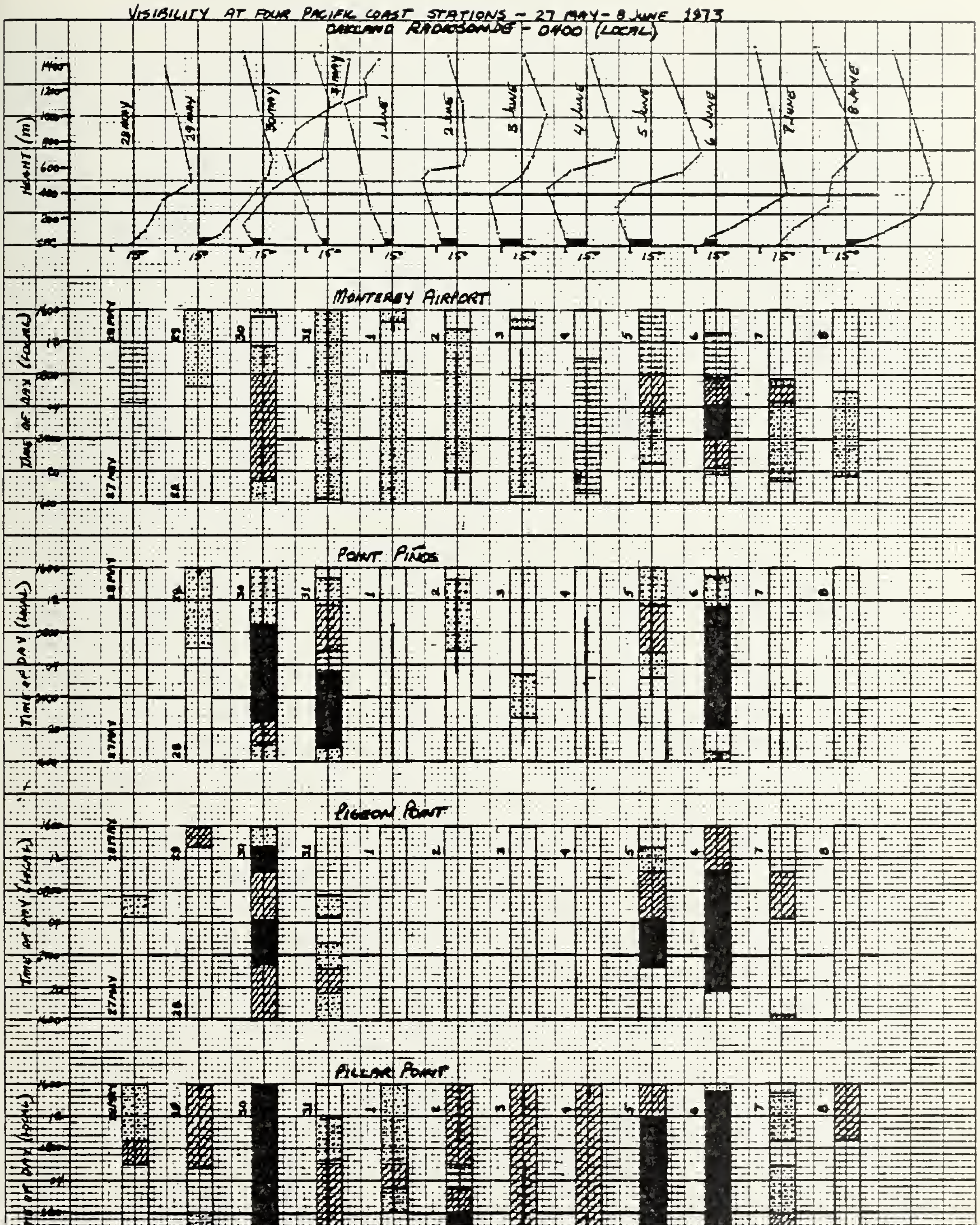


OAKLAND RADIOSONDE ~ 0400 (LOCAL) ~ 1973

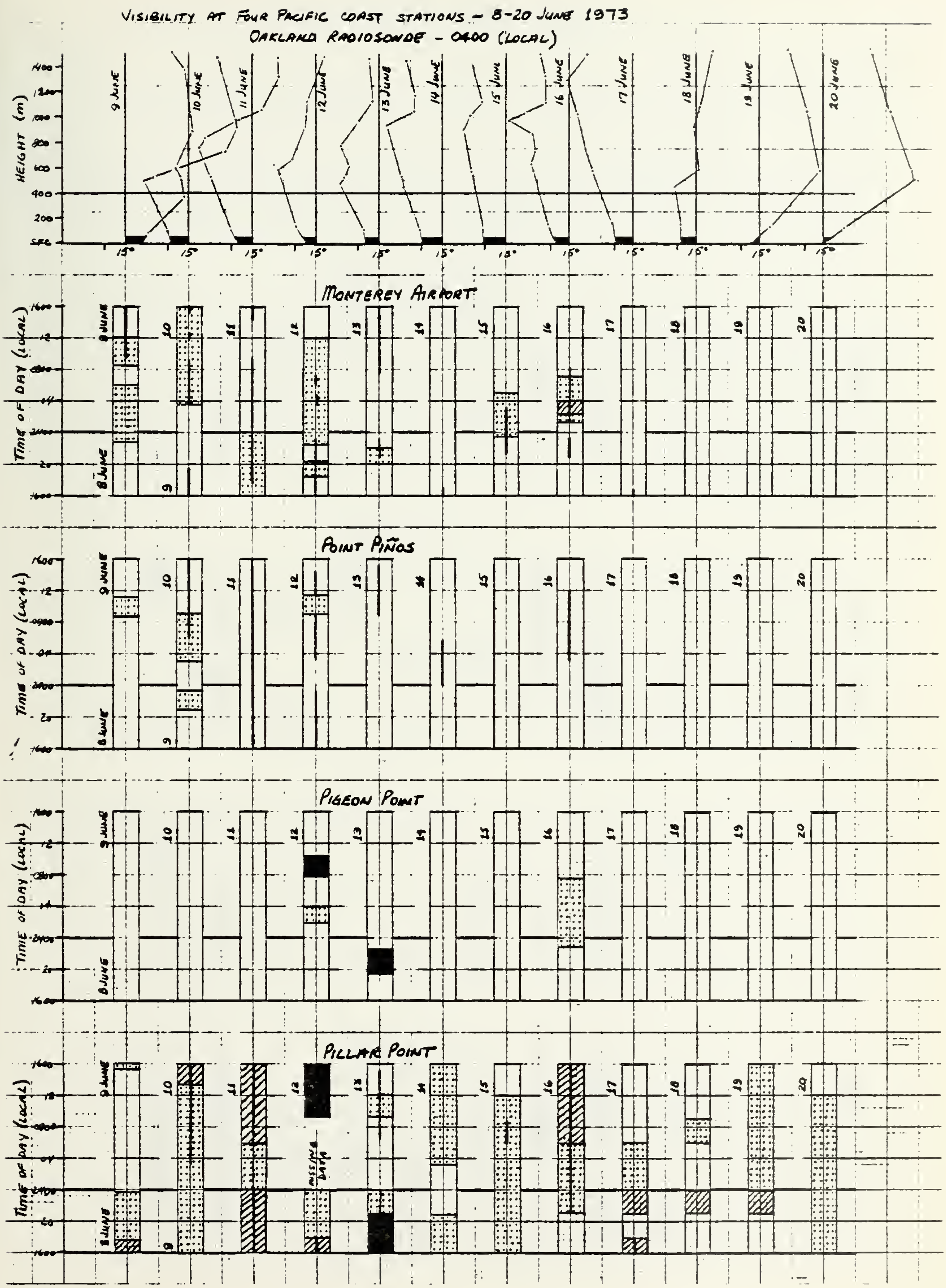



VISIBILITY AT FOUR PACIFIC COAST STATIONS ~ 3-15 MAY 1973
OAKLAND RADIOSONDE - 0400 (LOCAL)
MONTEREY AIRPORT
POINT PIÑOS
PIGEON POINT
PILLAR POINT

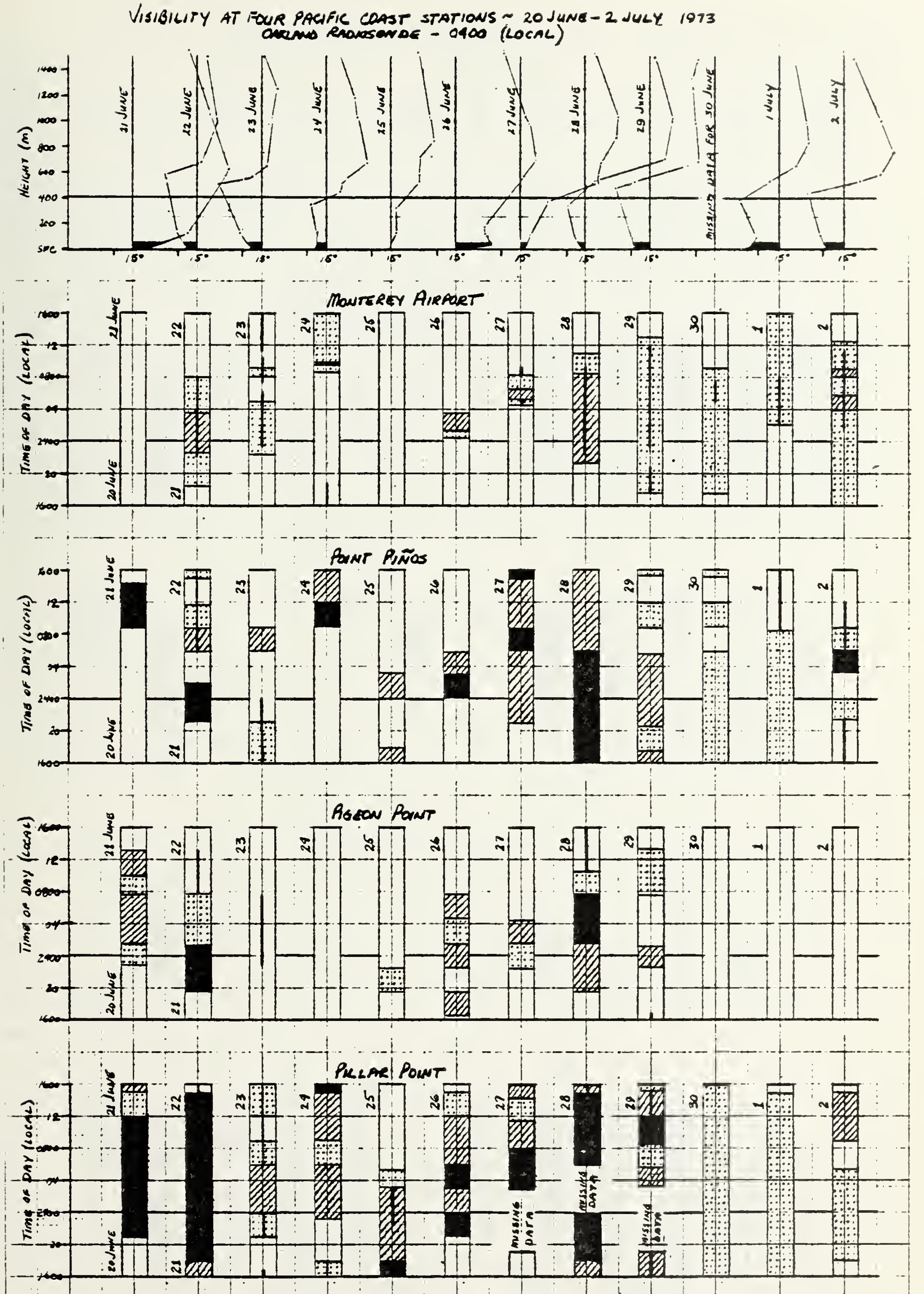

VISIBILITY AT FOUR PACIFIC COAST STATIONS - 15-27 MAY 1973
OAKLAND RADIOSONDE -0400 (LOCAL)
MONTEREY AIRPORT
POINT PIÑOS
PIGEON POINT
PILLAR POINT
TIME OF DAY (LOCAL)



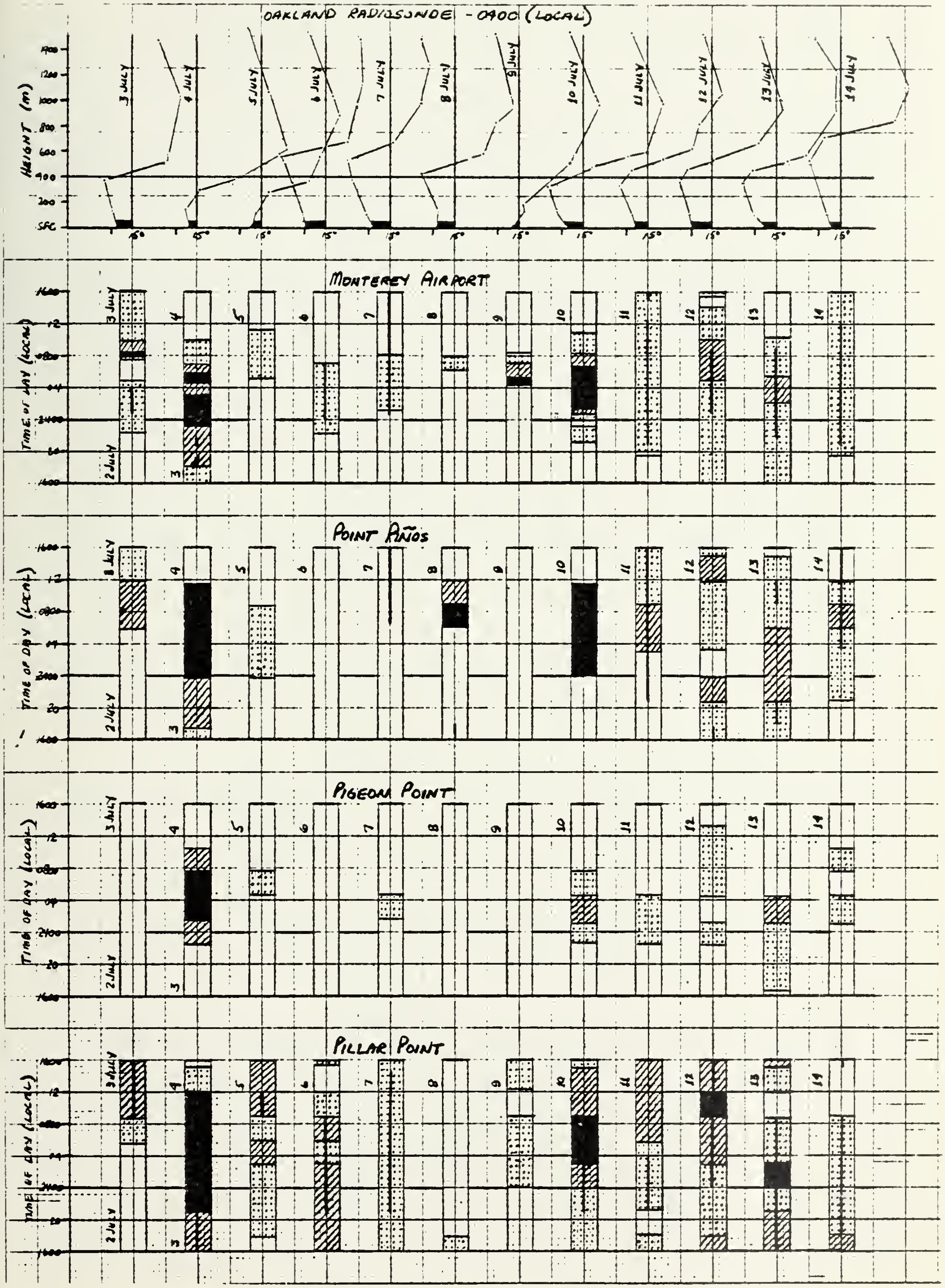
VISIBILITY AT FOUR PACIFIC COAST STATIONS ~ 27 MAY - 8 JUNE 1973
OAKLAND RADIOSONDE - 0400 (LOCAL)
HEIGHT (m)
28 MAY
29 MAY
30 MAY
31 MAY
1 JUNE
2 JUNE
3 JUNE
4 JUNE
5 JUNE
6 JUNE
7 JUNE
8 JUNE
MONTEREY AIRPORT
POINT PIÑOS
PIGEON POINT
PILLAR POINT
TIME OF DAY (LOCAL)

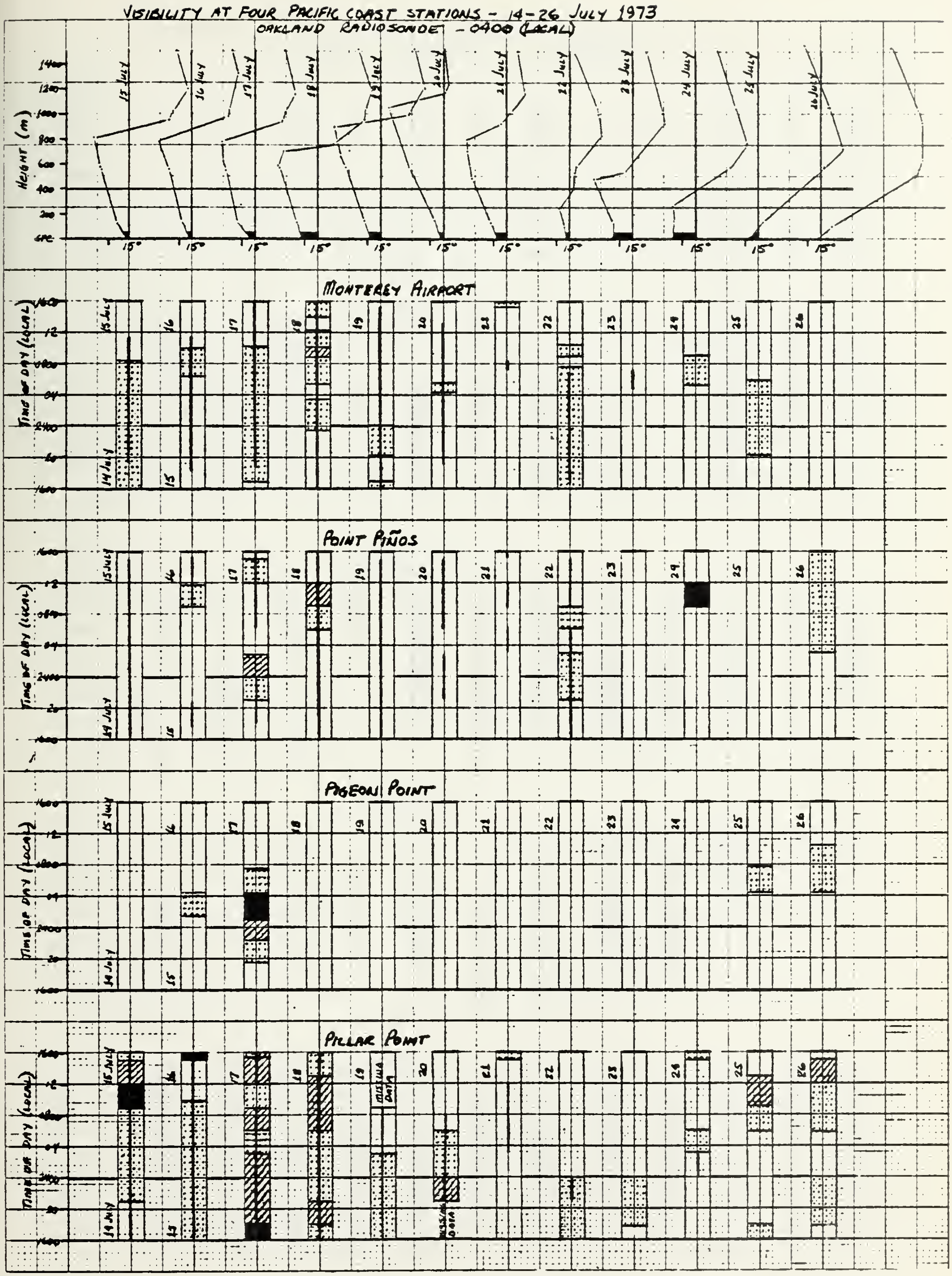


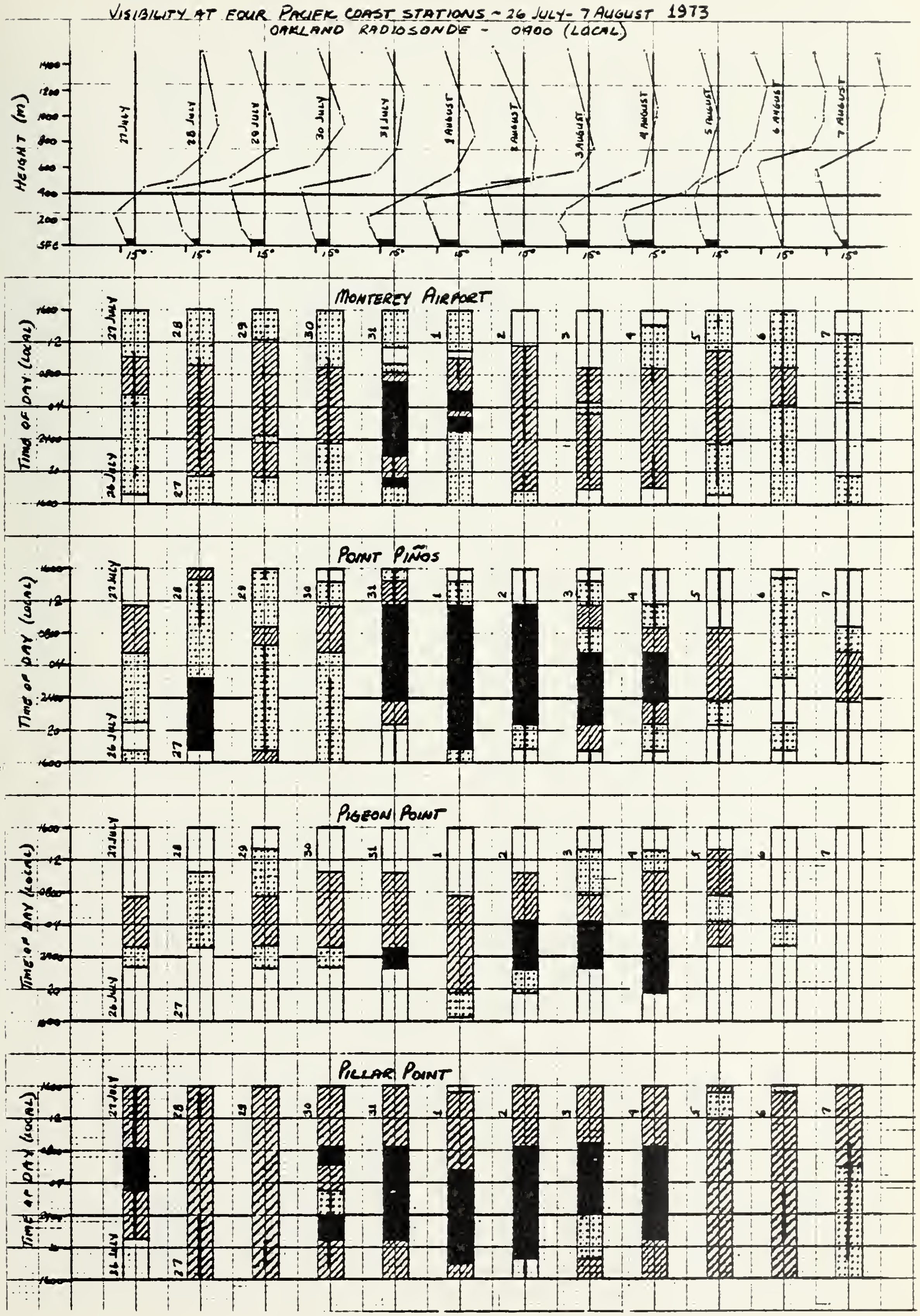
VISIBILITY AT FOUR PACIFIC COAST STATIONS - 8-20 JUNE 1973
OAKLAND RADIOSONDE - 0400 (LOCAL)
HEIGHT (m)
MONTEREY AIRPORT
POINT PIÑOS
PIGEON POINT
PILLAR POINT
TIME OF DAY (LOCAL)
MISSING DATA


VISIBILITY AT FOUR PACIFIC COAST STATIONS ~ 20 JUNE - 2 JULY 1973
OAKLAND RADIOSONDE - 0400 (LOCAL)
HEIGHT (m)
MONTEREY AIRPORT
POINT PIÑOS
PIGEON POINT
PILLAR POINT
TIME OF DAY (LOCAL)
MISSING DATA FOR 30 JUNE
MISSING DATA

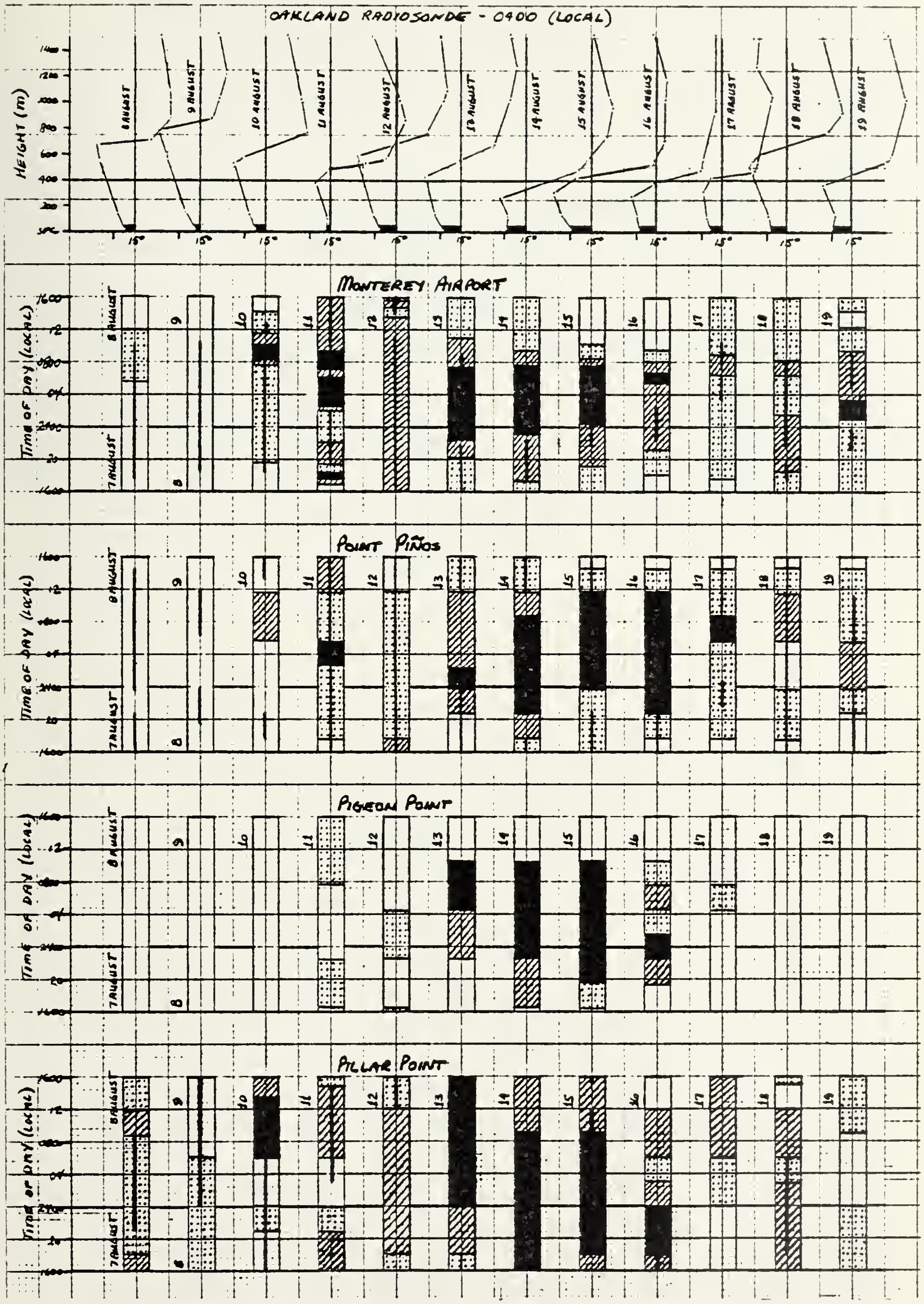
VISIBILITY AT FOUR PACIFIC COAST STATIONS - 2 JULY - 14 JULY 1973



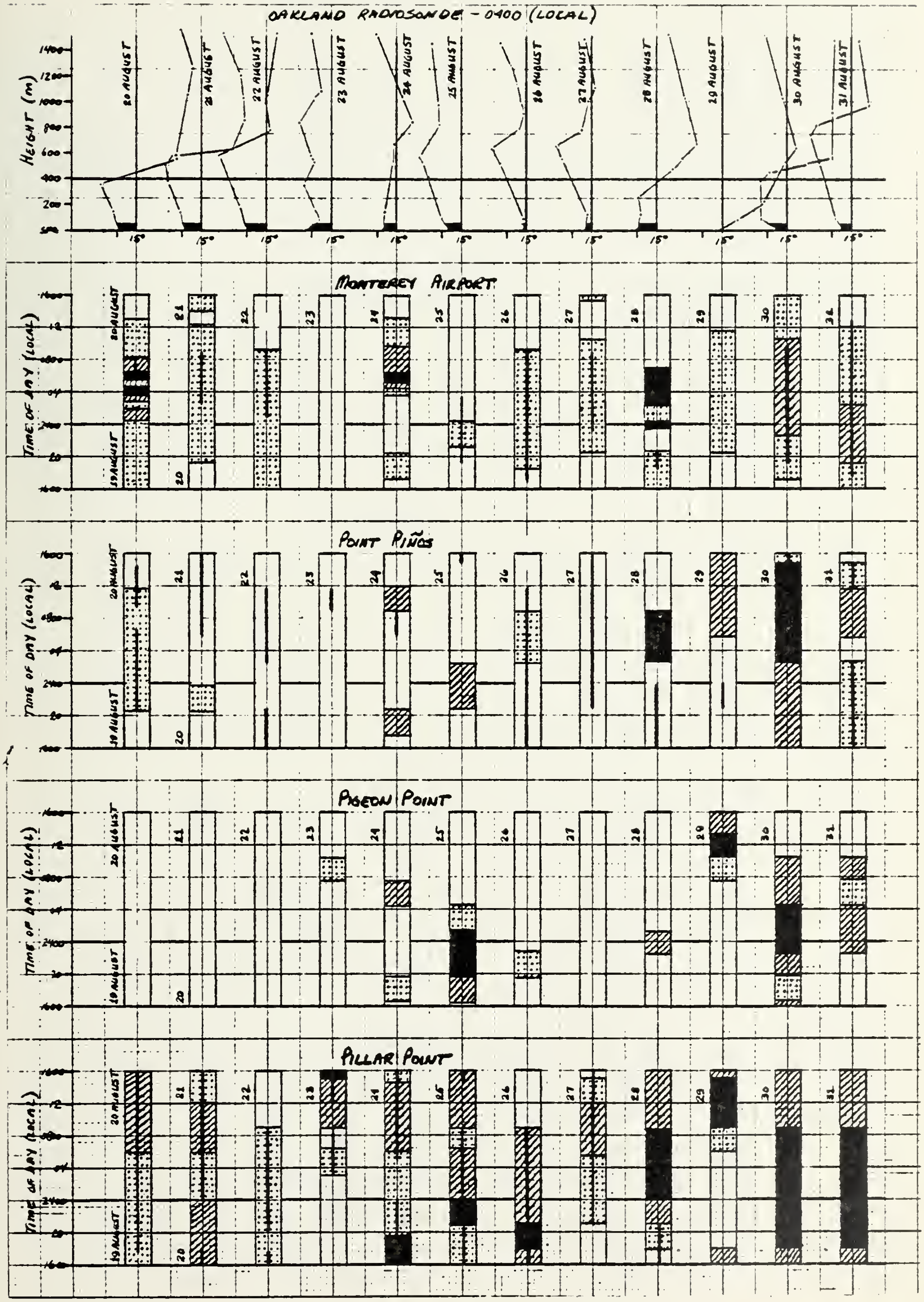

VISIBILITY AT FOUR PACIFIC COAST STATIONS - 14-26 JULY 1973
OAKLAND RADIOSONDE - 0400 (LOCAL)
HEIGHT (m)
MONTEREY AIRPORT
POINT PIÑOS
PIGEON POINT
PILLAR POINT
TIME OF DAY (LOCAL)
MISSING DATA


VISIBILITY AT FOUR PACIFIC COAST STATIONS ~ 26 JULY - 7 AUGUST 1973
OAKLAND RADIOSONDE - 0400 (LOCAL)
HEIGHT (m)
MONTEREY AIRPORT
POINT PIÑOS
PIGEON POINT
PILLAR POINT
TIME OF DAY (LOCAL)

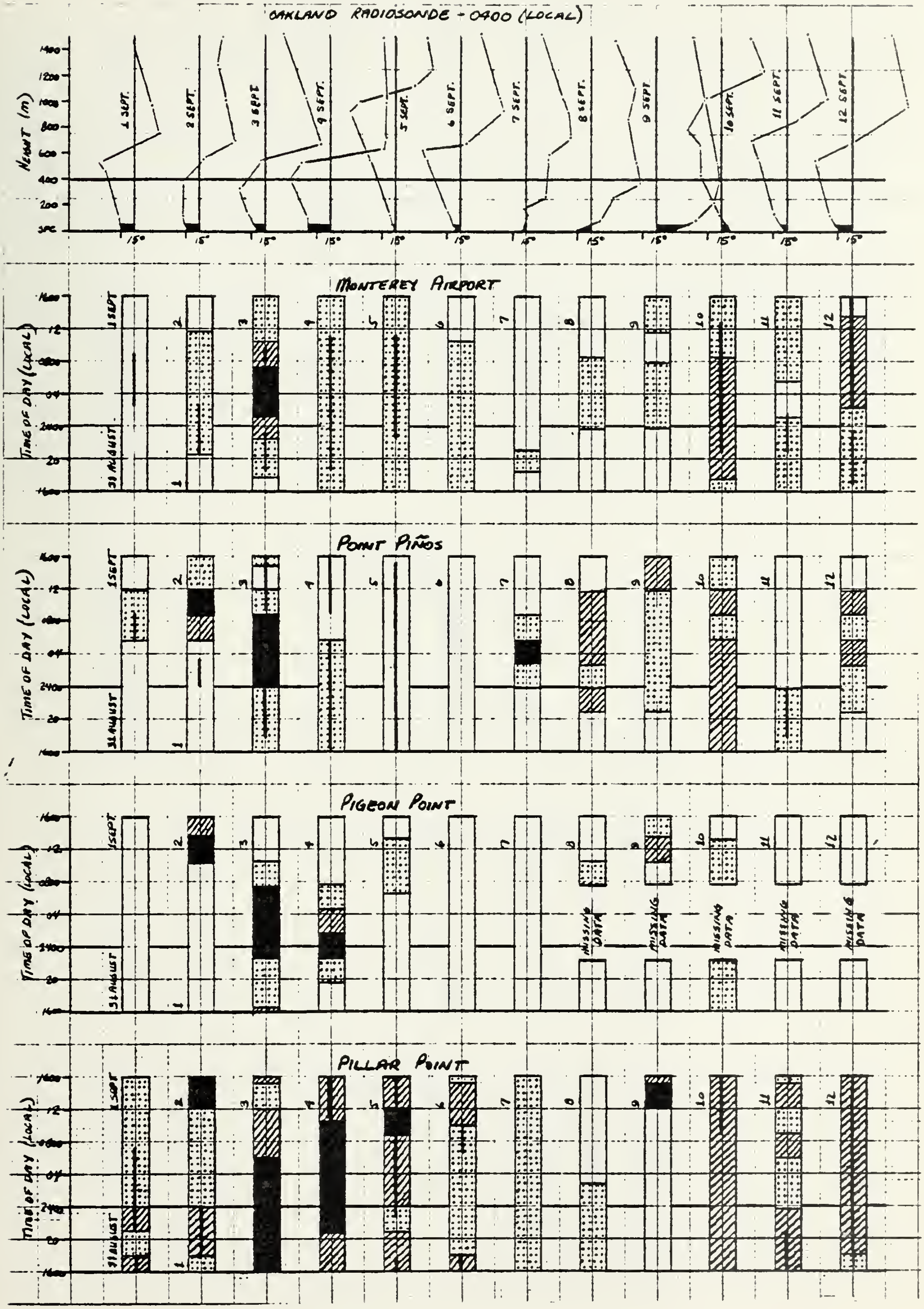
VISIBILITY AT FOUR PACIFIC COAST STATIONS - 7 AUGUST - 19 AUGUST 1973



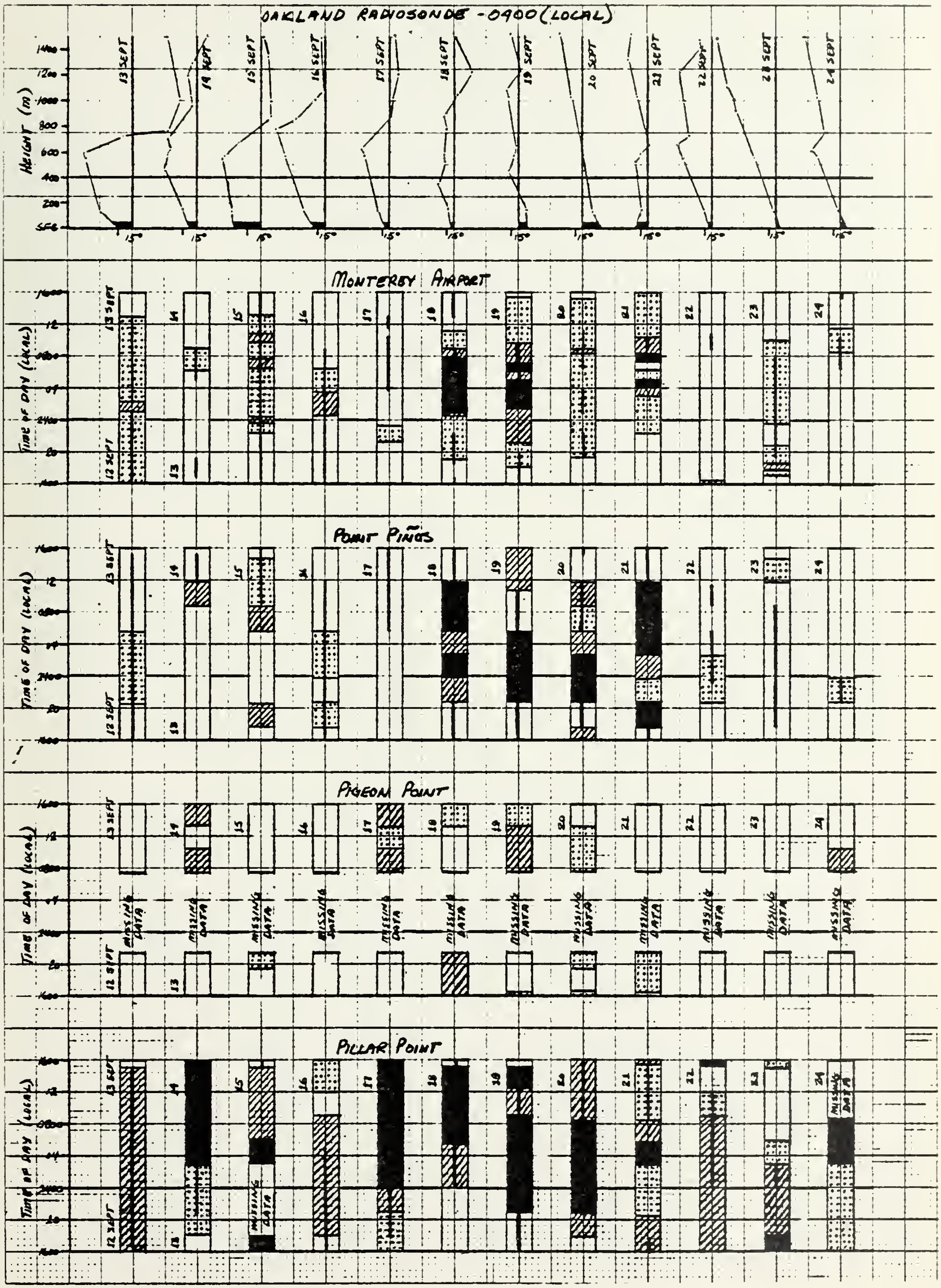
VISIBILITY AT FOUR PACIFIC COAST STATIONS - 19 AUGUST - 31 AUGUST 1973



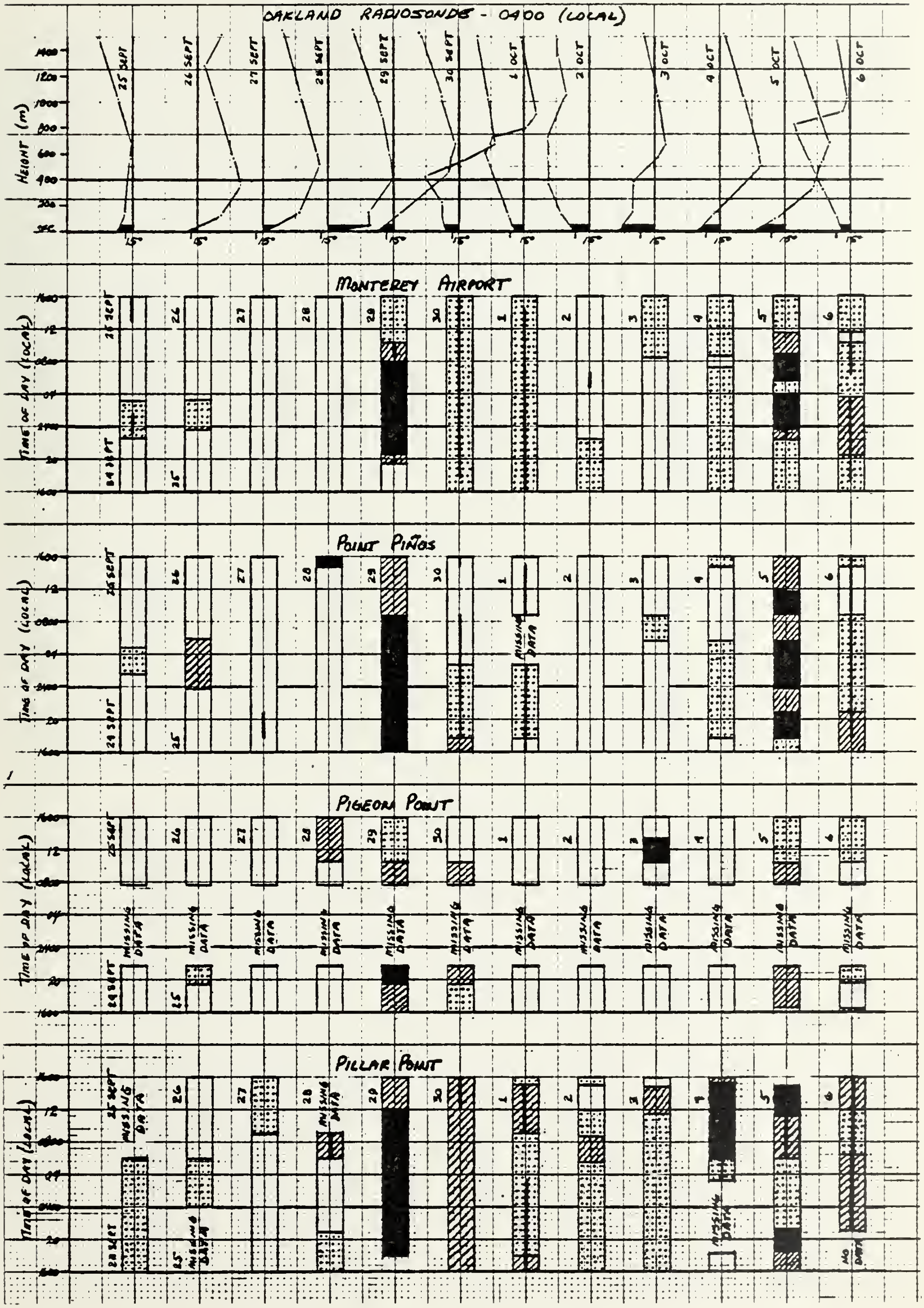
VISIBILITY AT FOUR PACIFIC COAST STATIONS - 31 AUGUST - 12 SEPTEMBER 1973



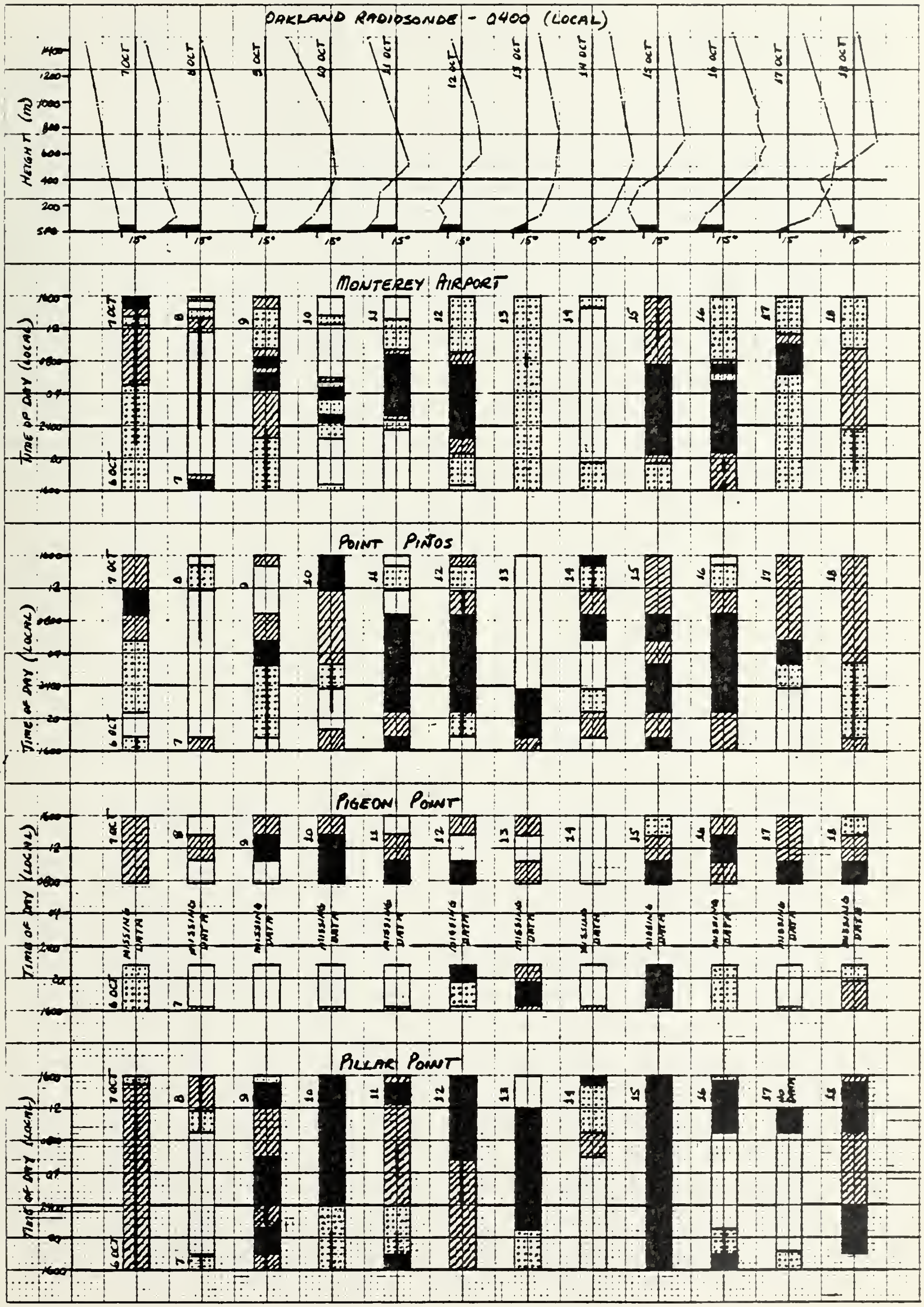
VISIBILITY AT FOUR PACIFIC COAST STATIONS - 12 SEPTEMBER - 24 SEPTEMBER 1973



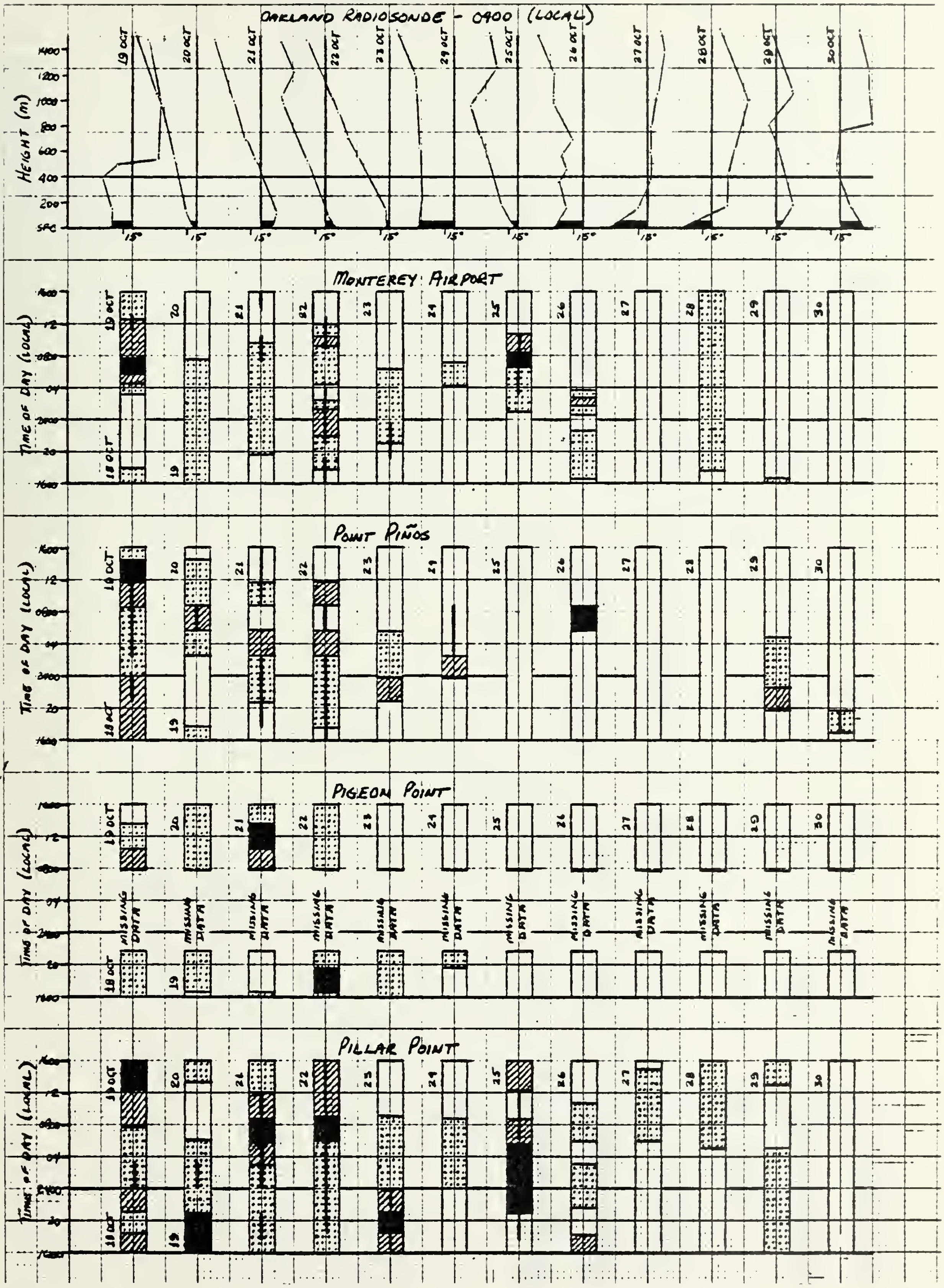
VISIBILITY AT FOUR PACIFIC COAST STATIONS - 24 SEPTEMBER - 6 OCTOBER 1973



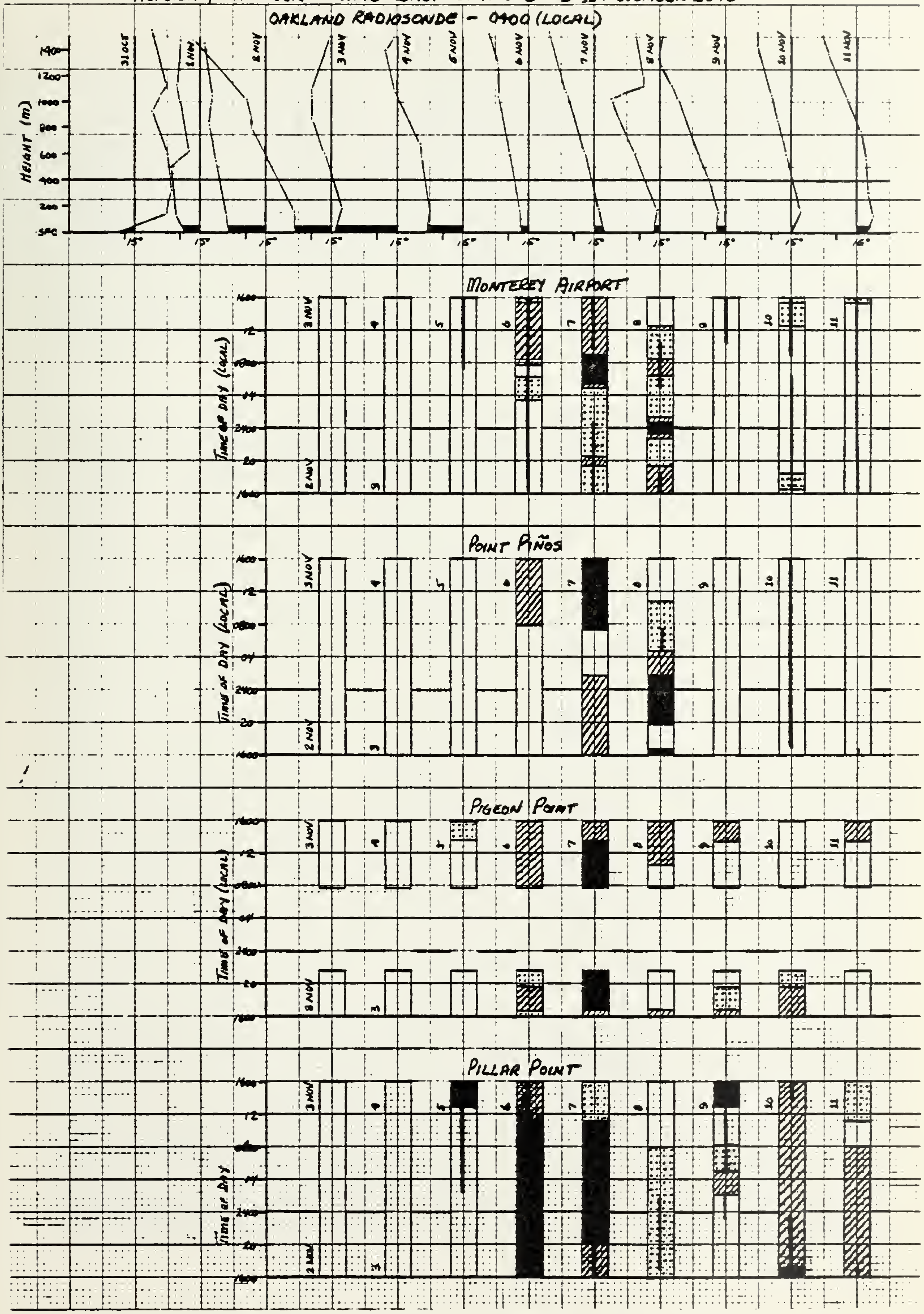
VISIBILITY AT FOUR PACIFIC COAST STATIONS - 6 OCTOBER - 18 OCTOBER 1973

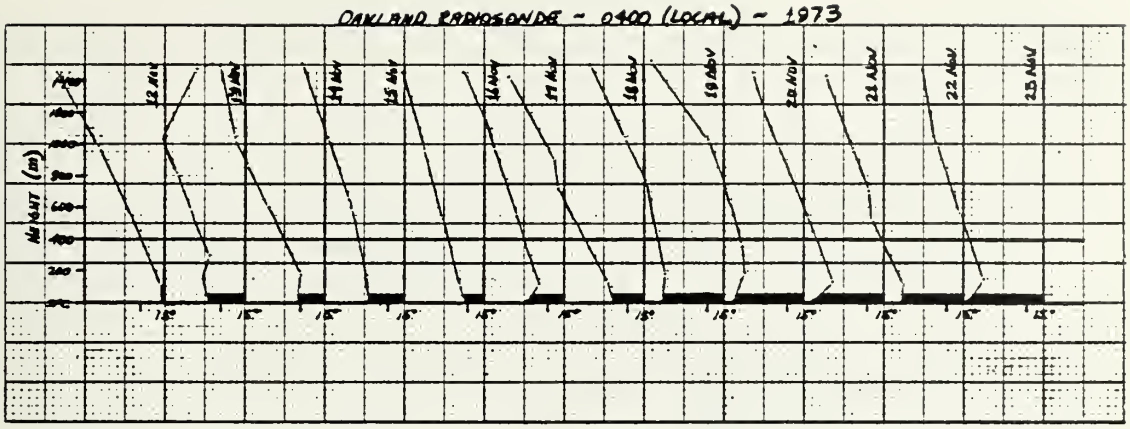


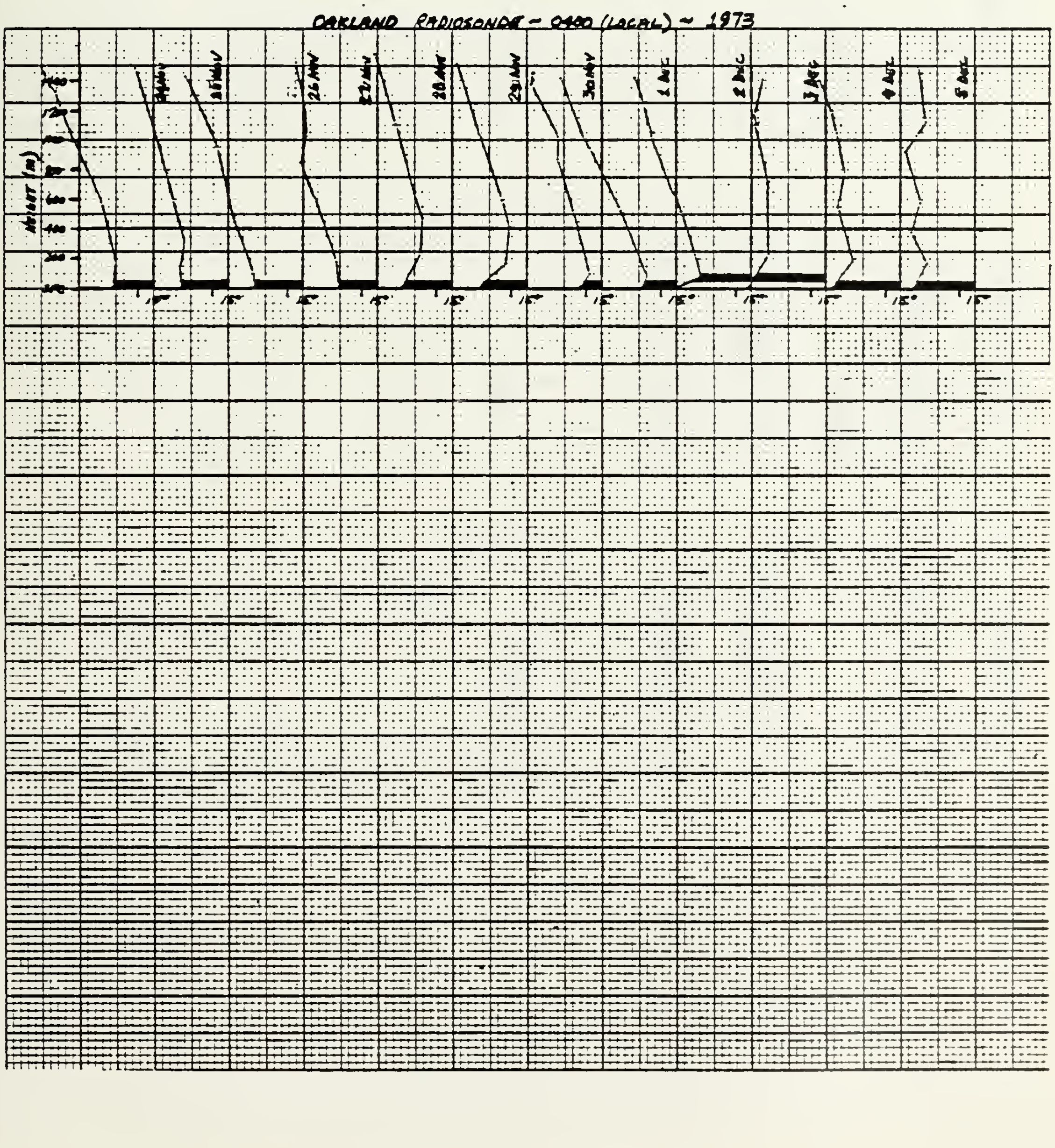
VISIBILITY AT FOUR PACIFIC COAST STATIONS - 18 OCTOBER — 30 OCTOBER 1973



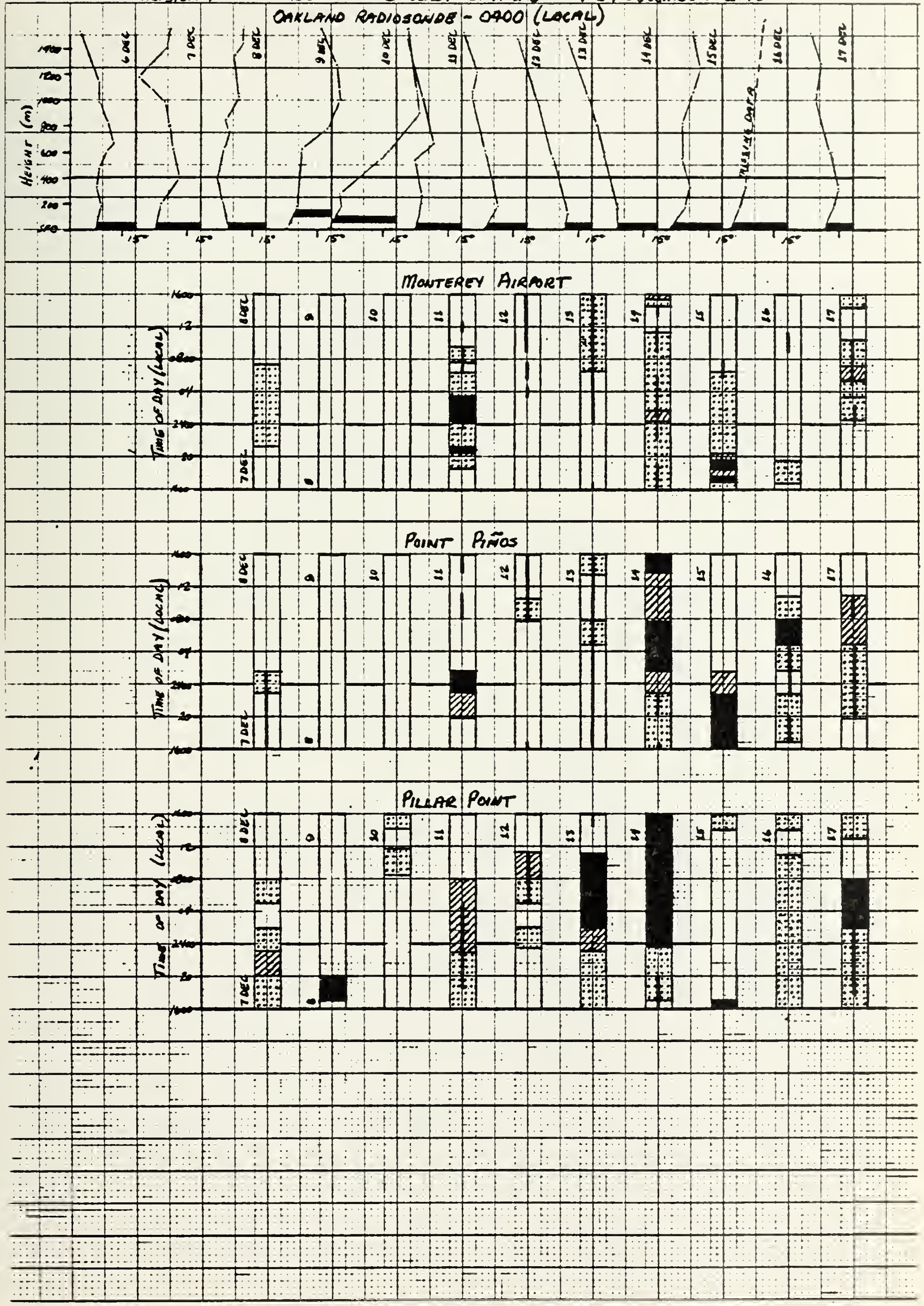
VISIBILITY AT FOUR PACIFIC COAST STATIONS - 2-11 NOVEMBER 1973



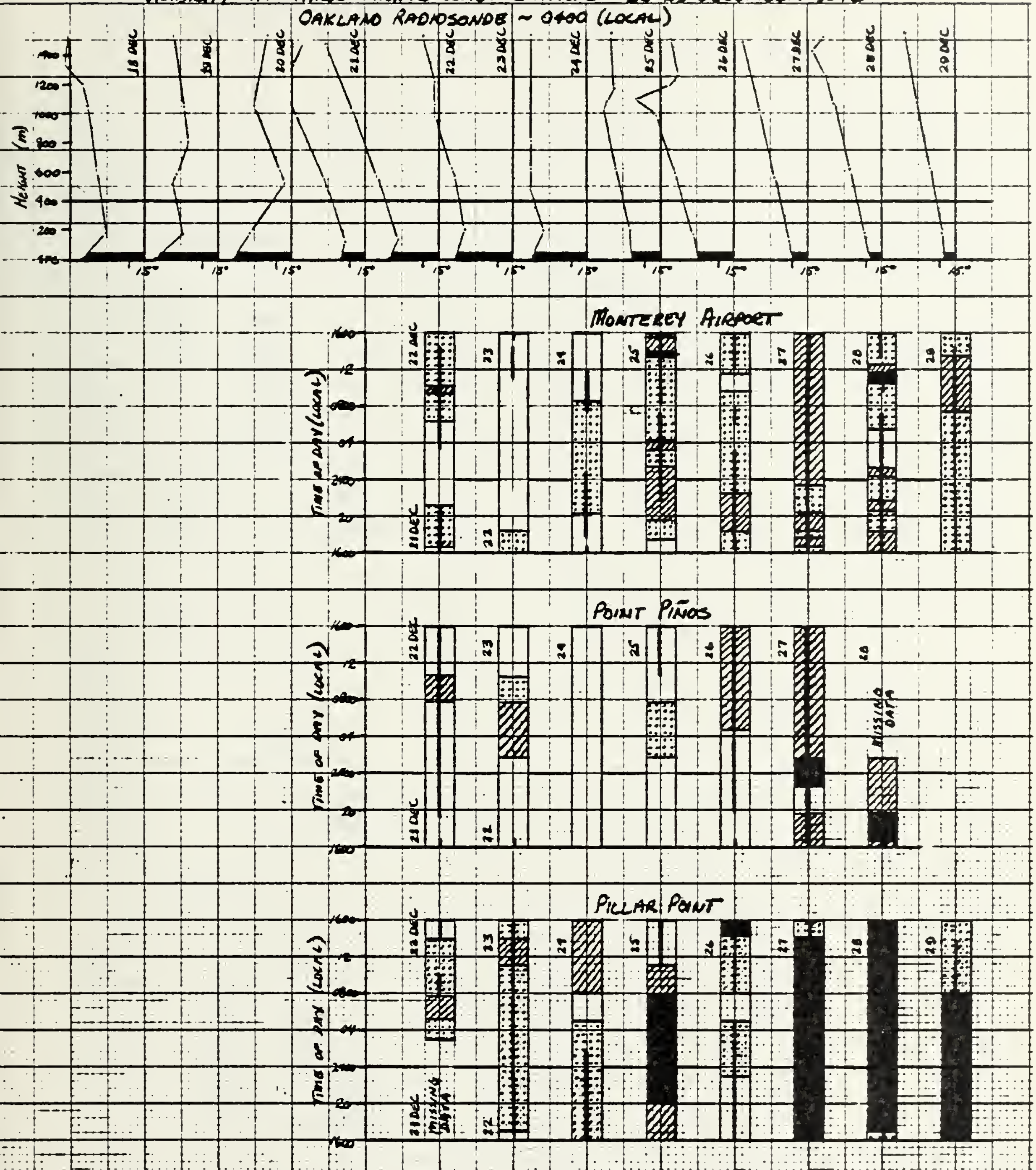

OAKLAND RADIOSONDE - 0400 (LOCAL) - 1973
HEIGHT (m)


OAKLAND RADIOSONDE - 0400 (LOCAL) - 1973
HEIGHT (m)

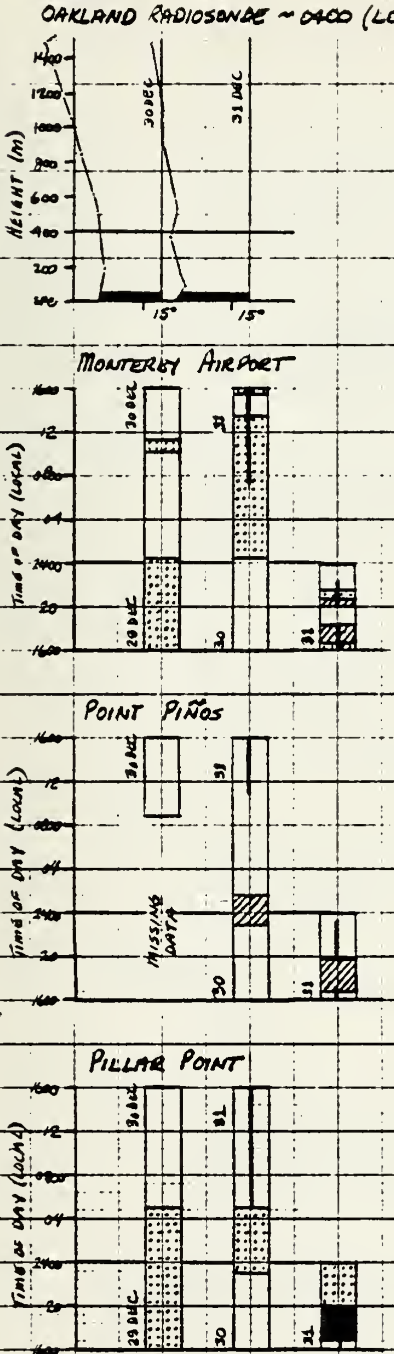
VISIBILITY AT THREE PACIFIC COAST STATIONS ~ 7-17 DECEMBER 1973



VISIBILITY AT THREE PACIFIC COAST STATIONS ~ 21-29 DECEMBER 1973



VISIBILITY AT THREE PACIFIC COAST STATIONS ~ 29-31 DECEMBER 1973



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