Title
Variability of Marine Fog Along the California Coast

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VARIABILITY OF MARINE FOG ALONG THE CALIFORNIA COAST

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Stratus and Fog at the Golden Gate Bridge

Photograph of the Golden Gate Bridge showing stratiform clouds and fog covering portions of the bridge. The view is from approximately over *Lime Point* (north end of the bridge) looking south toward *Fort Point* and the City of San Francisco. This photograph illustrates the patchy nature of coastal fog, especially at the San Francisco Bay-North Pacific Ocean transition.

Photograph courtesy of the late Dr. Albert Miller, Department of Meteorology, San Jose State University.

1. Introduction

Visibility in coastal regions has a significant impact on government, commercial, and private sector activities. The primary phenomenon significantly affecting visibility along the western United States coastal regions is fog. Fog is a natural hazard to boating, commercial shipping, and other waterway activities.

The West Coast of the United States has been identified as one of the major fog producing regions of the world. Present accuracy in predicting marine coastal fog and low stratus clouds is limited. Although most weather forecasting has improved with recent advances in atmospheric circulation models and satellite observations, there is relatively little operational guidance for the prediction of marine and coastal fog.

Currently the forecasting of visibility relies mainly on the availability of local observations and experience with local weather tendencies. National Weather Service and other forecasters typically focus on selected local conditions which usually presage fog formation and if a sufficient number are present, they will forecast possible fog for the region. However, this level of information and experience is not available in all coastal areas. Results in this study suggest that attention to the large-scale circulation in addition to local conditions may lead to increased skill and accuracy in extended range forecasts.

Numerous studies have examined local atmospheric conditions associated with fog formation. Pettersen (1938) was one of the first to investigate the causes of fog along the California coast. He showed that fog is not directly formed by cooling from below (due to the cold upwelled coastal water) but is formed when the temperature inversion caps the cool moist Pacific marine layer below warm dryer air aloft. Results from this study indicate that sea surface temperature (SST) connections are subtle and fog may develop regardless of the presence of cold upwelled water. This is supported by Leipper (1994), who pointed out that the San Diego area has neither cold, upwelled water nor strong SST gradients but still has a large number of dense fog occurrences.

Leipper (1948) defined three indicators of fog probability, and validated the occurrence of fog on most days that the indicators were favorable. Local conditions that were identified as being favorable for Southern California fog development are:

(1) a low temperature inversion (base <1 *km*);
(2) a sea surface temperature cooler than the warmest air temperature below the inversion; and
(3) a "least-fog" occurrence when sea surface temperature is more than 5°C warmer than the late afternoon dew point temperature.

Other local conditions found to be favorable for fog formation in the Southern California coastal area include: the dissipation phase of Santa Ana conditions, a strong temperature inversion in the lower atmosphere, and the approach of an upper level trough off the coast. Several of these factors are included in Southern California operational forecasting practices (NOCF, 1992; NOCD, 1993). Leipper's (1994) review of fog studies on the United States West Coast summarized factors useful in understanding West Coast fog including the formation of a strong but relatively shallow inversion, the presence of cooler waters off the coast, and the depth of fog development. All of these factors are based on relationships between physical variables, but have not been documented using extensive climatic data sets. Several cases of synoptic scale fog development are presented in *Appendix B.*

Leipper (1948) devised a model qualitatively illustrating the evolution of fog during Santa Ana conditions. Fog generally develops at the end of a Santa Ana condition because of the formation of a low inversion, creating a thin marine layer with weak offshore flow. He later generalized this model to create a four-phase sequence based on physical processes, and has applied it to other regions along the West Coast (Leipper, 1994). In the first phase, the Eastern North Pacific High is dominant over Northern California, causing an easterly (offshore) flow at the surface, a condition known as a "Santa Ana." Because of subsidence, the air column (below 1 *km*) at the coast is warm and dry. In phase two, the easterly flow weakens as the Eastern North Pacific High is split over the mountains. An inversion develops with its base below 250 *m*. Fog formation begins in a shallow layer offshore below the inversion. The third phase begins when northwesterly flow and the sea breeze return—then fog spreads inland along the coast. The inversion base in the third phase is between 250 and 400 *m*. In phase four, the marine layer expands above 400 *m* and continues to deepen until stratus clouds form as the fog base rises above 45 *m*. A case study of the development of fog along the California Coast over the course of a Santa Ana event is shown in *Appendix C*.

Results of marine fog studies conducted during the 1970's were presented by Noonkester (1979). Using surface-based remote sensors, surface weather observations, aircraft measurements, and satellite imagery, Noonkester concluded that nighttime outgoing longwave radiation from cloud tops is most important in the cooling process leading to fog formation. His scenario begins with warm, moist air below the inversion base moving over cooler water and reaching saturation. The stability of the boundary layer increases, inhibiting upward transport out of the layer, causing the temperature inversion to strengthen and stratus clouds to form. Radiational cooling from the top of the stratus layer then lowers the stratus-cloud base to the surface and fog develops. Reflection of incoming shortwave radiation and emission of longwave radiation from the top of the fog layer thus help the fog to persist. Using satellite imagery, Michaelsen *et al.*, (1988) observed a "cycle" of coastal stratus along California which is consistent with Leipper's 1948 model. Noonkester's (1979) results show that the features of Leipper's (1948) model provide basic guidance to fog occurrences, but more detailed wind and moisture observations might permit more reliable forecasts.

The large-scale structure and interannual variability of fog have not been well described because data has been unavailable and a large volume of data is required. In the present analysis, several years of observations from a set of coastal weather stations and a set of comprehensive marine weather reports (primarily ships) is used to examine large-scale processes and local conditions which affect fog formation. A discussion of fog observation criteria is given in *Appendix A*. In addition, evidence is provided by a collection of observations of hours of foghorn operations at several coastal sites over 15 years, starting in 1950 *(Appendix D)*.

The relationship between local and large-scale conditions, and fog and stratus formation may yield improved predictability of fog. This study indicates that large-scale conditions, especially regional-hemispheric circulation, are a vital component of both high and low fog occurrences; moreover, atmospheric circulation in the Eastern North Pacific Ocean and on the West Coast may contribute to improved forecasts for the development and persistence of fog.

2. Climatological and Topographic Influences

2.1 General Climatology

The United States West Coast is a region well-suited to the study of fog. The West Coast has frequent fog occurrences and an extensive data set is available. The West Coast is one of the three United States regions with frequent dense fog; the others are the mountain top areas in the Appalachians, and an area in central New England (Leipper, 1994). A more complete understanding of fog occurrence in this area can significantly aid government and commercial boating and airways operations.

The predominant meteorological feature influencing West Coast weather, including fog, is the strength and placement of the Eastern North Pacific High. As discussed by Neiburger and Edinger, (1954)

> The subsiding motion associated with the quasi-stationary anticyclone, which is the dominant feature of the circulation over the eastern North Pacific Ocean, gives rise to a semipermanent inversion on the eastern and southern sides of the anticyclone. . . . in an area extending hundreds of miles to the west and southwest of Southern California every sounding of the temperatures aloft made in the months June-September has shown an inversion. . . The inversion is lowest on the average, about 400 *m*, along the California coast and slopes upward to the west and south, reaching 2000 *m* over the Hawaiian Islands. Its average magnitude (increase in temperature from bottom to top) is greatest, 10°-12 *°C*, just off the coast, and decreases to about 2 *°C* over the Hawaiian islands.

During summer, the High is centered approximately 1000 *km* west of San Francisco. The anticyclonic circulation about the High produces a northwesterly flow which predominates along most of the California coastal region. This strong high pressure center deflects most extratropical storms to the Pacific Northwest. Only occasionally do tropical storms stray north of the Gulf of California into the Southern California region. With the assistance of a thermal trough over the desert southwest, a strong marine layer forms with low stratus clouds present during late night and early morning hours. The marine layer is the boundary region where the cool, humid marine air meets the warm subsiding air that characterizes the anticyclonic high pressure. The adiabatic heating of the subsiding air combined with the cool marine layer below creates a temperature inversion of approximately 200-600 *m* above the surface. The thin layer of marine air exchanges heat and moisture with the sea surface and becomes a cool, humid insulating layer between the cool ocean and the warm, dry air over it (Edinger, 1963). The temperature inversion acts as a cap, inhibiting mixing between the cool moist air below the inversion and the dry, stable air above. The marine layer depth and the subsidence inversion heights and strengths vary with the movement of synoptic features in the westerly flow aloft (Neiburger *et al.*, 1961). For example, with the development or approach of an upper level ridge, the height of a constant pressure surface increases, the marine layer thins, and the inversion base lowers and intensifies (NOCF, 1992). The opposite occurs with the incursion of an upper level trough when the westerly flow dominates the region.

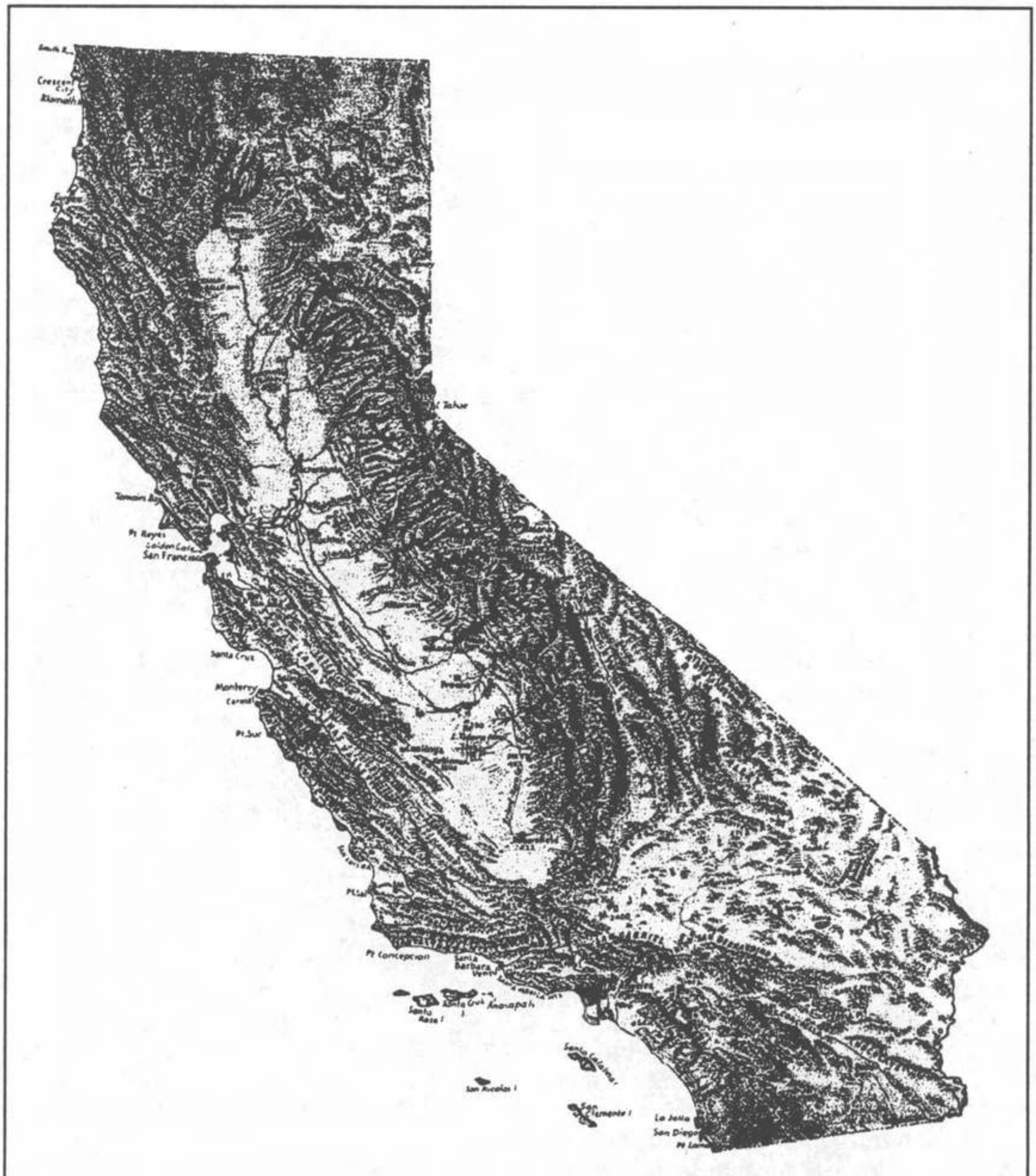
Neiburger (1944) described changes in the height of the inversion as it relates to convergence in the sea breeze circulation. Variations in the inversion height depend on the intensity of the sea breeze which, in turn, is related to the temperature difference between the land and sea. During the day, heating over the land causes warm air to rise over the coastal mountains and deserts. This air must be replaced by cooler moist sea air—thus a sea breeze is generated. The minimum inversion height is observed at this time due to the great horizontal spread of the marine layer. At night, the land cools, the air cools and stops rising, sea breezes cease, and the thickness of the marine layer increases—the cycle is ready to begin again.

2.2 *Topography*

Coastal topographic features affect fog development. Most significant along the California coast and the near inland region are the mountains of the Coast Range. The Coast Range lies from 1 to 120 *km* inland from the Pacific Ocean and extends southward from the state of Washington to Los Angeles. The Coastal Range is a nearly continuous, overlapping arrangement in Northern and Central California. In Southern California, however, the coastal range has a more east-to-west orientation with breaks in the chain forming irregularities along the coast (Figure 1).

The coastal mountains promote diurnal changes in the inversion height by inducing

Figure 1. The Physiography of California



California Landforms Map by Erwin Raisz

vertical motion in the air. In the Southern California region, the proximity of the Coast Range to the sea helps to establish a strong marine layer, thus influencing fog formation. In Northern California, where the only complete breach in the Coast Range exists (in the San Francisco Bay region), the complex topography of mountains and valleys assists in modifying the weather and creating dense, patchy fog areas. In Northern California, the Coast Range differs from Southern California in that it is a double chain of mountains with a number of gaps that allow penetration of coastal weather inland (Gilliam, 1962). In winter especially, cool air is collected in the inland valleys and drains to the coast. This produces a winter fog maximum in the San Francisco Bay area which is discussed in the following sections.

Coastal mountains act as a barrier to the stable stratified marine air, blocking air flowing past them or acting as a wall along which Kelvin waves may propagate (National Research Council, 1992). These trapped coastal waves perturb the marine layer depth and affect coastal stratus formation and dissipation. Dorman (1987) examined the role of gravity currents as they pertain to wind direction reversals and changes in the marine layer depth along California's coast. During a four- to six-day time period leading up to a shift in winds, the marine layer gradually thickens or thins. From the Southern California Bight (the region between San Diego and Point Conception), the marine layer moves north along the coast; inland movement is restrained by the topography. It then becomes elevated along the Central Coast and overcast stratus forms (Dorman, 1985); surface winds slowly weaken while the marine layer continues to thicken and surge northward. Within the marine layer, stratus or fog development is dependent on its strength and depth, as well as advection and condensation. A low subsidence inversion base with a shallow marine layer promotes the development of stratus and fog, forming a boundary between the warm, dry air aloft and cool, moist air in contact with the coast and sea surface. Dorman's (1985) results indicate that gravity waves propagating in the marine layer modulate the variability of fog along the coast.

3. Background and Objectives

3.1. Fog Mechanisms

Fog is defined as a visible aggregate of minute water particles (droplets) based at the earth's surface, which reduces horizontal visibility (NWS 1973, 1991). Fog can further be described as a stratus cloud cover formed at the ground or so close to it that surface visibility is affected (Byers, 1974). Condensation occurs quite frequently with less than 100% relative humidity, but can fail to occur until the relative humidity is greater than 100%, depending on the physical nature of the available nuclei (Byers, 1974). Both aviation and marine weather observations are made in accordance with different operational requirements. The operational definition of fog for the aviation and marine weather observational sets considered in this study are given in *Section 4*, and further detailed in *Appendices A* and *B*.

The atmosphere contains numerous types of cloud condensation nuclei of micron and submicron size which attract water and serve as centers for condensation (Rogers, 1976). The availability of atmospheric condensation nuclei is dependent on geographical location, topography, seasonal factors, and meteorological conditions.

Clouds of maritime origin are composed primarily of salt nuclei which result from the bursting of wave bubbles and range in size from 0.01 to 1 micron (Rogers, 1976). Industrial processes contribute a high number of condensation nuclei, with sizes ranging from 0.001 to 10 microns (Rogers, 1976). Condensation nuclei stirred up by strong winds are probably a strong factor in subsequent fog development.

The most common type of fog in coastal regions is advection fog which is formed when winds move moist air over colder water or land. A warm air mass being advected over a colder surface will give off heat, causing condensation to occur at or near the dew point (the point at which a cooling parcel of air would reach saturation). A second type of advection fog occurs when cold air passes across warmer water causing condensation in the evaporating vapors. This produces "steam fog" or "Arctic smoke" (Donn, 1951). Advection fogs are most common in areas where warm and moist air parcels cross a colder surface. Such areas include the Labrador Current in the North Atlantic, the Bearing Sea inside the Aleutian Island chain, and along the California coast, due to the California Current or upwelled water (Kotsch, 1983).

Frictional effects over land can cause the formation of low stratus or stratocumulus instead of fog when wind speeds become greater than 10 ms^{-1}, or 20 knots (Hsu, 1988). Higher wind speeds over rough terrain mix the air through a deeper layer, thus raising the condensation level off the ground. Kotsch (1983) pointed out that over water, wind speeds are of little importance on fog formation because of small frictional turbulence; advection fog will form even at wind speeds greater than 20 knots. Results from this study tend to support this, with some fog occurrences at quite high wind speeds, although most fog is observed during wind speeds of less than 12 ms^{-1}.

Radiation fog is quite different from advection fog in that it usually occurs at night when the wind is light, skies are clear, and relative humidity is high (Kotsch, 1983). Light winds cause little mixing of the cooler air at ground level after sunset, and the moist air cools to the dew point, forming fog. Radiation fog is prevalent in the fall and winter seasons. Kotsch (1983) indicated that radiation fog occurs primarily over land; this appears to be borne out by some of the California stations used here, but some ocean reports also display a secondary maximum in fog occurrence during winter, which may have a similar origin.

Marine fog (or sea fog) can also be found in coastal areas. It forms when the air over the sea is *saturated* and reaches a degree of *supersaturation* due to either evaporation or cooling (Binhua, 1985). This fog can move over the land in coastal areas if winds are strong enough to displace it but not strong enough to dissipate it.

3.2. Objectives

The objectives of this study are to answer the following questions.

(1) *What are the climatological patterns of fog along the California coast and how do these patterns change with the season and with the region?*
(2) *Does ocean fog differ from coastal (land) fog?*
(3) *What is the spatial scale of fog?*
(4) *What is the association of fog to wind speed and wind direction, air temperature and sea surface temperatures?*
(5) *Is fog along the California coast related to atmospheric circulation patterns?*

4. Data

Two primary sources of data are used in this study: *(1)* surface observations at coastal and island stations along California (aviation weather or "surface airways" reports); and *(2)* open ocean surface ship observations (marine weather reports). A third auxiliary set is a collection of foghorn hours of operation, available during the early part of the study period.

Aviation weather reporting criteria consider visibility to be obstructed when it is less than 7 statute miles. On the other hand, marine observations report fog only if the visibility is reduced to less than one kilometer (see *Appendix A*). Any obstruction due to suspended water droplets where the visibility is equal to or greater than one kilometer is categorized as mist. Present weather categories most likely to obstruct visibility are precipitation (liquid, freezing, and solid), blowing dust or sand, haze, and fog.

This great difference between the visibility thresholds of the two weather reporting systems is due to the speed of the respective modes of transport. Ships typically travel at 10-20 *knots (nautical miles per hour)* or 18-37 *kph* (*kilometers per hour*). At 15 knots (28 *kph*) a ship travels one kilometer in just over two minutes. Aircraft operating close to the surface (below 3 *km*) typically travel at 150-250 *knots* or 275-460 *kph*. So, in the same two minutes, an airplane moving at 200 knots (370 *kph*) would travel 6.7 nautical miles (12.3 *km*). Thus, in terms of response time (but not distance), the aviation and marine criteria are essentially equivalent. The coastal aviation weather stations used in this study are shown in Figure 2a.

The surface ship observations {from the Comprehensive Ocean Atmosphere Data Set or "COADS," (Woodruff *et al.*, 1987)} are supplied by the National Center for Atmospheric Research (NCAR) in Boulder, Colorado for the years 1949-1991. Individual marine observations from COADS provide air and sea surface temperatures, wind speed and direction, pressure, humidity, cloudiness, and "present weather" along with several auxiliary indicators (Slutz *et al.*, 1985). Marine fog definitions and present weather codes are provided in *Appendix A*.

For purposes of this study, the California coastal marine area was divided into eight regions as shown in Figure 2b. The present weather indicator in marine observations differentiates between 14 fog categories. Eleven categories are for heavy fog that restricts visibility to less than 1 *km*. Two are for shallow fog that is less than 10 m (33 *feet)* in height. The remaining category is "mist" or fog greater than 10 *m* in height, but with visibility greater than or equal to 1 *km* (NWS 1991).

The coastal station data were obtained from the National Climatic Data Center (NCDC) and include: Arcata (National Weather Service), San Francisco (National Weather Service), Naval Air Station Alameda, Naval Air Station Moffett Field, Santa Barbara (National Weather Service), Naval Air Station Point Mugu, San Nicholas Island (Navy), San Clemente Island (Navy), Naval Air Station Miramar, San Diego (National Weather Service), and Naval Air Station North Island (Figure 2a, Table 1). Coastal

Table 1. Coastal Weather Stations.

Station	*WBAN ID No*	*WMO*	*Period*	*Elev*	*Major Gaps*
Arcata	24283	none	1950-1990	66 m	
NAS Alameda	23239	74506	1949-1990	6 m	
San Francisco	23234	72404	1949-1990	5 m	
NAS Moffett Field	23244	74509	1949-1990	12 m	
Santa Barbara	23190	none	1949-1990	6 m	1965-73 1977-83
NAS Point Mugu	93111	72391	1949-1990	4 m	
NAS San Nicolas Island	93116	72291	1949-1988	154 m	1984-87 1987-90
San Clemente Island	93117		1963-1983	55 m	1979 1984-85 1989-90
NAS Miramar	93107	72293	1949-1990	145 m	1984-85
San Diego	23188	72290	1949-1990	9 m	
NAS North Island	93112	none	1949-1990	8 m	1984-85

NAS = Naval Air Station; Data extracted for each station at 3-hour intervals

Figure 2a. Location of the Coastal Stations Used in this Study.

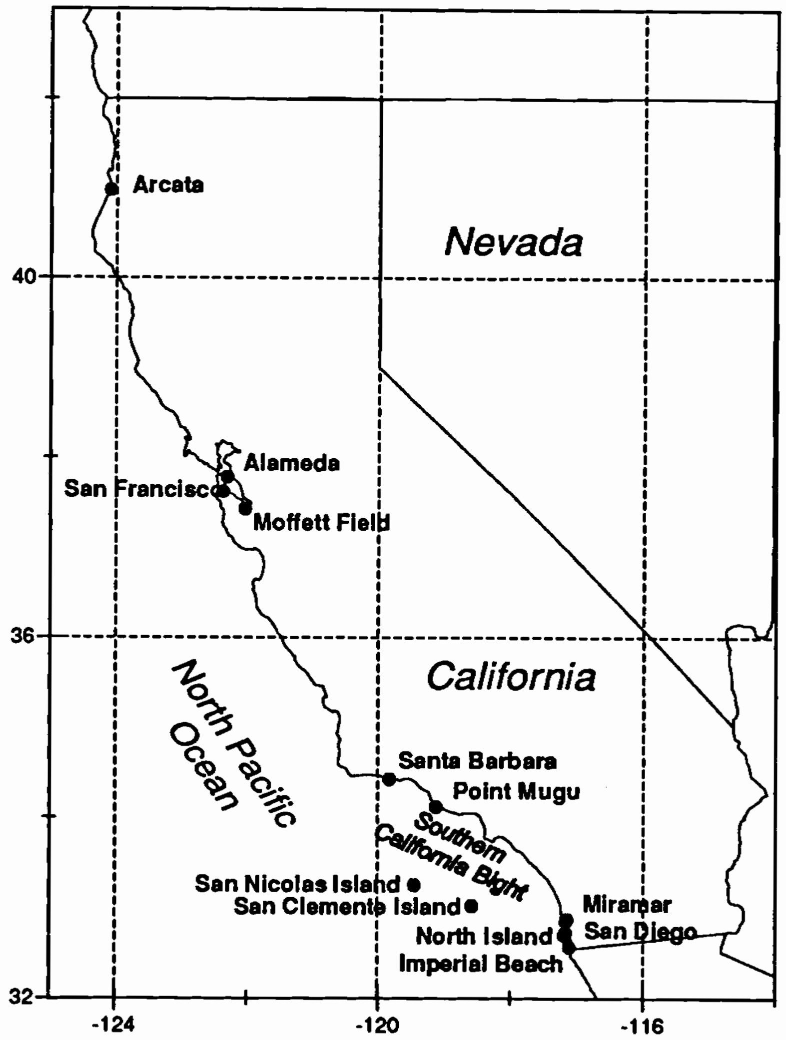
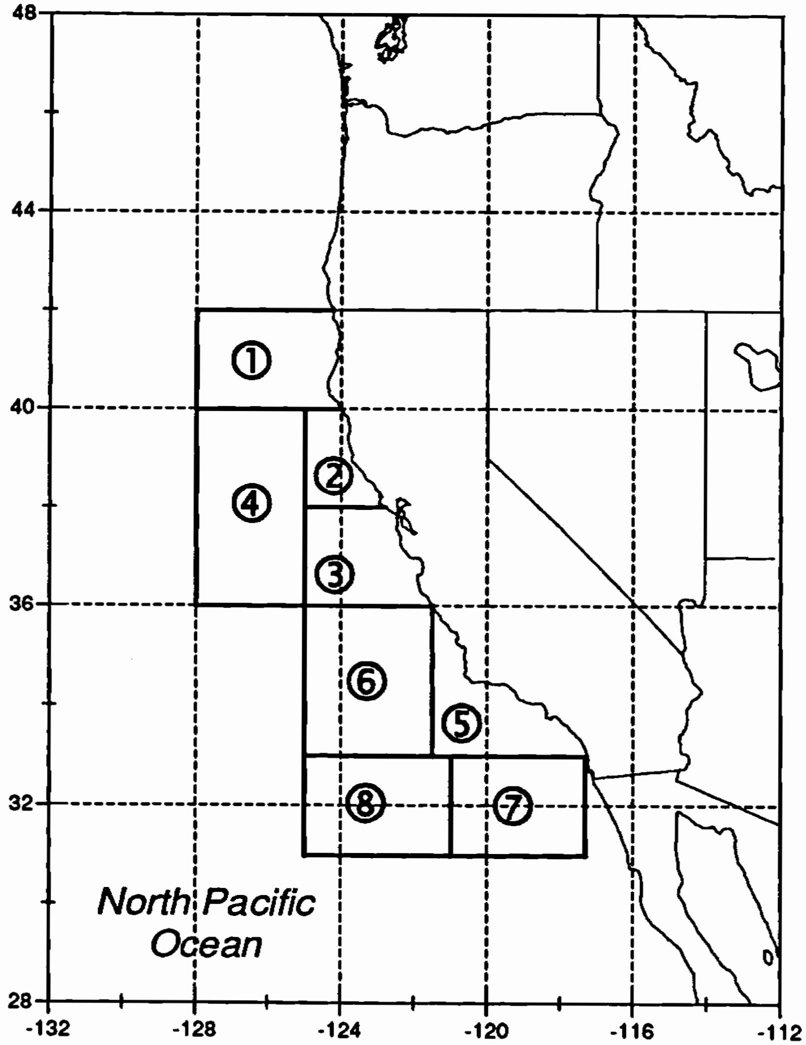


Figure 2b. Marine Observation Regions Used in this Study.



station observations (aviation weather observations) were generally taken at hourly intervals, beginning with 00Z (GMT). We used only the "three hourly" observations (00Z, 03Z, 06Z etc.) for a total of eight possible observations per day. With eight observations per day, a month contains 224 to 248 possible observations, depending on the number of days in a month.

The coastal stations examined in this study contain records from 1949 to 1990, though some stations have gaps with no observations. Fog is indicated at the coastal stations by recorded "present weather" for fog or ground fog, (shown as "F" or "GF" in the observations). Obstructions to visibility are reported if visibility is less than 7 *miles*.

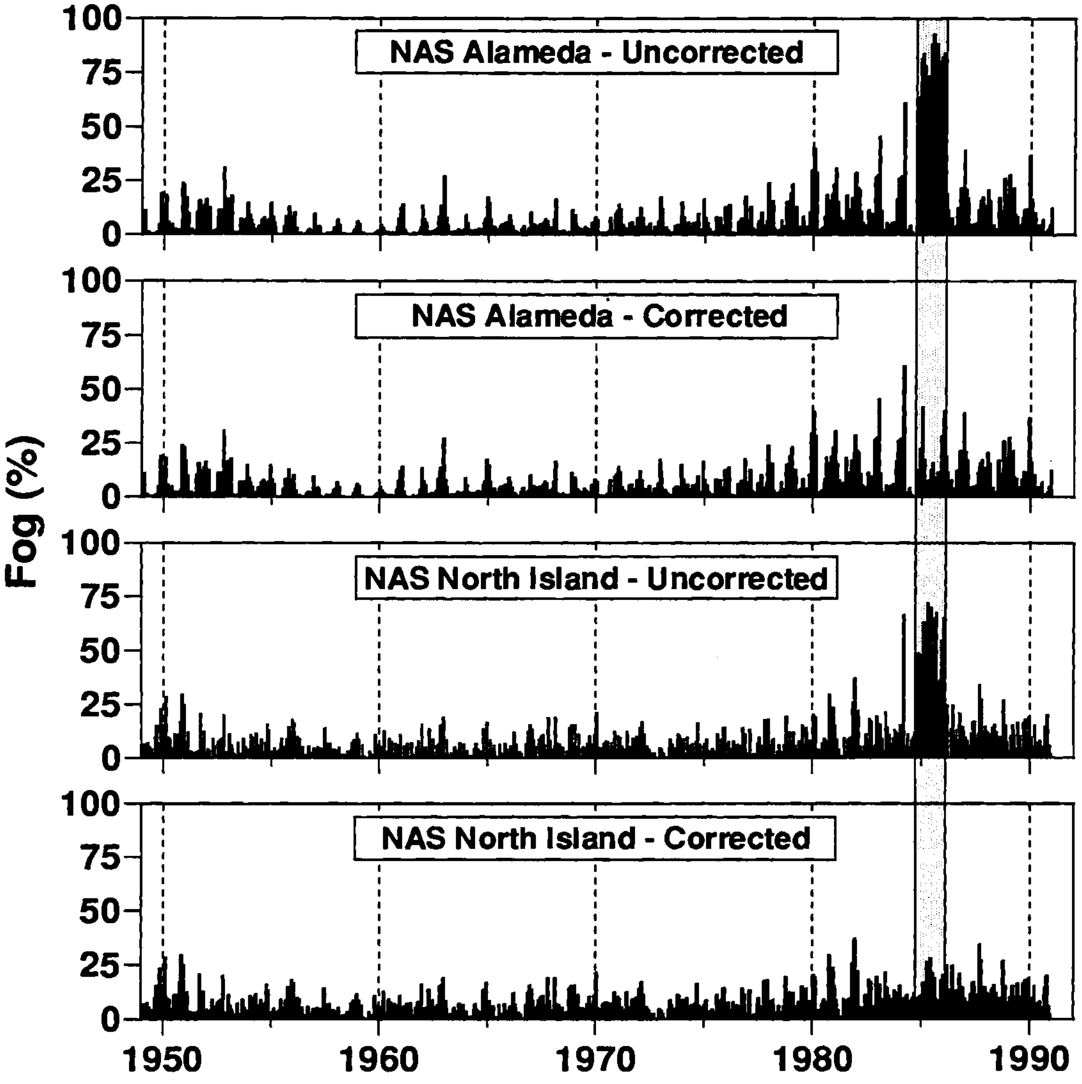
At the coastal stations, for months in which at least 50% of the three hourly observations were available, the fraction of observations having fog was computed, yielding a time series of fog occurrence for each month beginning in 1949. Beginning in 1984, a data sampling problem occurred at most of the United States Navy coastal stations (Alameda, Moffet Field, Point Mugu, San Clemente, San Nicolas, Miramar, North Island). For the month of March 1984, and October 1984 through January 1986, less than 120 observations were taken. Of those observations, generally at least 50% reported fog which is anomalously high relative to the frequency of the fog during the remainder of the record. A possible explanation for this reporting discrepancy was a temporary change in reporting procedures at Navy stations where observations were only taken if a significant weather phenomenon (such as rain or fog) occurred (Mikoly, 1993). Assuming this is true, the missing observations were then reinserted and counted to be "fog free." The resulting monthly fog values appear to be quite realistic. The time series in Figure 3 is an example of two of the stations, NAS Alameda and NAS North Island, before and after correction.

A set of regional marine surface observations was extracted from COADS (Woodruff *et al.* 1987) for the 1949-1991 period. Monthly totals for the Eastern North Pacific COADS region (between 20°N and 52°N and west from the coast to 136°W) range from 225,000 observations for all Februarys to 285,000 for all Julys. The uneven density of observations in each one degree grid square for a typical year, 1975, is shown in Figure 4. Overall, approximately 3.5 million observations were in the Eastern North Pacific region.

The coastal regions used in this study (Figure 2b) had both temporal and spatial variability in the number of observations. The density of observations ranged from approximately 2000 per month in Region 1 (Northern California, 40-42°N) to 14,000 per month in Region 7 (Southern California, 31-33°N). Offshore regions contained 2000 to 5000 observations per month (Table 2). The greatest percentage of open ocean weather observations lie along the major ship tracks to Hawaii and the Western Pacific. Away from these shipping routes, considerably fewer surface ship observations exist (Figure 4).

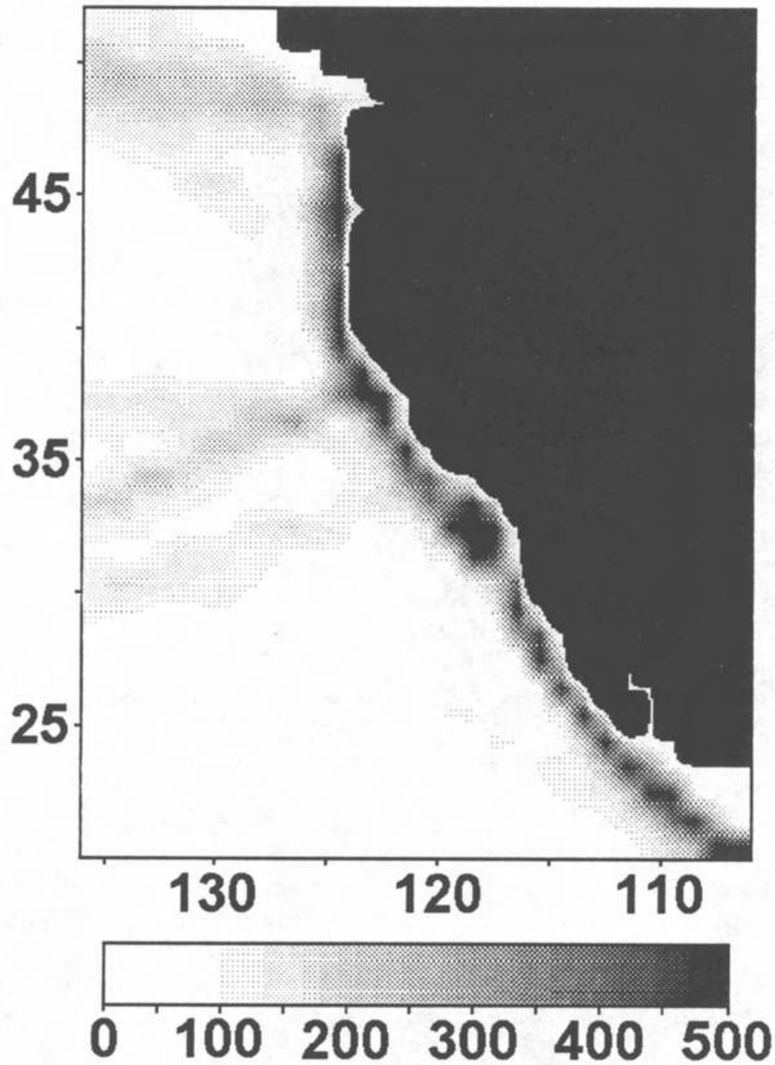
The "present weather" code in the marine data, which accounts for 100 different weather categories (codes 00-99), was used to indicate fog or no fog. Fog is recorded if the weather at the time of the observation, or just prior to it, coincides with one of 14 fog categories. Ten of the 14 categories (40-49) are for fog present at the ship at the time of observation. One code (28) designates fog present during the preceding hour but not at time of observation. The remaining three codes (10-12) describe light fog ("mist" or deep fog with visibility greater than or equal to 1 *km*), or shallow fog (not deeper than 10 *m*). The weather is coded into one of the first 11 fog categories (28, and 40 through 49) only if visibility is less than 1 *km* (NWS, 1991).

Figure 3. Monthly Fog Occurrence at NAS Alameda and NAS North Island Before and After Correction



The shaded area shows the period (Oct 1984-Jan 1986) of the temporary change in US Navy weather reporting criteria (see text).

Figure 4. Density of Marine Weather Observations in 1975



The gray scale represents the number of marine weather observations reported in calendar year 1975 by 1x1 degree grid squares. The maximum observation count was 2,393 observations in the Southern Californ Bight. The minimum was 8 observations near 20 N.

Table 2. Number of Total Observations and Number of Fog Observations by Region for the Marine Data Set (1949-1991).

	Region		Total Observations	Observations with Fog	Percent with Fog
1	(40°-42°N)	(125°-128°W)	24,467	2,089	8.54
2	(38°-40°N)	(121°-125°W)	38,129	4,755	12.47
3	(36°-38°N)	(121°-128°W)	66,034	7,217	10.93
4	(36°-40°N)	(125°-128°W)	62,228	4,279	6.88
5	(33°-36°N)	(121.5°-125°W)	54,140	3,572	6.60
6	(33°-33°N)	(117°-121.5°W)	89,611	9,370	10.46
7	(31°-33°N)	(117°-121°W)	156,903	9,407	6.00
8	(31°-33°N)	(121°-125°W)	35,351	905	2.56

We computed the fraction of observations in which fog was reported within a given time interval, (e.g. over a month) to analyze the spatial and temporal variability. "Fog occurrence" is defined here as the number of observations with fog, divided by the total number of observations within this unit of time.

Problems encountered with deducing fog occurrences from the COADS observations included the introduction of automated marine weather buoys in the early 1980's and a change in ship marine weather reporting practices in 1982. The number of missing present weather codes increases dramatically in the 1980's because automated ("unmanned") buoys cannot report present weather conditions, while ships normally reported present weather. But in 1982, ship weather reports began neglecting to report present weather if fair weather conditions prevailed (the practice of not reporting present weather under fair weather conditions also occurred prior to 1982 but to a much lesser degree). As a result, beginning in the early 1980's data could be incorrectly weighted because the "no fog" observation count was biased low, increasing the apparent fraction of reports with fog.

To account for this discrepancy, observations were examined for reported cloud cover along with present weather since the unmanned buoys also cannot report cloud data. Observations with cloud data but with missing present weather were considered to have skipped the present weather report because the weather was fair—these were counted as "no fog" observations. Observations that were missing both cloud cover and present weather were considered to be truly missing the present weather indicator and were not used in calculating the fog fraction.

Appendix D shows an auxiliary fog data set from foghorn data over 1950-64. We examined this data for compatibility with the other two fog data sets. This data is expressed as monthly frequency of occurrence, derived from the length of the month and hours of foghorn operation. The foghorn collection is an important source of information because it provides much better spatial detail in the Northern and Central California Coast and in the San Francisco Bay region than the other two data sources.

To represent the atmospheric circulation, gridded analyses of 700 *mb* height over the northern hemisphere during 1949-1991 were obtained from the NOAA Climate Analysis Center (CAC). These came in two forms, monthly averages and twice-daily (00Z and 12Z) data sets. Monthly anomalies were constructed by subtracting their long-term mean (1947-1972) for each particular month.

Daily anomalies were constructed by subtracting the long-term mean (1950-1979). In the analyses shown here, only the 12Z anomalies are used.

A daily mean temperature anomaly set was employed (1950-1990) on a 2.5° latitude-longitude grid over the conterminous United States. These were constructed (as in Roads and Maisel, 1991) from first order and cooperative weather station records obtained from the National Climatic Data Center.

5. Climatology of West Coast Fog

5.1. Seasonal Variability

5.1.1. Coastal Station Fog Climatology

Two dominant patterns of seasonal fog occurrence are revealed by the California coastal station records: peak fog occurrence in summer/fall and peak fog occurrence in winter. Stations with dominant fog maxima during winter (December and January) include San Francisco, NAS Moffet Field, and San Diego. Stations with dominant summer maxima (July and August) are Arcata, Santa Barbara, and San Nicholas and San Clemente Islands (Figures 5 and 6).

Arcata, the only station studied in extreme Northern California, has a pronounced summer maximum (with fog being recorded in 41% of all observations in the month of August) and a late winter-early spring minimum (Figure 5). This peak is consistent with the summer peak in marine fog in the nearby coastal region (as discussed in the next section) and suggests an ocean origin for Arcata's fog.

At all three locations in the San Francisco Bay area (San Francisco, Alameda, and Moffet Field), on the other hand, fog occurrences are near 0% during summer months and reach their maxima in December and January. As discussed earlier, the complex topography in the San Francisco Bay area most likely contributes to the high winter fog maxima. Much of the winter fog, especially in Central and Northern California, is radiation fog caused by the large diurnal temperature differences that occur with the trapping of cool air in the valleys. Also, fall and winter months are more likely to have moist ground from North Pacific storms breaking into this area (Kotsch, 1983). The foghorn records *(Appendix D)* reveal how the fog climatology undergoes a rapid transition from a summer maximum in the outer regions (see San Francisco Light Ship and Lime Point) to the winter maximum of the inner region (Yerba Buena Island and Oakland) just a few kilometers inland. The foghorn records show that there is actually an intermediate region with a mixed climatology having both summer and winter maxima (Alcatraz North and Alcatraz South).

Stations in the northern portion of the Southern California Bight and in the Channel Islands exhibit a fog pattern that has less month-to-month variation than stations to the north. Although these stations have a more uniform fog frequency throughout the year, they do have summer maxima as well. Peak fog occurrences are consistent among the four stations in the region (Santa Barbara, Point Mugu, San Nicolas Is., and San Clemente Is.) with a maxima in summer of approximately 20% (Figures 5 and 6). Similar seasonal maxima are found for the adjacent marine coastal regions, suggesting an oceanic "advection fog" regime at these sites. In the southern portion of the Bight, coastal stations exhibit a mixed pattern of fog occurrence, with a primary maximum in winter and a secondary peak in summer, particularly June ("June gloom") (Figure 6).

Examining the entire coastal region, the seasonal peak is not particular to any individual site, but instead is common to several locations from Northern to Southern California. At most stations with an open-ocean exposure, a warm season fog maximum (summer and fall) prevails. This is consistent with the seasonal marine fog climatology, presented next and in *Section 8.1*. In contrast, stations located further inland tend to show a winter maximum. Miramar is the only exception, but it lies on a broad coastal plain with relatively good

Figure 5. Percent of Fog Monthly Means for the Fog Study Northern Coastal Stations (1949-1990)

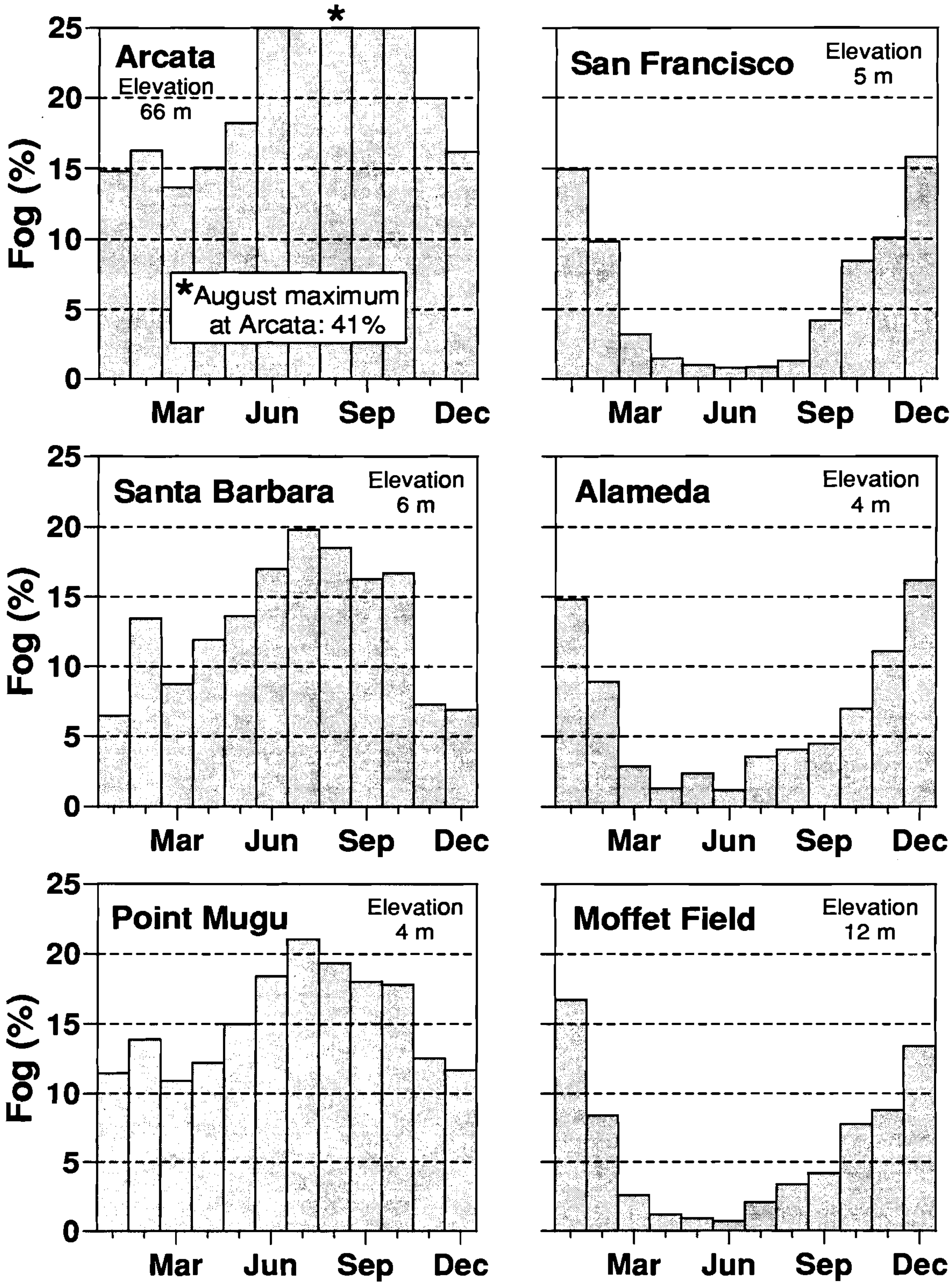
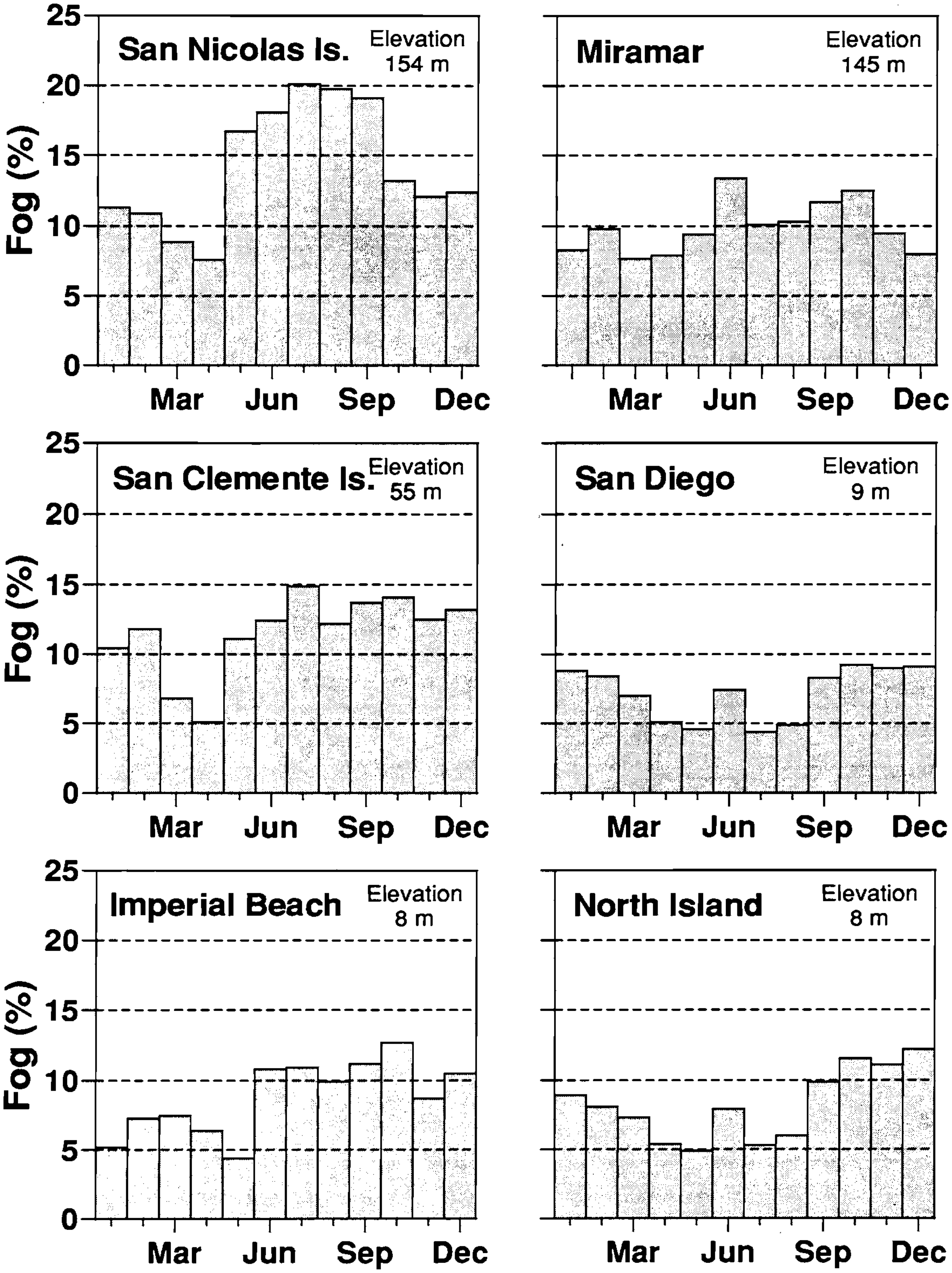


Figure 6. Percent of Fog Monthly Means for the Island and Southern Coastal Stations (1949-1990)



exposure to the coastal ocean and is significantly higher (145 *m*) than any other coastal station except San Nicolas Island (154 *m*).

5.1.2. Marine Fog Climatology

The occurrence of fog along the California coast falls off from north to south, from a high of 21% (August) in Northern California (Region 2), to a low maximum of approximately 8% (July) in Southern California (Region 7). There is even less fog in the Southern California offshore area (Region 8), with a maximum of only 5%.

The marine regions have seasonal fog patterns similar to the coastal stations, with some regions having strong summer maxima and other regions having winter maxima (Figures 7-10). Northern California (Region 2, 38-40°N), and the Southern California Bight (Region 5), exhibit the summer maximum/winter minimum pattern. The San Francisco Bay area (Region 2) has a summer peak of 20% in July and August, while the Bight reaches a maximum in July at 16%.

The two southernmost coastal regions (Southern California, Regions 7 and 8), differ from the others in that they have a winter maximum. However, they are similar in that they do have a secondary maximum in summer. The Central Coast (Region 3), is similar to that of Northern California (Region 2) in that it still has pronounced winter maxima with secondary maxima in the summer. The climatology of fog along the Central Coast (Region 3), is similar to that of Northern California (Region 2) in that it still has a pronounced winter/spring minimum and summer maximum. Offshore, in Regions 4, 6 and 8, the climatological fog patterns closely resemble that of the nearshore regions with summer maxima in all three but with lower percentages of occurrence in nearly all months.

One reason for the changes in the seasonality and magnitude of fog over the California coastal region is the structure of the temperature inversion capping the marine layer. This structure is strongly modulated by the large-scale atmospheric circulation as discussed in the context of anomalous variability in *Section 7*. Variations in the height of the inversion, due to local topography (the proximity of coastal mountains) and the atmospheric circulation along the California coast, control vertical motion and the thickness of the marine layer.

While a lower inversion produces more marine fog (Leipper, 1994), a thinner boundary layer over land evidently results in less fog since it is more readily broken by surface heating and turbulent mixing. Thus, coastal station fog with a marine origin, such as occurs at the Southern California Bight stations, has a maximum in summer when the Eastern North Pacific High and the accompanying temperature inversion are strongest.

At stations where fog develops primarily from land influences, such as the San Francisco Bay area, winter maxima prevail. The mixed seasonal fog regime at San Diego contains fog developed from both origins. Summer fog appears to have a maritime origin and is carried by northwesterly winds (Noonkester, 1979). Santa Ana conditions in winter produce offshore flow moving warm dry air over the cool coastal waters. As these Santa Anas decay, conditions become ideal for producing fog, as described by Leipper's model of fog development (Leipper 1949, 1994; *Appendix C)* and work done by Noonkester (1979).

The effect of a strong, low inversion base is prevalent along the entire West Coast. Cooler inshore waters probably enhance the presence of fog by cooling the near saturated air advected in from warmer offshore waters (Noonkester, 1979)—in the north, the cooler waters are closer to shore. The decrease in fog occurrence moving both southward and offshore may be attributed to an increase in the height of the subsidence inversion to the west and to the south, and possibly the waters warming to the west and to the south.

A comparison of the annual cycle of fog at coastal stations with marine observations

Figure 7. Percent of Fog Monthly Means for the Northern California Regions (1949-1991)

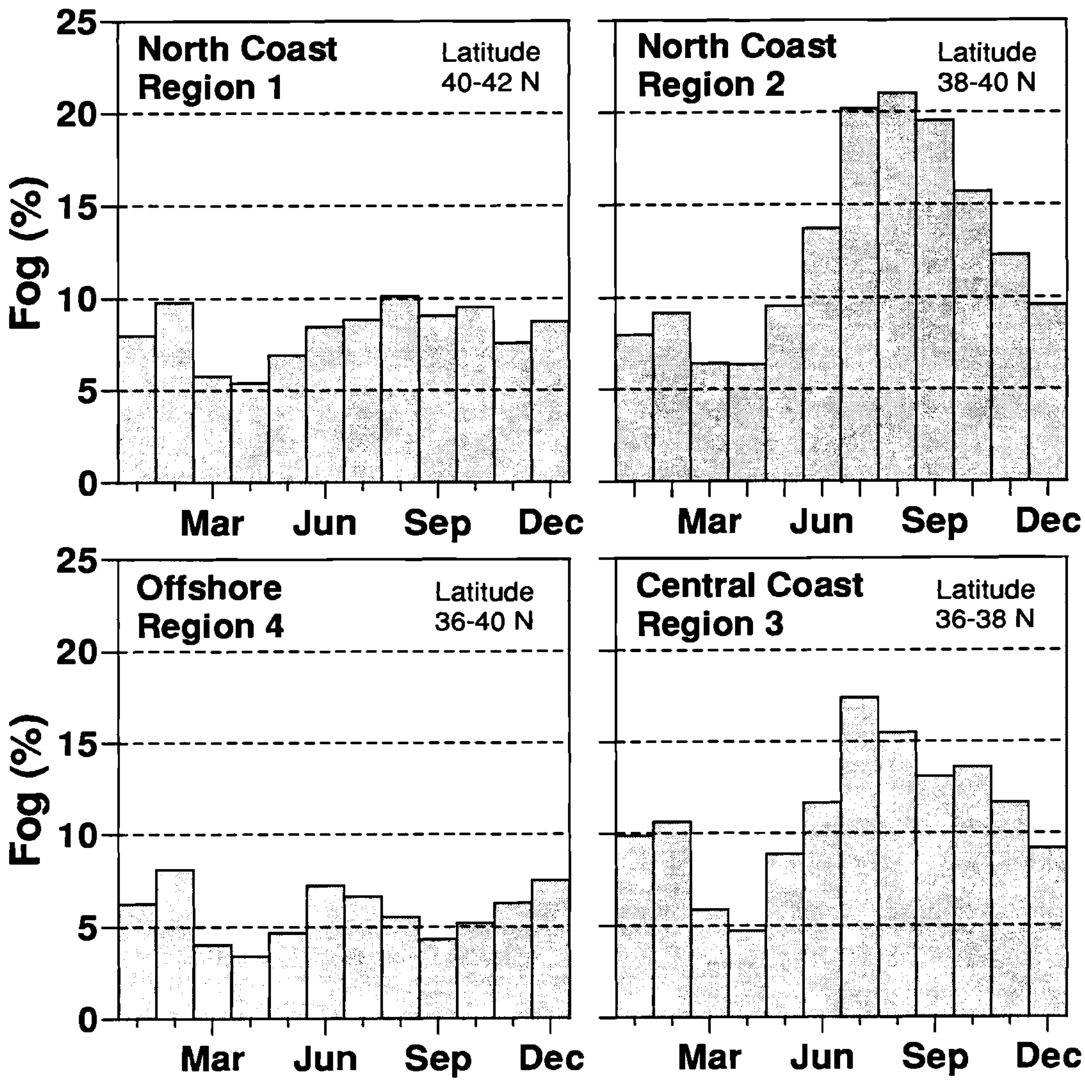


Figure 8. Percent of Fog Monthly Means for the Southern California Regions (1949-1991)

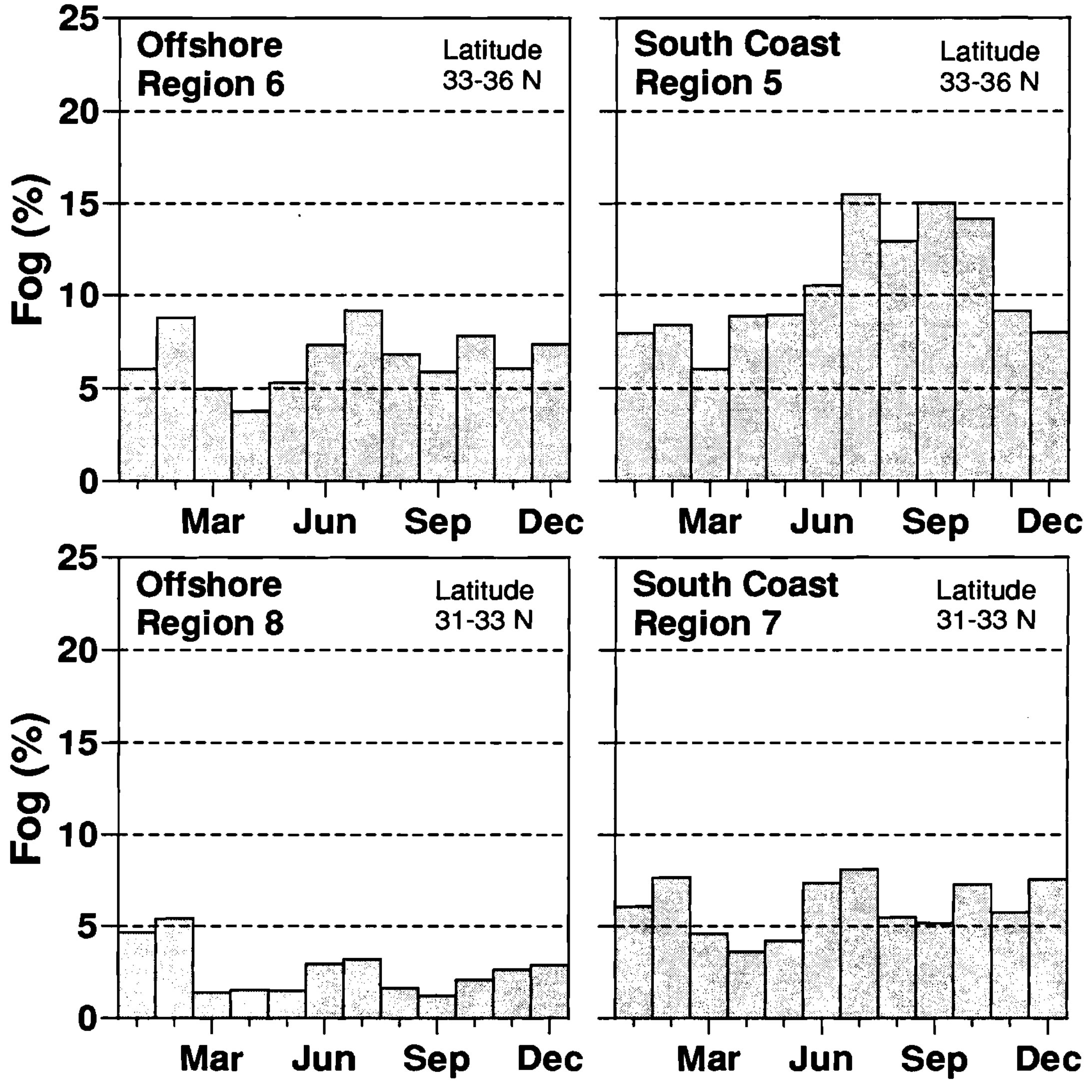


Figure 9. Percent of Fog Monthly Means for the North and Central Coastal Regions (1949-1991)

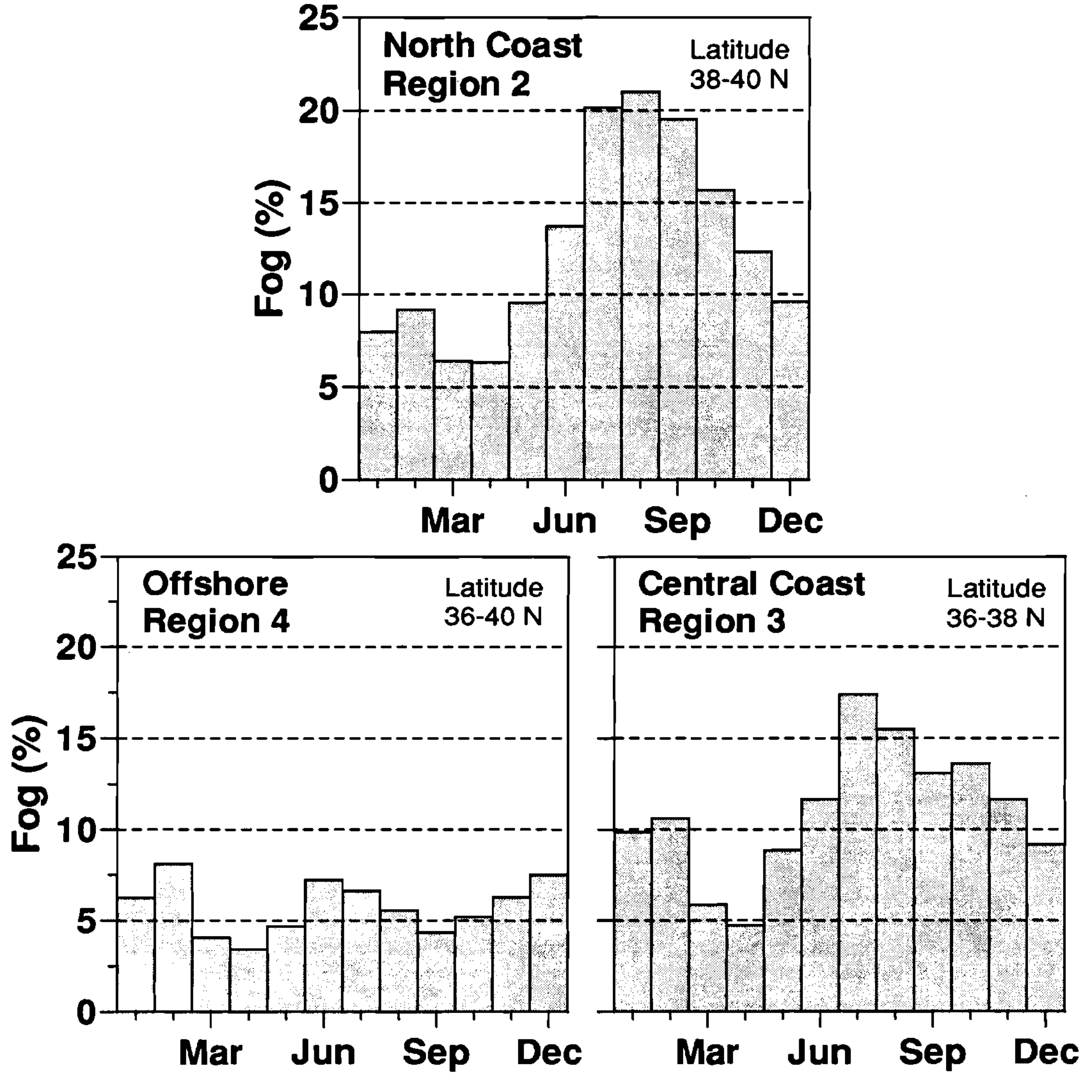
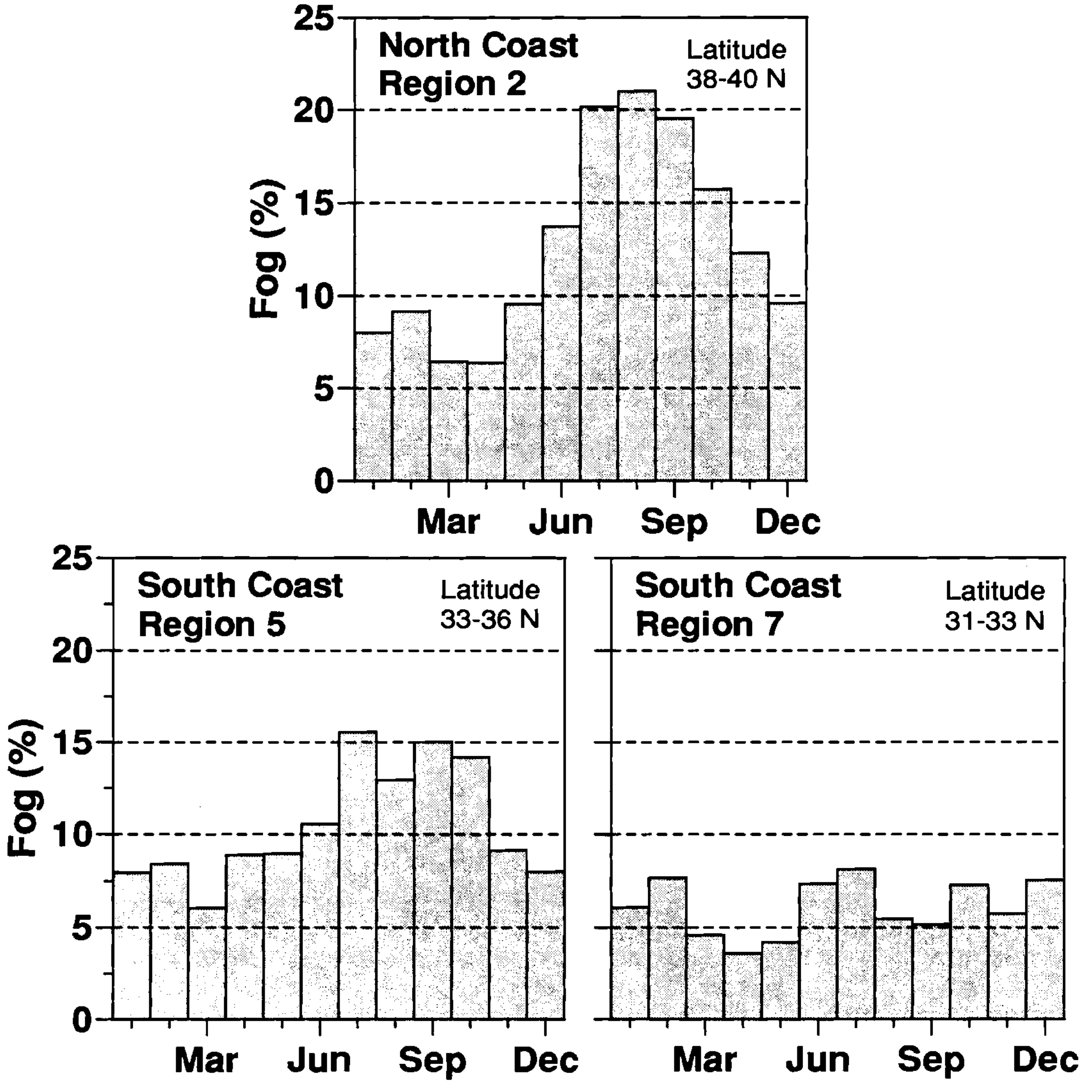


Figure 10. Percent of Fog Monthly Means for the North and South Coastal Regions (1949-1991)



indicates a strong correspondence of coastal land fog to nearby ocean fog patterns. This correspondence is further developed from correlations between fog anomalies of the coastal sections *vs.* those of ocean regions in *Section 8*. The greatest exception is winter maxima in the fog pattern at San Francisco Bay area stations in contrast to the characteristic summer maximum of fog over the adjacent ocean. Thus, Region 3 is nearly the opposite that indicated by the San Francisco Bay area coastal stations which had a near 0% occurrence in the summer months *(Appendix D)*.

Referring to Figure 8, the Region 1 (40-42°N) fog pattern is similar to Arcata (Figure 5), with a strong summer maximum, although the ocean Region 1 has a much lower fog occurrence than does Arcata. Coastal stations in the Southern California Bight exhibit a pattern similar to the year-round fog occurrence in the Central Coast, (Region 3) and the Bight, (Region 5) (Figures 5 through 8). Southern California coastal stations are also quite similar to the coastal marine fog pattern. This is especially true at North Island and San Diego (Figures 6 and 8), which contain June and December/ January maxima, nearly equal at about 8%. The San Diego climatology is similar to the mixed season climatology of some of the stations just inside the San Francisco Bay *(Appendix D)*, which exhibit summer and winter maxima.

It is interesting that North Island, while only about 4.5 *km* south of Lindbergh Field (San Diego), experiences significantly more fall/early winter fog (~25% more). This may be a function of geography. Aside from local cold air drainage effects, one of the major advection fog patterns affecting the Southern California Bight has a thin fog layer moving northward along the coast from Baja California (Noonkester, 1979). This fog would reach North Island first and, as it recedes, still be over North Island after it had left Lindbergh Field.

Examining the two dominant fog patterns at coastal stations and marine observation regions, summer fog is a marine phenomenon, while winter fog is produced at coastal land sites and to a more limited extent over the coastal ocean. Thus, two types of fog exist along the California coast. The winter fog pattern found in San Francisco, Alameda and Moffet Field, and in Southern California appears to be primarily influenced by radiation processes, with advection probably playing a secondary role.

The spatial distribution of the seasonal fog climatology is presented in *Section 8.1*. Strong summer maxima are seen at Arcata, at the Southern California Bight stations, and in the San Diego area. Similar maxima are found in the fog climatology of the marine regions, so it is likely that the heavy summer fogs along the coast are of marine origin. Previous studies indicate that these marine fog episodes are controlled by the strength of subsidence inversions and the structure of the marine layer.

5.2. *Interannual Variability*

5.2.1. Coastal Stations

As a prelude to an examination of interannual variability, the stability of the monthly fog climatology was examined. Figures 11 through 14 show the monthly mean fog for Marine Regions 2, 5, 6, and 7 for each of four periods, 1949-1961, 1962-1971, 1972-1981, and 1982-1991. The basic seasonal pattern is quite well-presented at each region across the four decades. However, coastal Southern California Regions 5 and 7 show a drop off in fog occurrence during the 1982-1991 period. This may be an artifact of the sampling and reporting practices used with COADS data discussed earlier in *Section 4*.

Substantial year-to-year fluctuations exist in the monthly fog percentages. Time series of the nine coastal stations for the period 1949-1990 are shown in Figures 15 through 17. Considering the amplitude of the variability for each month, a strong seasonal signal is seen in the variability of fog occurrence. The temporal variability changes throughout the year, spatially north to south, with the highest variability occurring at the locations and months having the highest

Figure 11. Decadal Percent of Fog Monthly Means for North Coast Region 2 (38-40N)

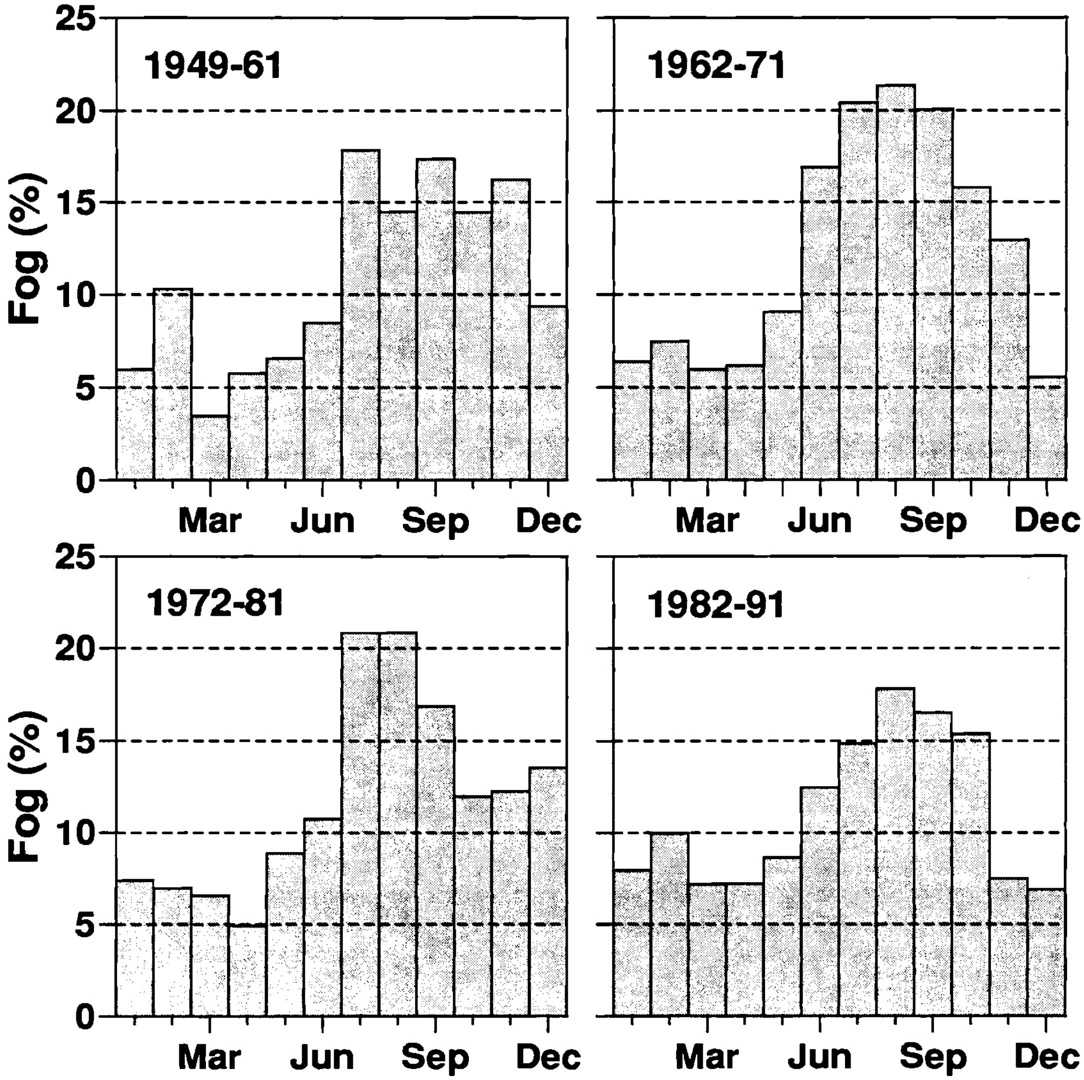


Figure 12. Decadal Percent of Fog Monthly Means for South Coast Region 5 (33-36N)

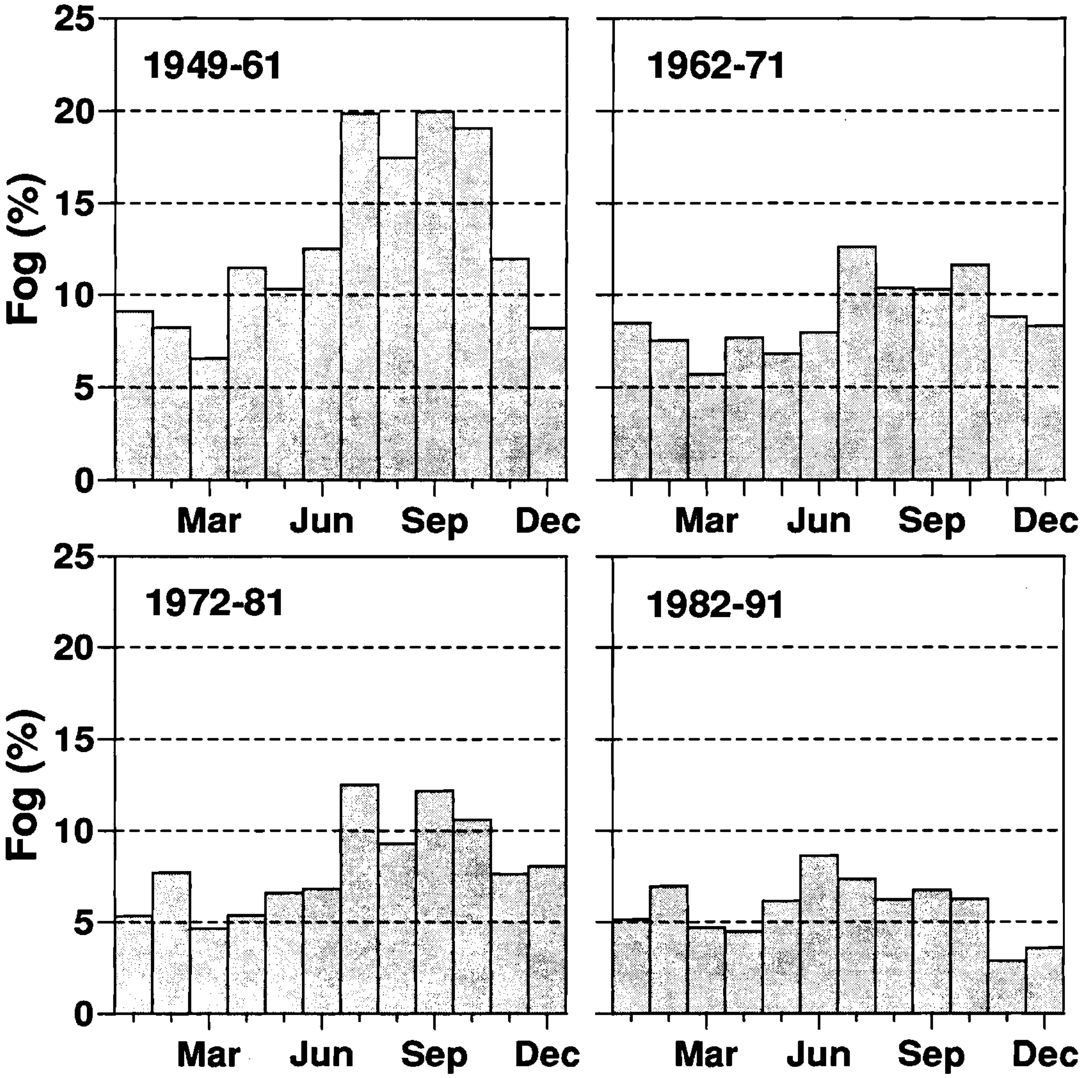


Figure 13. Decadal Percent of Fog Monthly Means for Southern Offshore Region 6 (33-36N)

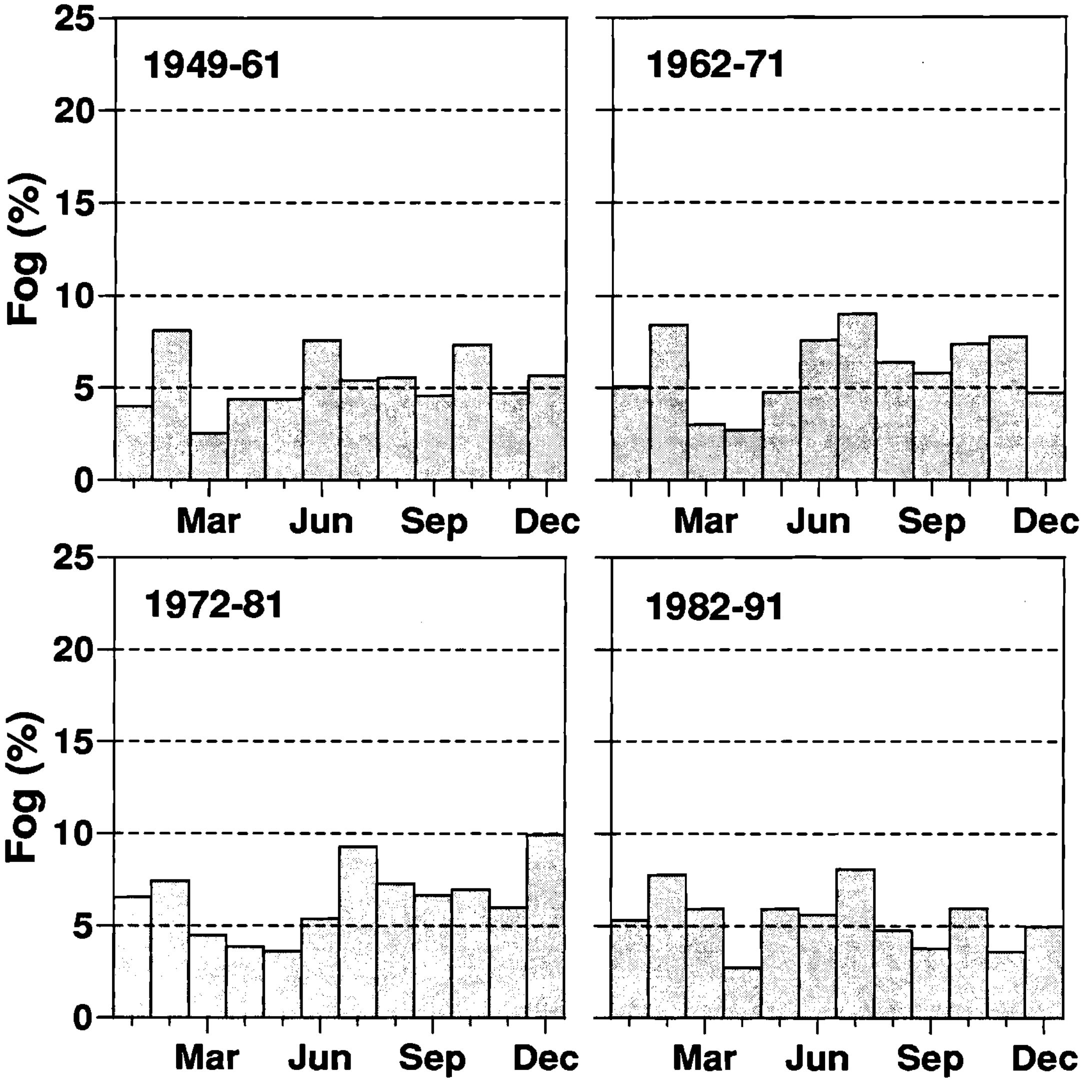


Figure 14. Decadal Percent of Fog Monthly Means for South Coast Region 7 (31-33N)

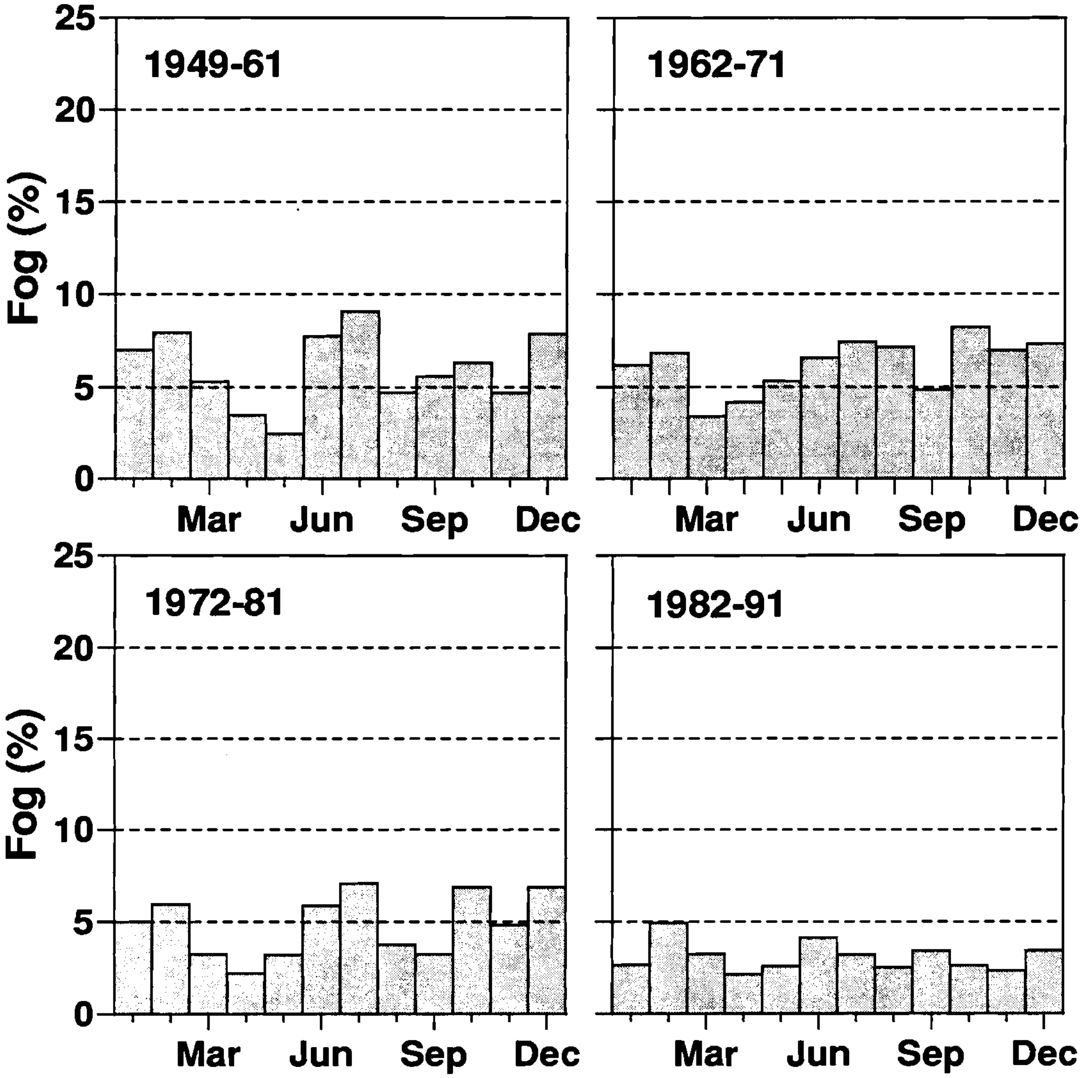


Figure 15. Monthly Percent of Fog for Northern California Coastal Stations (1949-1990)

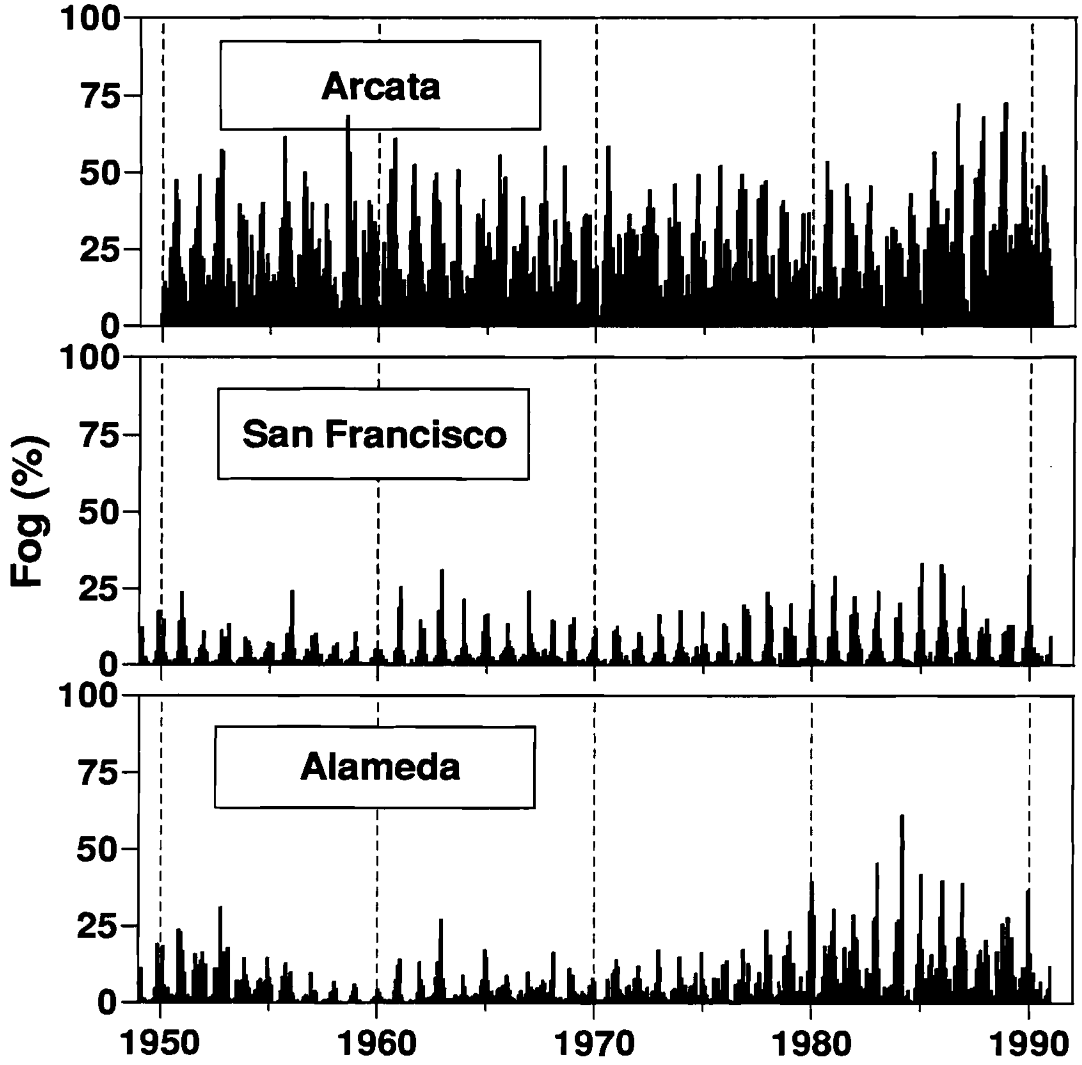


Figure 16. Monthly Percent of Fog for the Southern California Bight Coastal Stations (1949-1990)

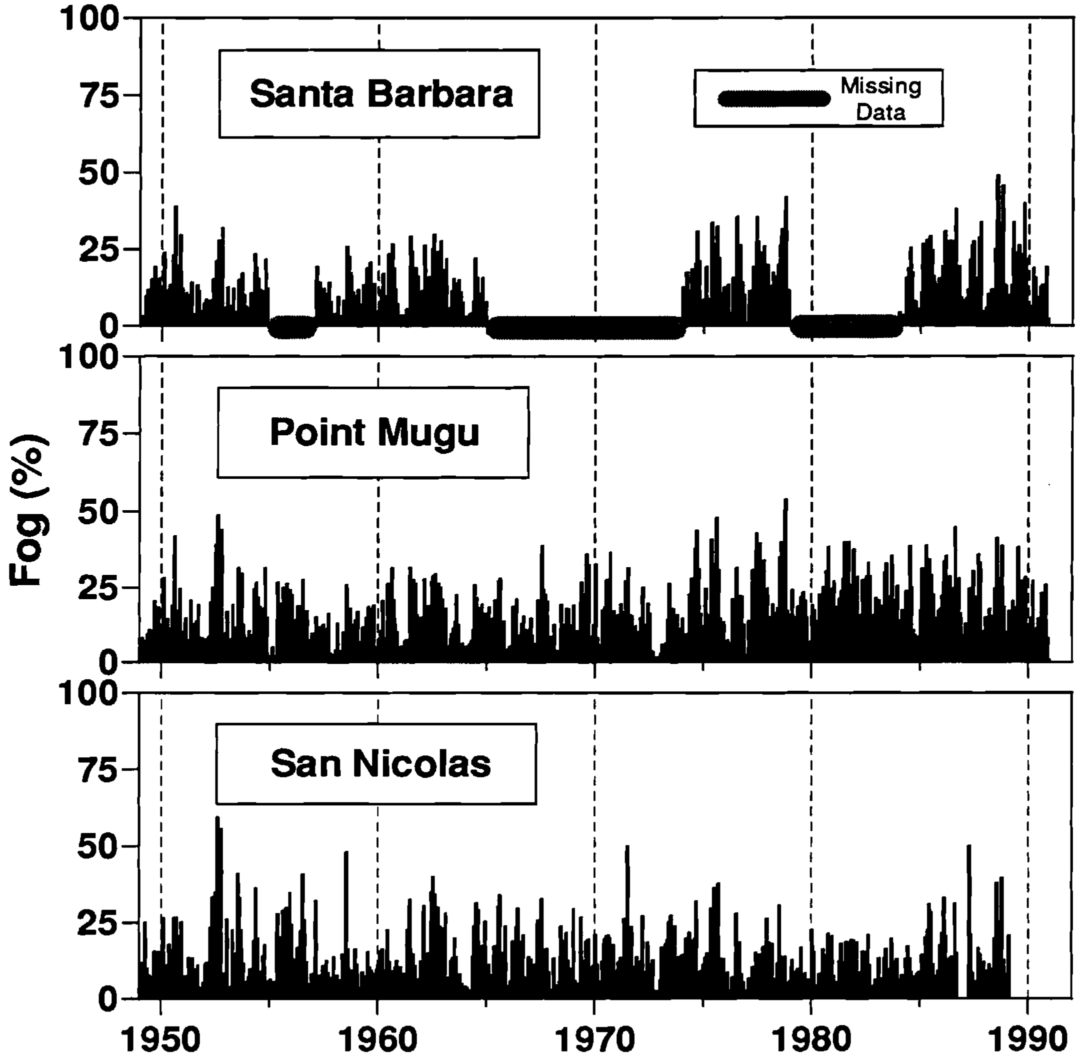


Figure 17. Monthly Percent of Fog for Southern California Coastal Stations (1949-1990)

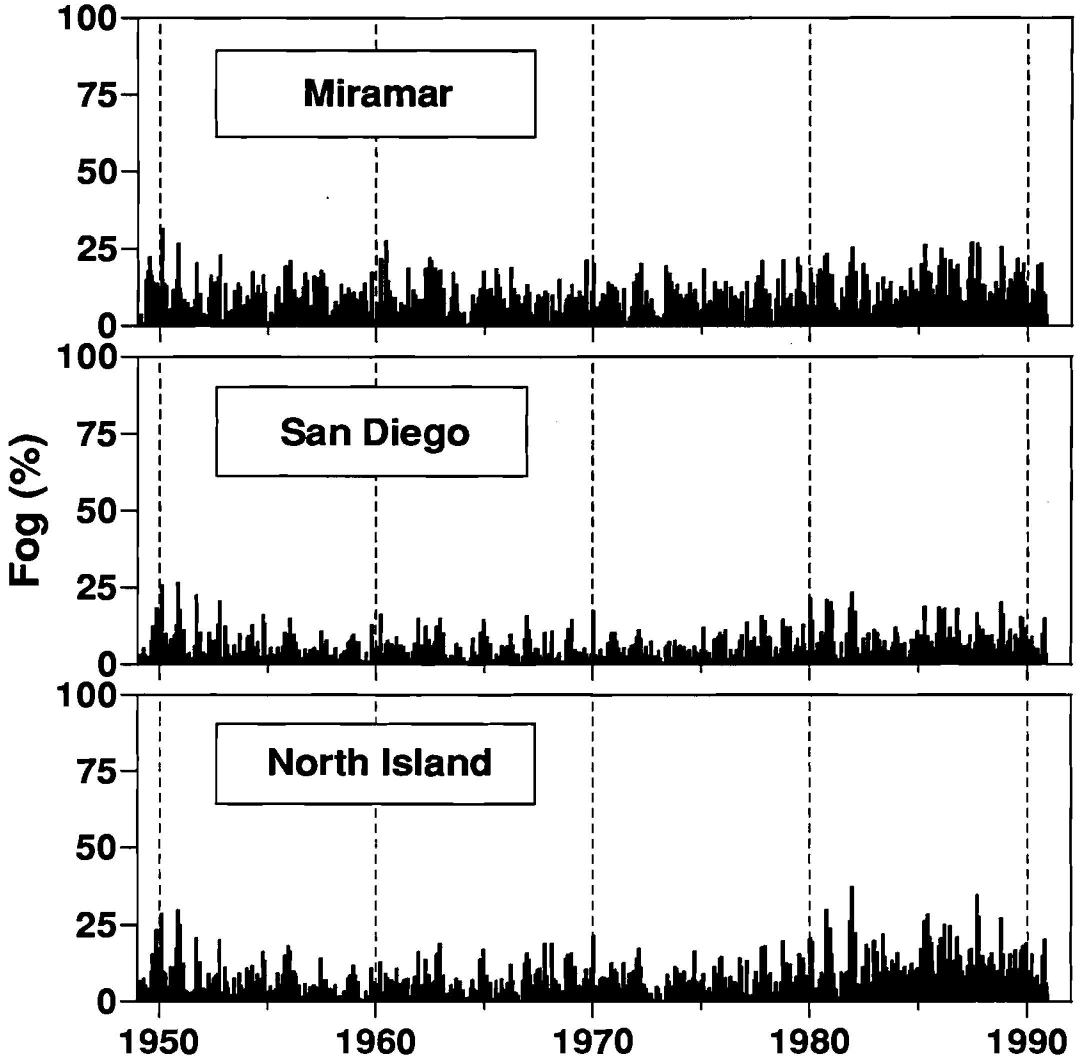


Figure 18. Monthly Percent of Fog for the Northern COADS Regions (1949-1991)

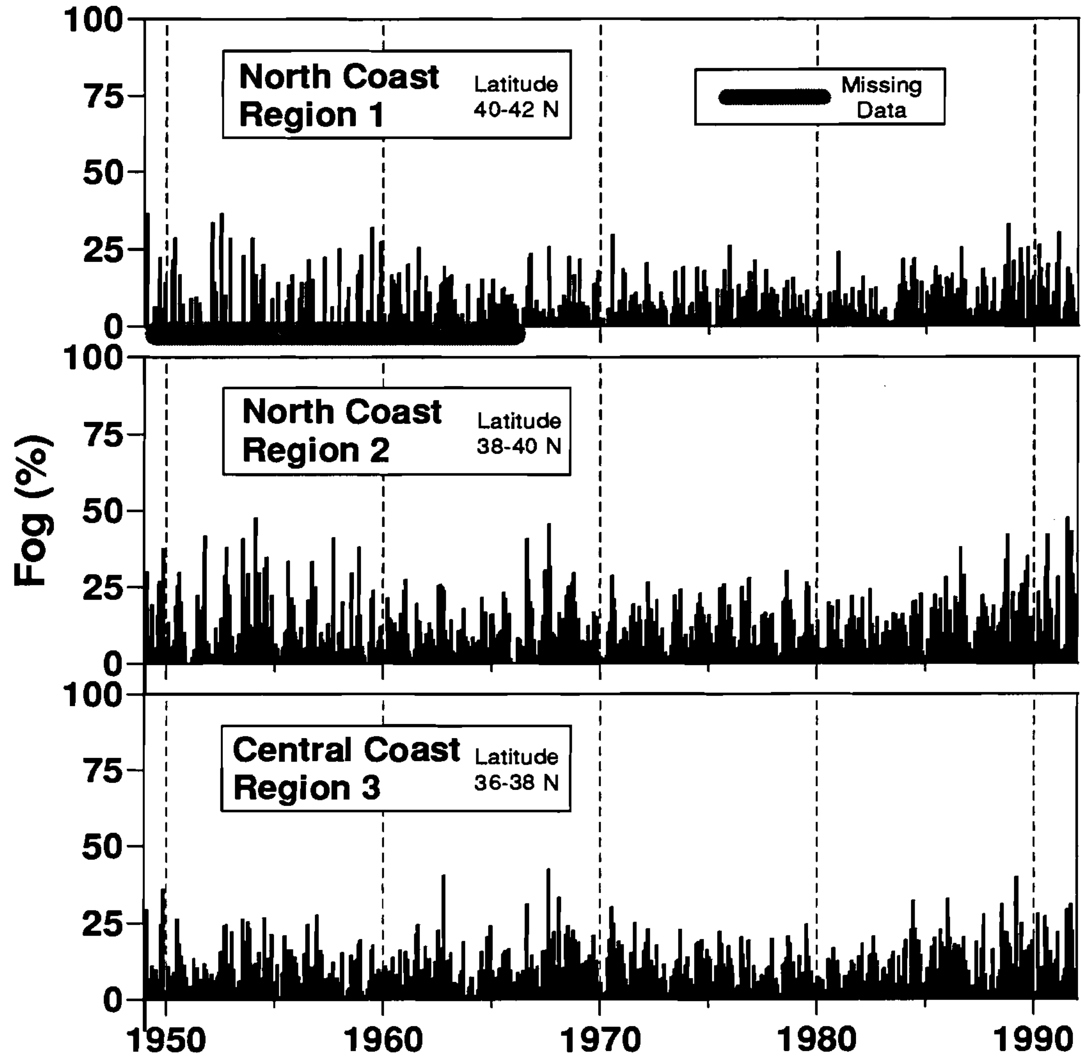
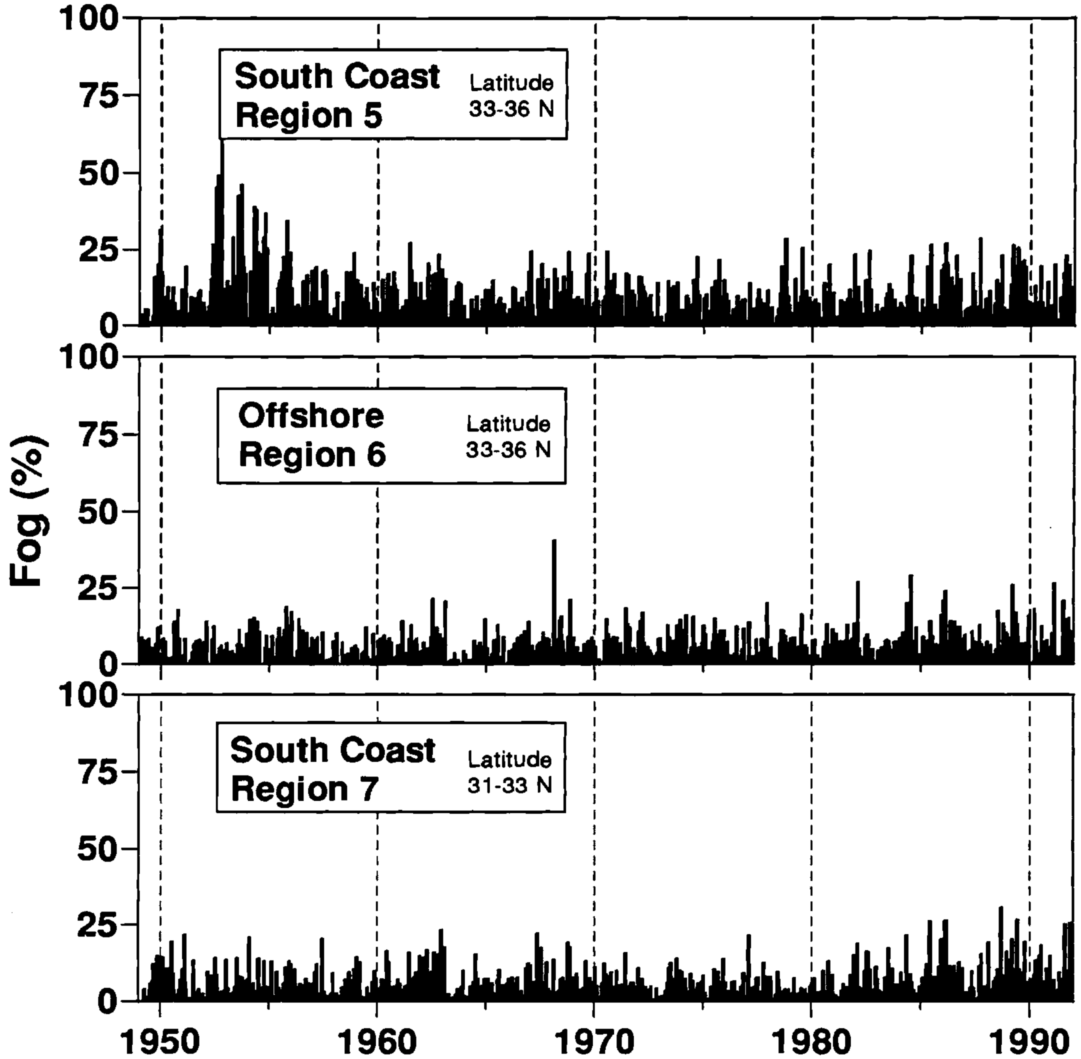


Figure 19. Monthly Percent of Fog for the Southern COADS Regions (1949-1991)



mean values. Of all the coastal stations, Arcata contains the greatest frequency of fog—for several months fog occurrence exceeded 50%. The stations in the Southern California Bight rarely exceed 50% fog occurrence but many months have fog occurrence greater than 25%. Variability is heightened in the winter months in the San Francisco Bay area compared to its more year-round distribution in the Southern California Bight region. As described in the previous section, this difference evidently is a result of the different processes (land *vs.* oceanic) operating in these two regions.

Extremes in monthly fog occurrence were examined at several individual stations. Using the Northern and Central California stations as examples, fog occurrences range from a low of near 0% (San Francisco) to a value exceeding 70% (Arcata). The year 1952 was extremely high in fog occurrences at the Santa Barbara, Point Magu, and San Nicolas Island sites. The year 1988 had high fog at several stations (Arcata, Alameda, Santa Barbara, San Nicolas Island, and North Island). 1963 and 1973 are noteworthy in their lack of fog at most stations (1963—San Francisco, Santa Barbara, San Nicolas, Point Mugu, and Miramar; 1973—Arcata, San Francisco, Alameda, Point Mugu, Miramar, and North Island). The spatial coherence of monthly fog anomalies among the coastal regions and among the marine regions is highlighted by a correlation analysis in *Section 8.* Several of these extremes (during the 1950-64 period) are also found in nearby foghorn sites as plotted in the time series in *Appendix D.*

5.2.2. Marine Observations
The eight marine regions also exhibit substantial monthly fluctuations in fog occurrence. Figures 18 and 19 compare the monthly time history of fog for Northern California (Regions 1 through 3), Southern California (Regions 5 and 7), and offshore of Southern California (Region 6). There is a much greater frequency of monthly fog occurrence in the Northern California regions than in the Southern California regions; offshore (Region 6) is particularly small.

Like the coastal stations, seasonal extreme episodes can be identified from these station records. As with the coastal stations, 1952 stands out as a high fog year, particularly in Regions 1, 2 and 5. For all six regions, 1968 is unusually high as well, but 1963 and 1973 were years of reduced fog occurrence. There appears to be strong correlations between the monthly fog anomalies at nearby regions for the entire record (these correlations are discussed in *Section 8*). From the foghorn records in *Appendix D*, the heavy fog during 1952 and the light fog during 1963 can be seen from Humboldt Bay southward to the San Francisco Bay area.

6. Local Connections with Marine Fog

6.1. Sea Surface Temperature (SST)
In this section, local parameters associated with fog (or lack of fog) are examined. Because the development of fog at coastal stations may be strongly affected by topographic features peculiar to individual locations, only the marine regions were employed in this section. The following variables were considered: the sea surface temperature (SST), the sea surface temperature minus air temperature (ΔT), wind direction, and wind speed. Previous studies have also asserted that cool SST is not the primary cause of fog and stratus formation (e.g. Pilie, *et al.*, 1979, and Leipper, 1994).

We examined the association of SST and fog occurrence in the marine study regions (Figures 20 through 23). This was accomplished by the comparison of the distribution of SST for all observations where fog was reported, to that associated with observations where no fog was reported. Note that in this and the other comparisons of various fog *vs.* no fog distributions that follow, there was no discrimination between different fog categories—all 14 categories are pooled. Counts of fog/no fog occurrence were accumulated into 0.5°*C* SST bins, the data in the two groups were then plotted together in histograms.

Figure 20a. Distribution of SST for Fog and No Fog in North Coast Region 1 (40-42N)(1949-1991)

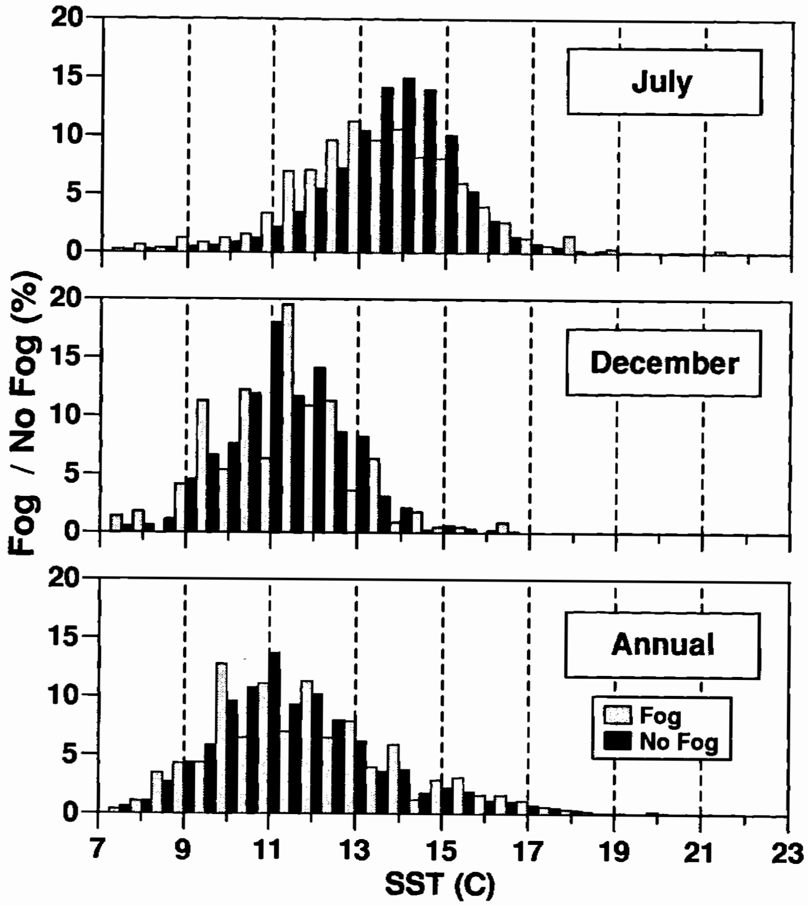


Figure 20b. Distribution of SST for Fog and No Fog in North Coast Region 2 (38-40N)(1949-1991)

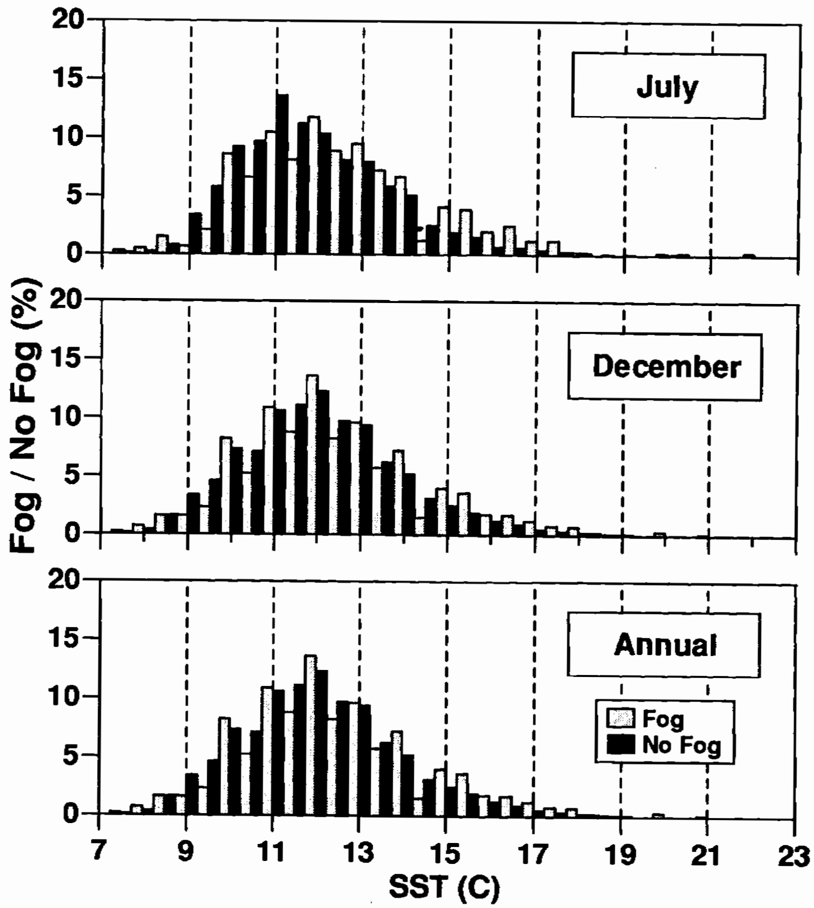


Figure 21a. Distribution of SST for Fog and No Fog in Offshore Region 4 (36-40N)(1949-1991)

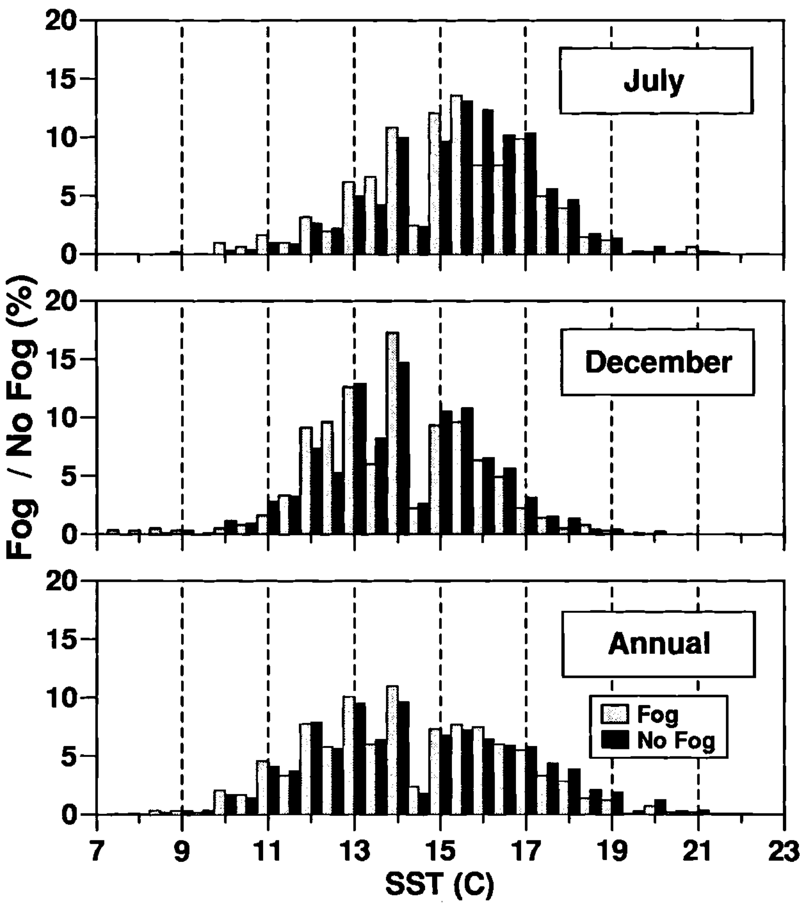


Figure 21b. Distribution of SST for Fog and No Fog in Central Coast Region 3 (36-38N)(1949-1991)

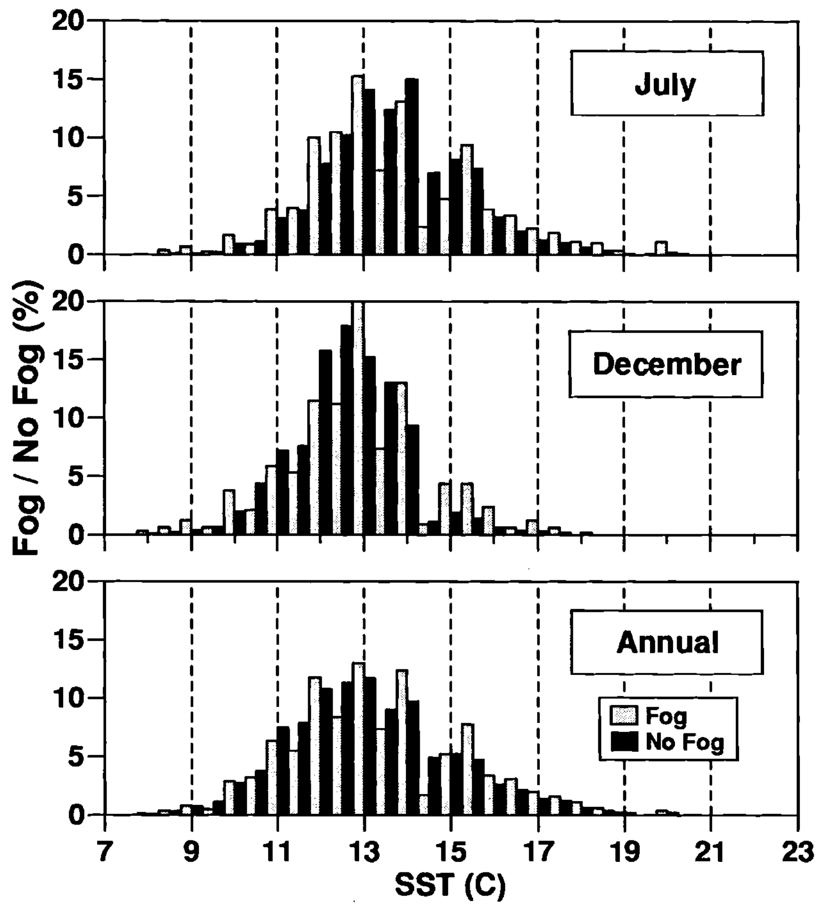


Figure 22a. Distribution of SST for Fog and No Fog in Offshore Region 6 (33-36N)(1949-1991)

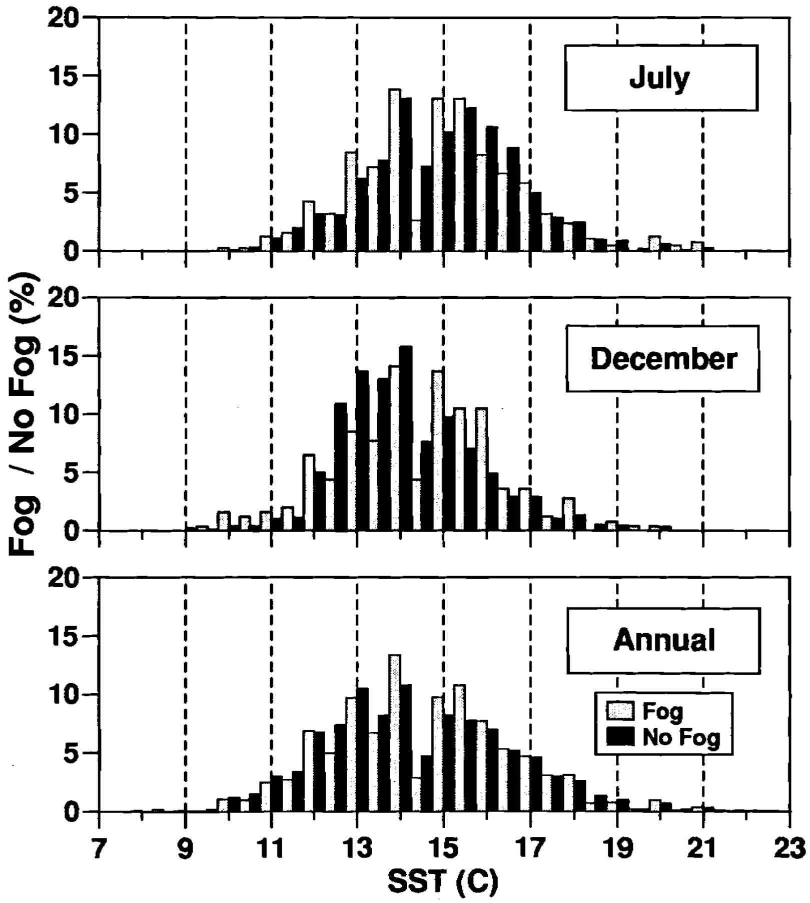


Figure 22b. Distribution of SST for Fog and No Fog in South Coast Region 5 (33-36N)(1949-1991)

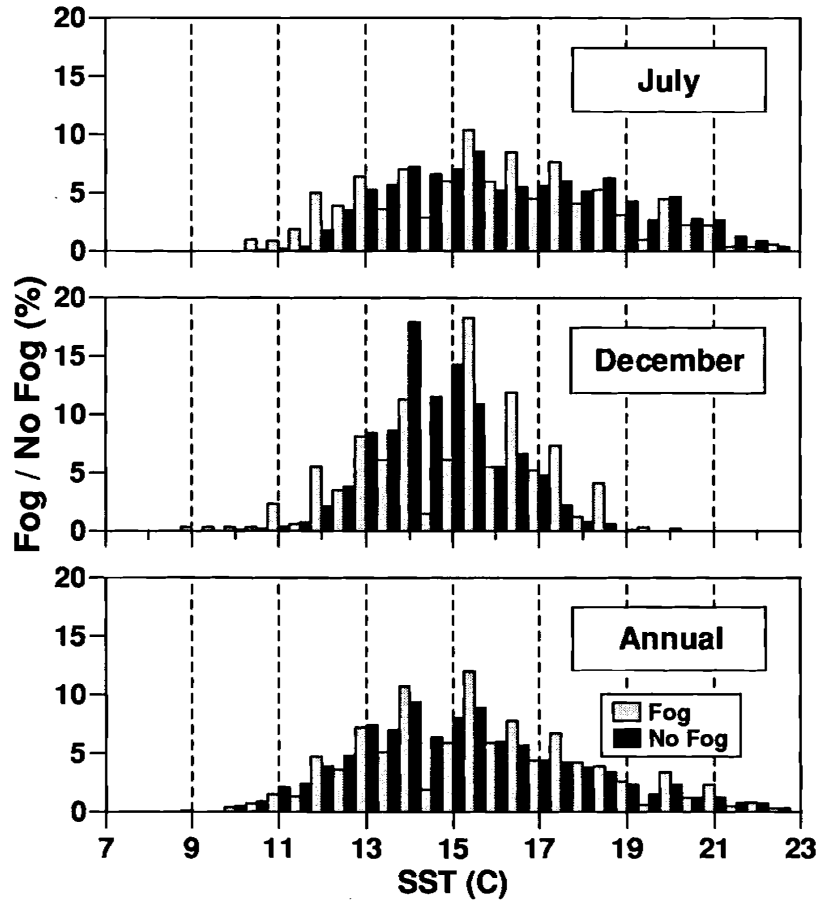


Figure 23a. Distribution of SST for Fog and No Fog in Offshore Region 8 (31-33N)(1949-1991)

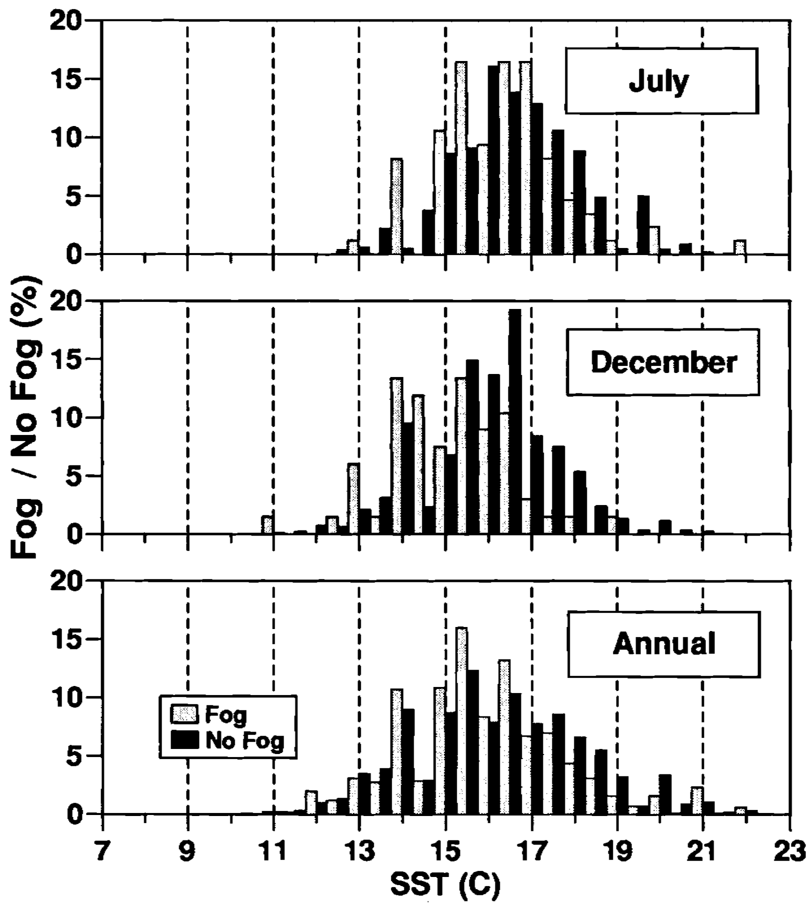
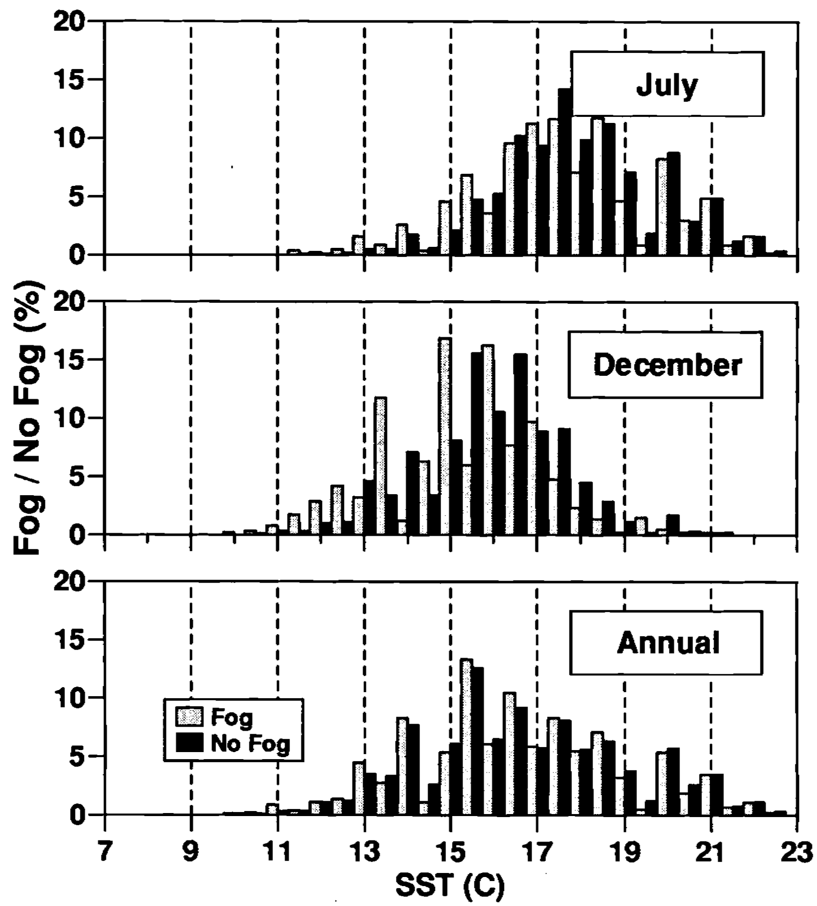


Figure 23b. Distribution of SST for Fog and No Fog in South Coast Region 7 (31-33N)(1949-1991)



In Northern California (Region 1, Figure 20a), summer months display a fairly strong tendency for increased fog with cooler SSTs, a weak tendency toward fog with warm SSTs and a significant decrease in fog in the mid-range (13.5-15 °C). The other seasons display no significant patterns for varying 0.5 °C increments in SST. Interestingly, the neighboring Northern California Region 2 (Figure 2b) shows a tendency for increased likelihood of fog with warmer SSTs during both winter and summer months. Farther south, an interesting feature is the strong occurrence of December fogs in the Southern California Bight (Region 5, Figure 22b) at around 15.5 °C, while further south (Region 7, Figure 23b) the temperature for fog formation in December is nearly 1° cooler. This may be a product of Region 7, which is offshore, having more observations occurring in the California Current. A large portion of Region 5 (Southern California Bight) is shielded from the cold current. Note also that the Region 5 spread of temperatures for high and low fog occurrence is greater during July than in December. This is evidence of the influence of the mix of upwelling and seasonal warm water in summer. In offshore Southern California (Region 8, Figure 23a), both July and December show a marked increase in fog vs no fog at cooler (13-15 °C) SSTs and a corresponding decrease of fog vs no fog observations at warmer (16-20 °C) SSTs.

6.2. *Sea Surface-Air Surface Temperature Difference (ΔT)*

The air temperature near the ocean surface (the air-ocean interface) is regulated by the temperature of the ocean; strong inversions are, therefore, primarily a result of heating of the air by atmospheric processes rather than a cooling by the ocean surface (Leipper, 1994). It is likely that a measure of sea surface temperature relative to the overlying air temperature may have a stronger association to fog formation than does the sea surface temperature alone. Thus, we might expect fog formation to be favored during situations when the air temperature is warmer than the SST. To test this hypothesis, as in the previous investigation of SST, the distributions of SST-air temperature differences (ΔT) are compiled separately for the two subsets of observations: "fog" and "no fog." These distributions, shown in Figures 24 through 27, are cast in terms the fraction of fog occurrence for 0.5 °C increments of SST minus air temperature (ΔT). Three time periods are portrayed: January, July, and all months together. For most of the regions and most time periods, the fog distribution has a higher incidence of cases with negative ΔTs (SST cooler than air temperature) than does the "no fog" distribution (Figures 24a, 24b, and 25b). In Southern California (Region 7), the fog distribution has shifted during winter months toward more positive ΔTs (SST warmer than air temperature), but there are no significant differences (Figure 27b) when all months are taken together.

Thus, in most cases, cool SSTs relative to the air temperature appear to be conducive to fog. In Southern California, there are some cases where fog is associated with negative ΔT, but in this region most fog occurs with SSTs warmer than the air temperature, so other mechanisms must be present. It is possible that in these cases, the cool air temperature is an effect of the fog (presumably reducing the solar radiation reaching the surface) rather than a forcing mechanism that produces fog.

It is interesting to note the differences in the ΔT distribution between Southern California and the rest of coastal California. In Northern and Central California, the mode of ΔT is negative in summer (air warmer than SST) and positive in winter (air cooler than SST). The California Current is just offshore in Northern and Central California. In Southern California, where the current is well offshore, the mode of ΔT is positive in all seasons.

6.3. *Wind Directions and Speeds*

We examined the influence of wind speed and direction on the presence or absence of fog. Similar to the SST and ΔT analyses, two groups of observations (those with fog and those with no fog), were partitioned into

Figure 24a. Distribution of ΔT for Fog and No Fog in North Coast Region 1 (40-42N)(1949-1991)

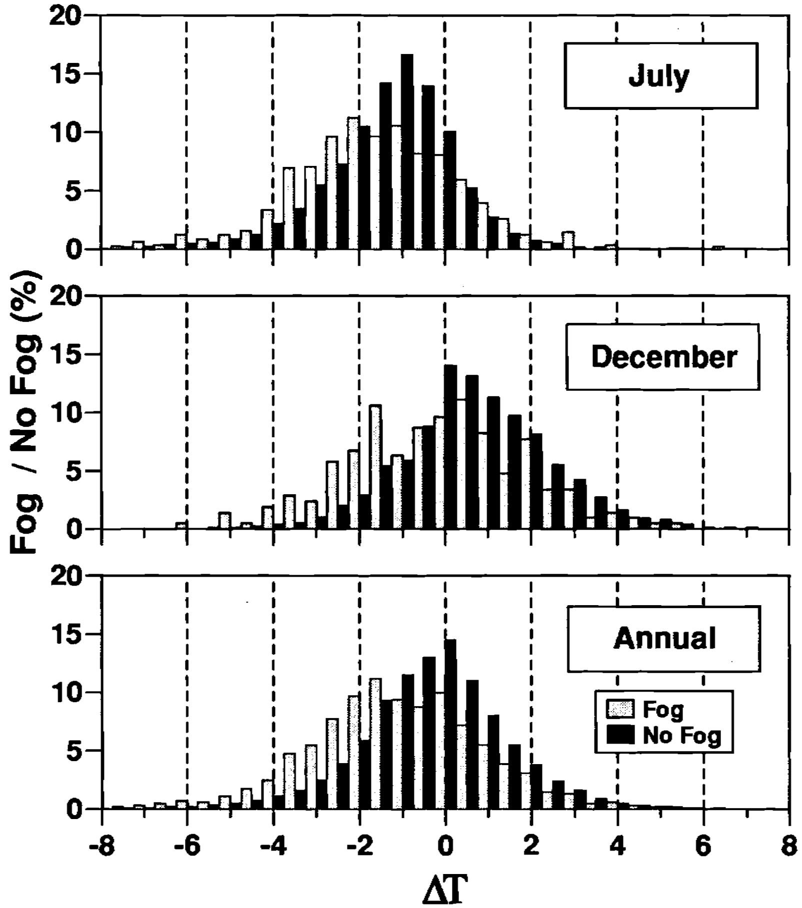


Figure 24b. Distribution of ΔT for Fog and No Fog in North Coast Region 2 (38-40N)(1949-1991)

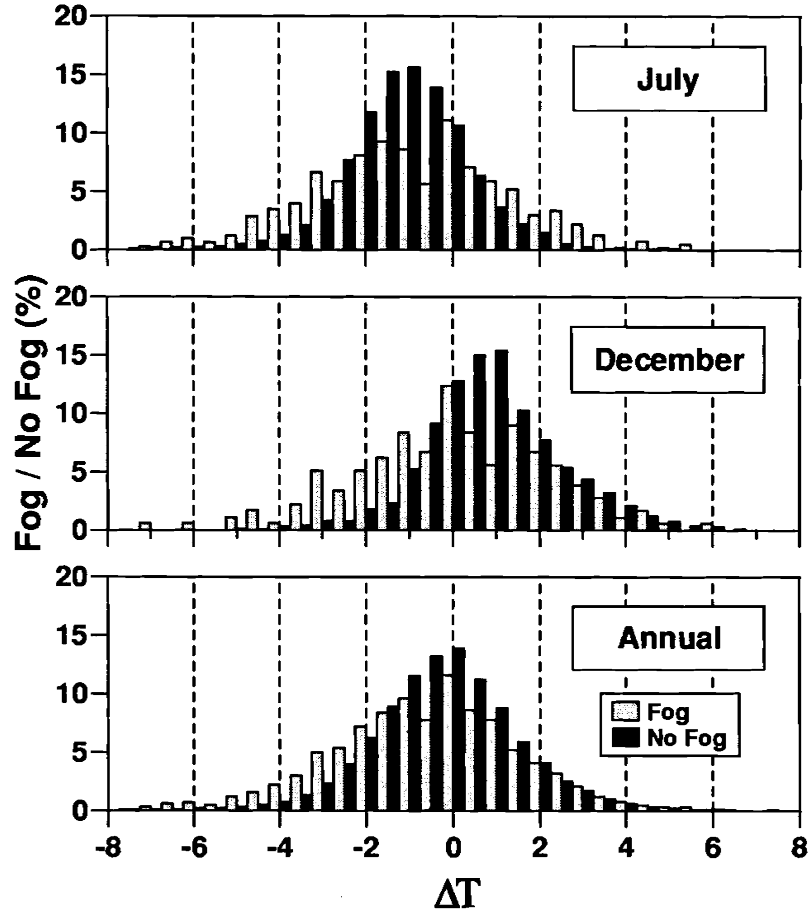


Figure 25a. Distribution of ΔT for Fog and No Fog in Offshore Region 4 (36-40N)(1949-1991)

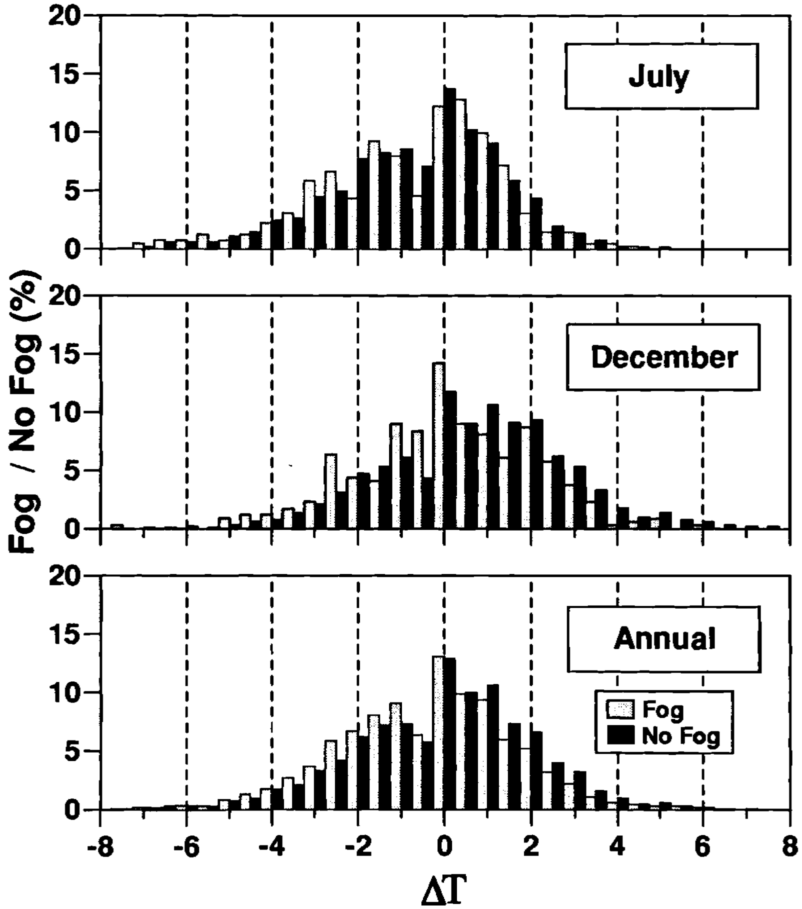


Figure 25b. Distribution of ΔT for Fog and No Fog in Central Coast Region 3 (36-38N)(1949-1991)

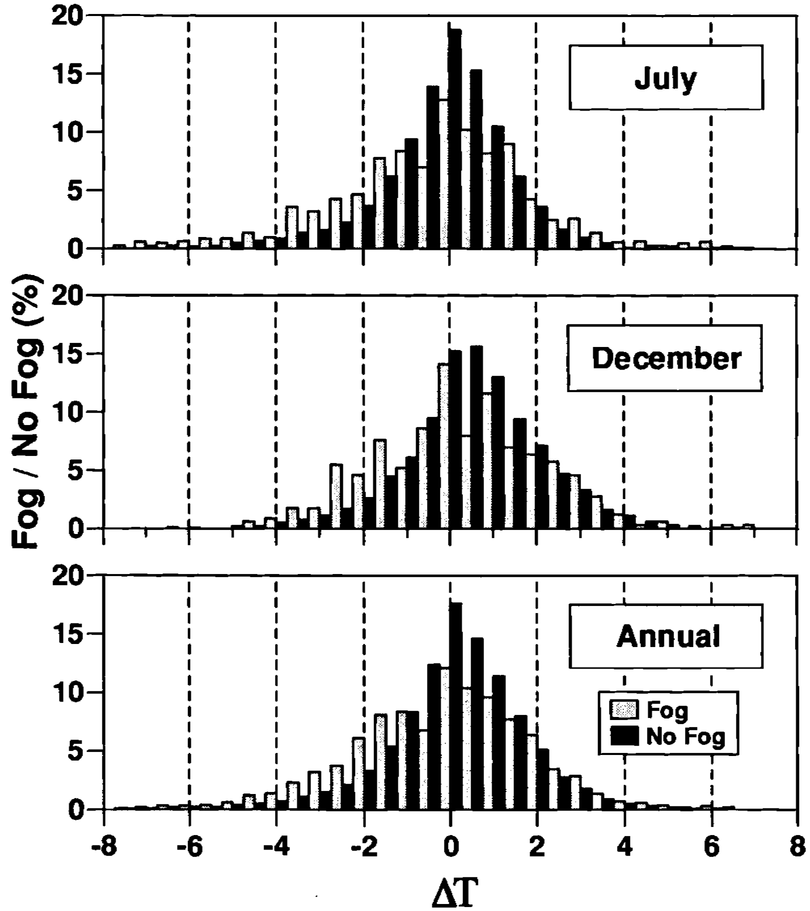


Figure 26a. Distribution of ΔT for Fog and No Fog in Offshore Region 6 (33-36N)(1949-1991)

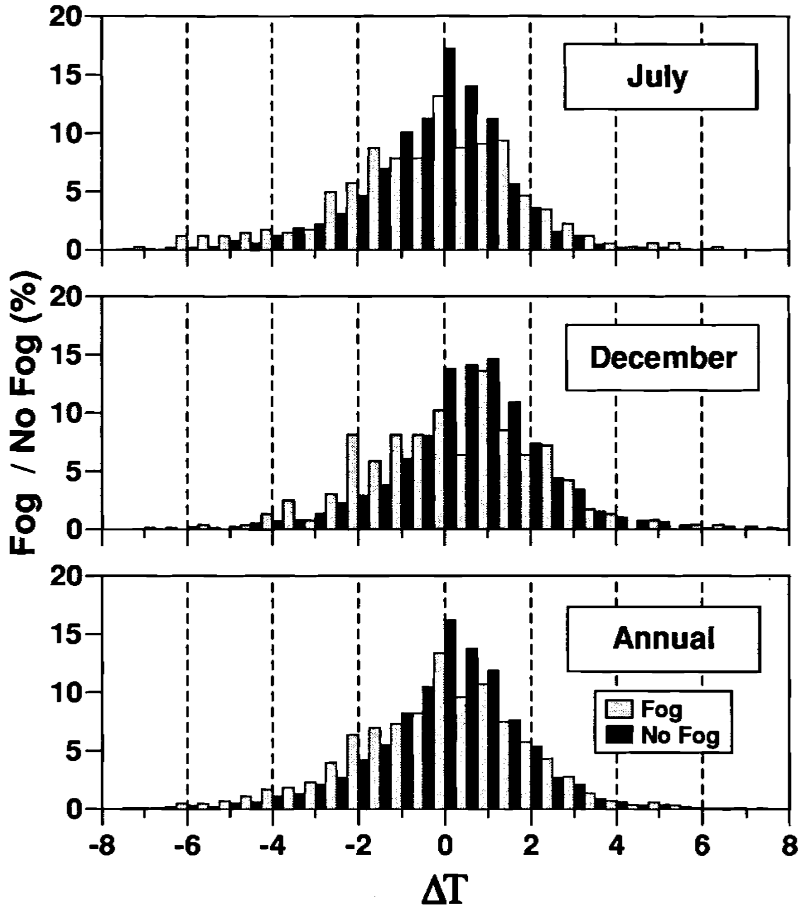


Figure 26b. Distribution of ΔT for Fog and No Fog in South Coast Region 5 (33-36N)(1949-1991)

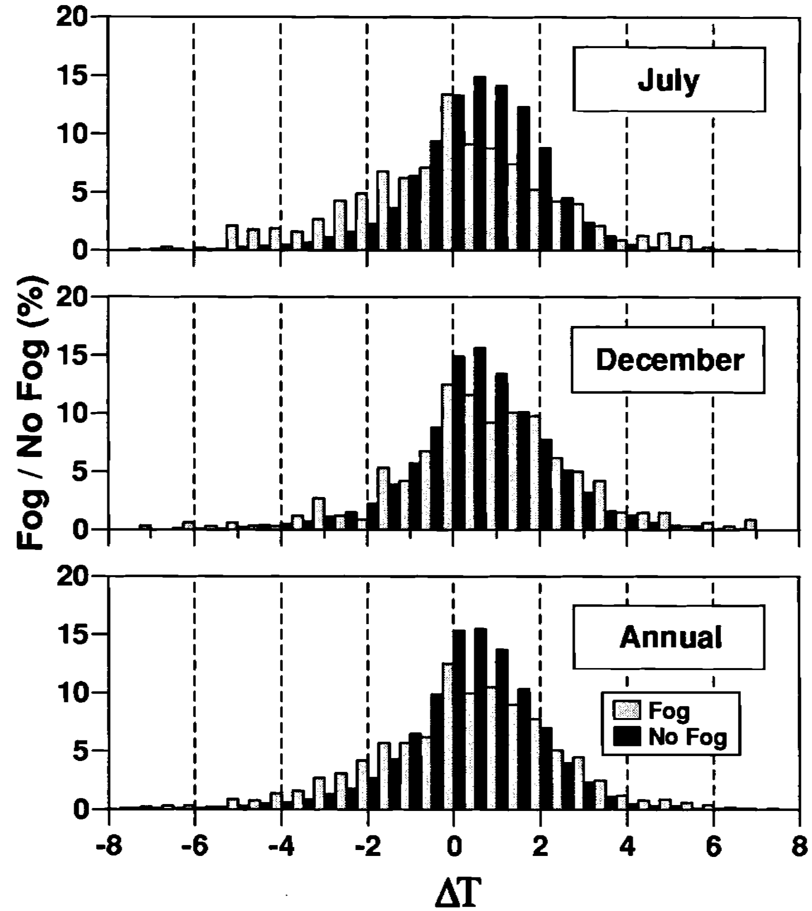


Figure 27a. Distribution of ΔT for Fog and No Fog in Offshore Region 8 (31-33N)(1949-1991)

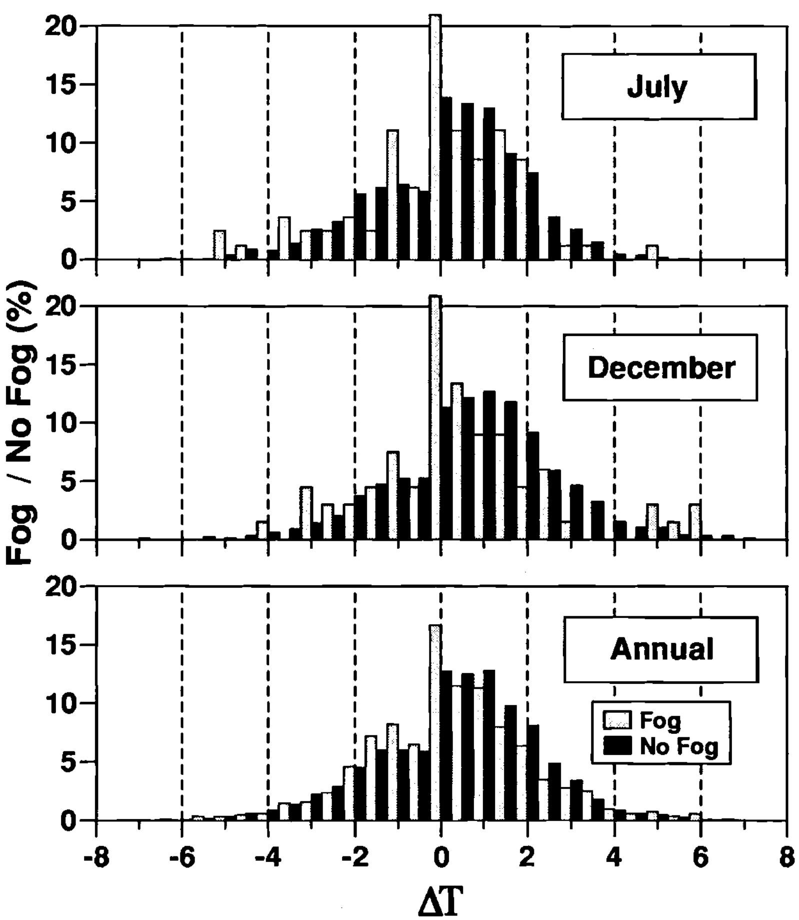


Figure 27b. Distribution of ΔT for Fog and No Fog in South Coast Region 7 (31-33N)(1949-1991)

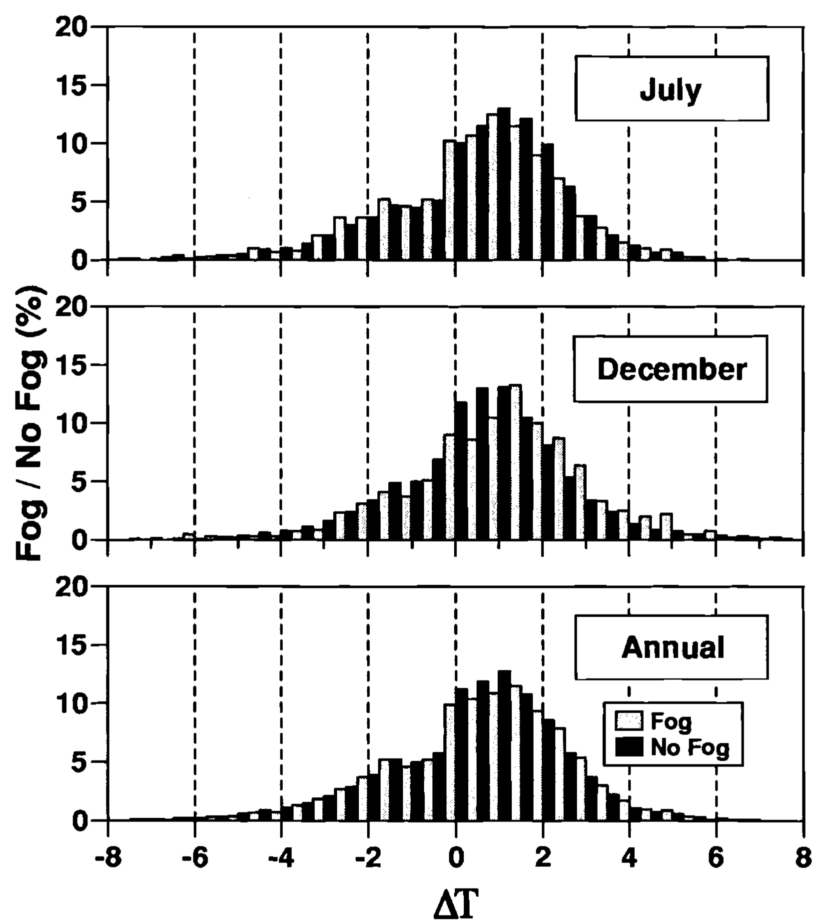


Figure 28. Distribution of Wind Speed for Fog and No Fog North Coast Region 1 (40-42N)(1949-1991)

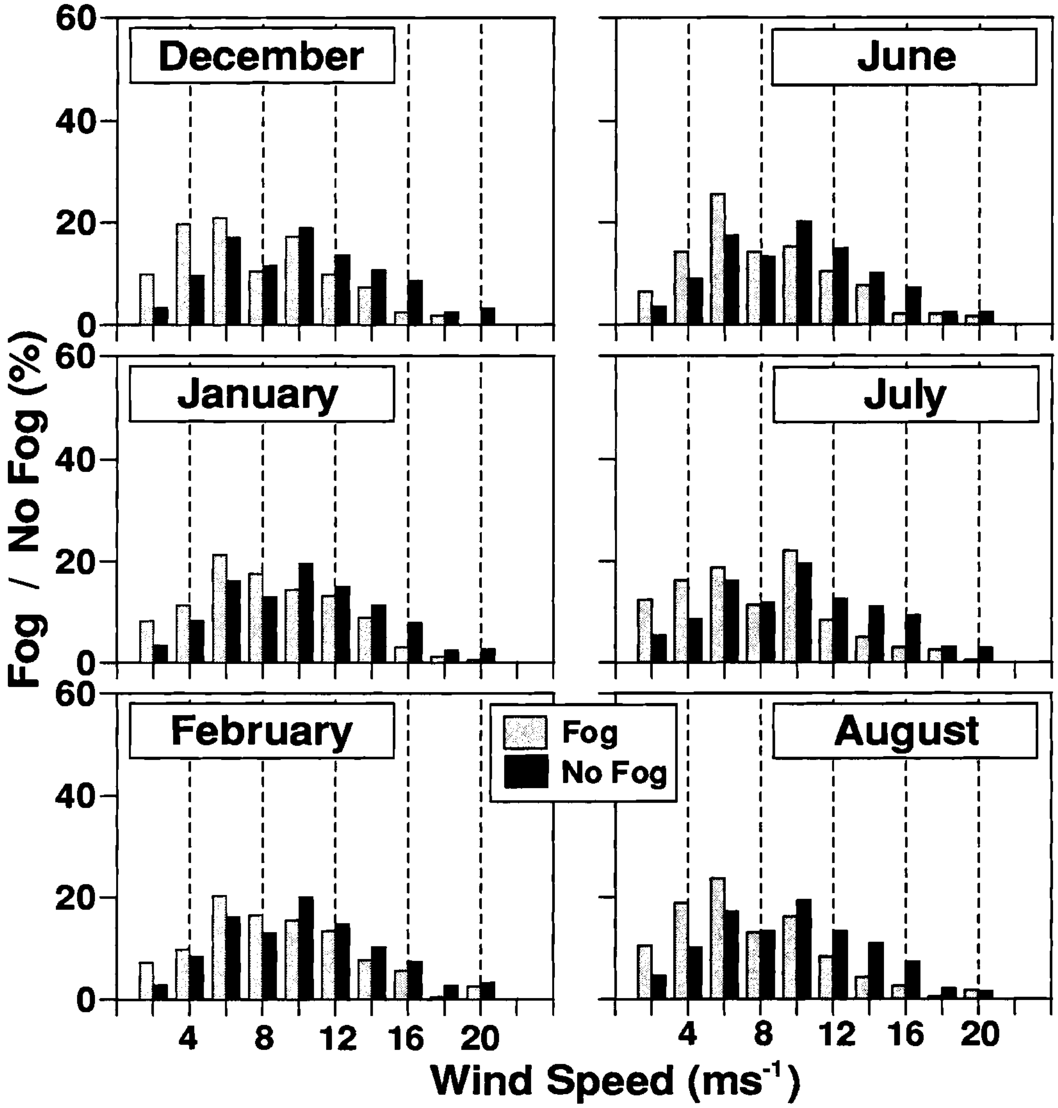


Figure 29. Distribution of Wind Speed for Fog and No Fog North Coast Region 2 (38-40N)(1949-1991)

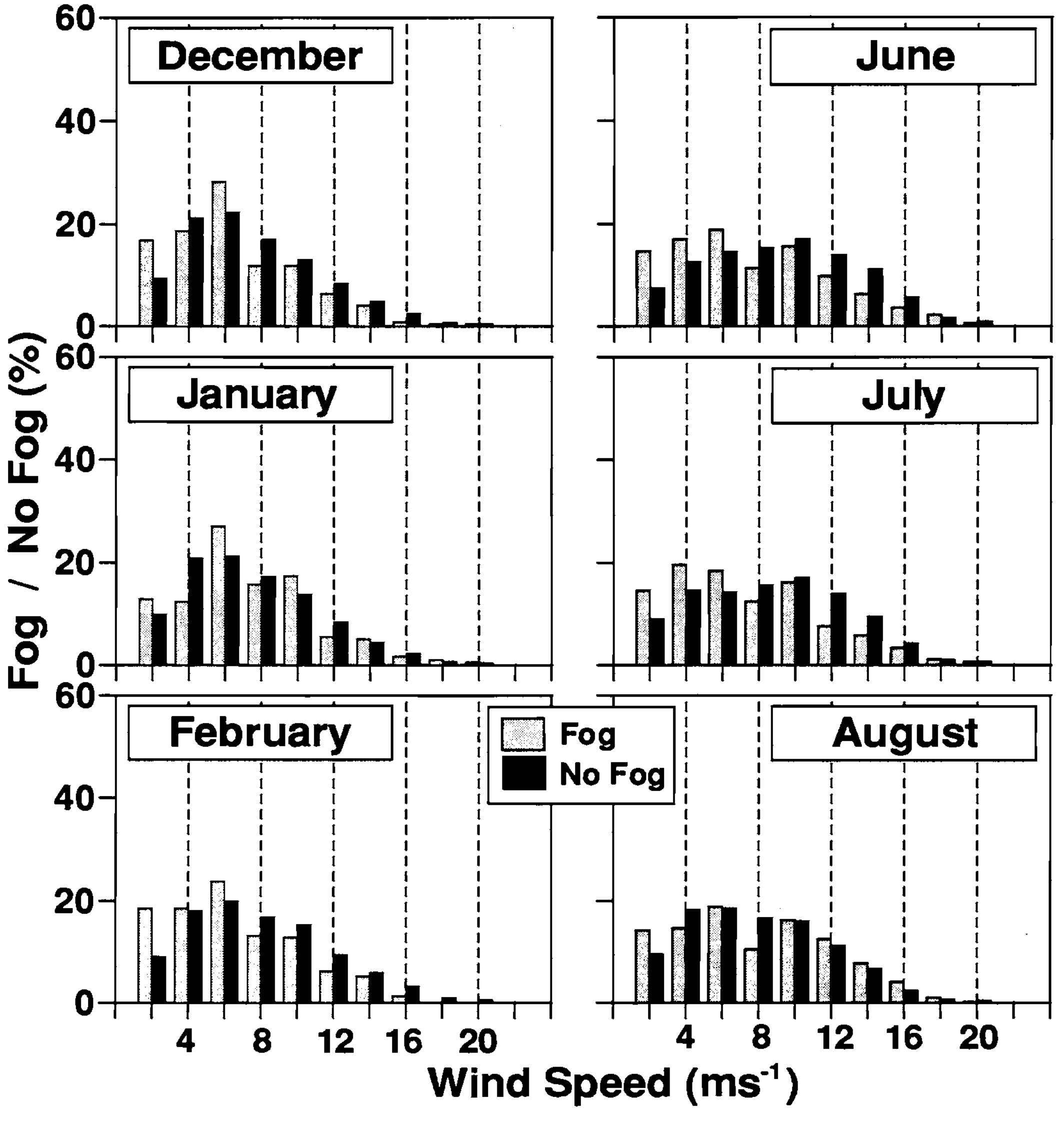


Figure 30. Distribution of Wind Speed for Fog and No Fog South Coast Region 5 (33-36N)(1949-1991)

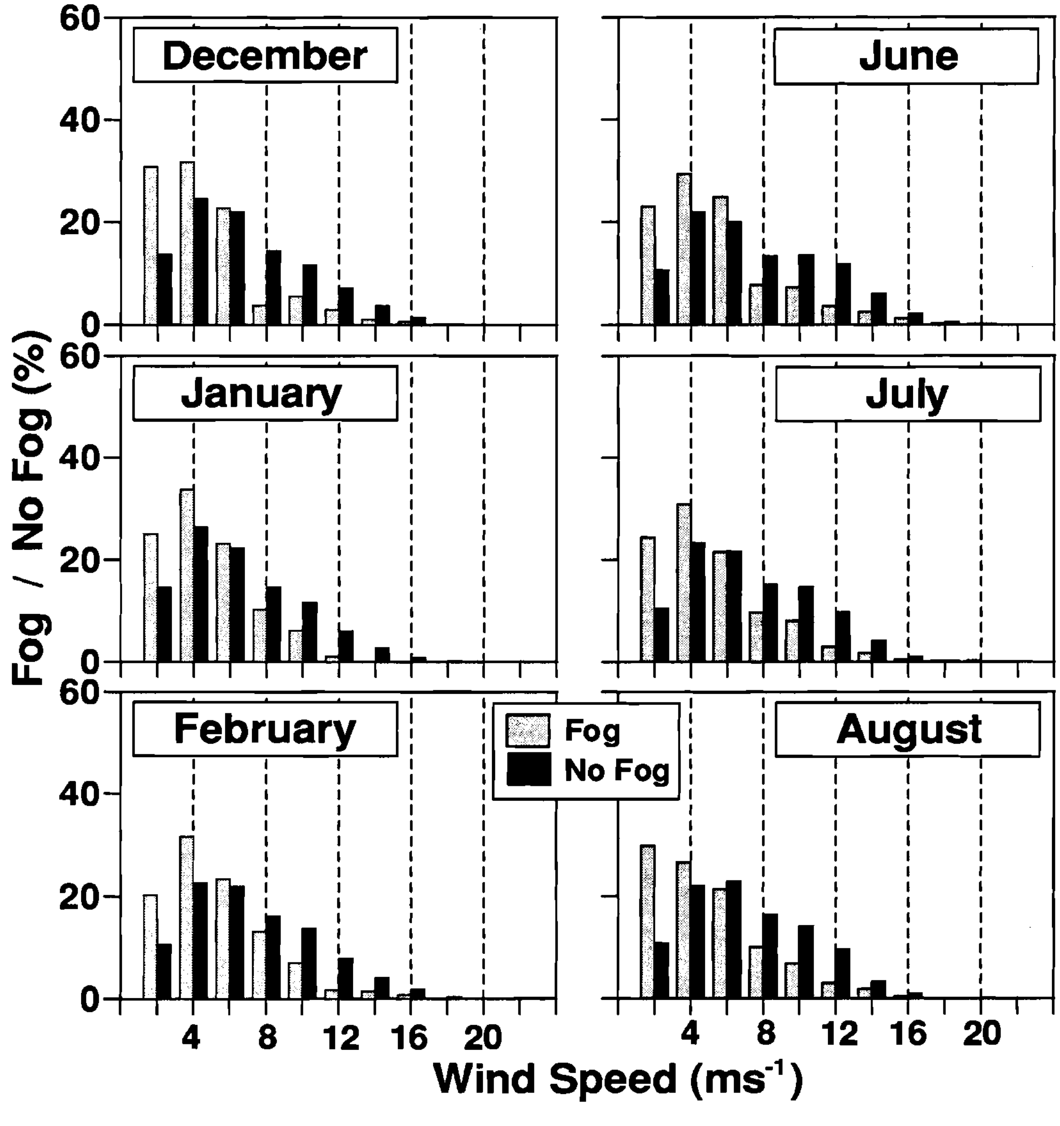
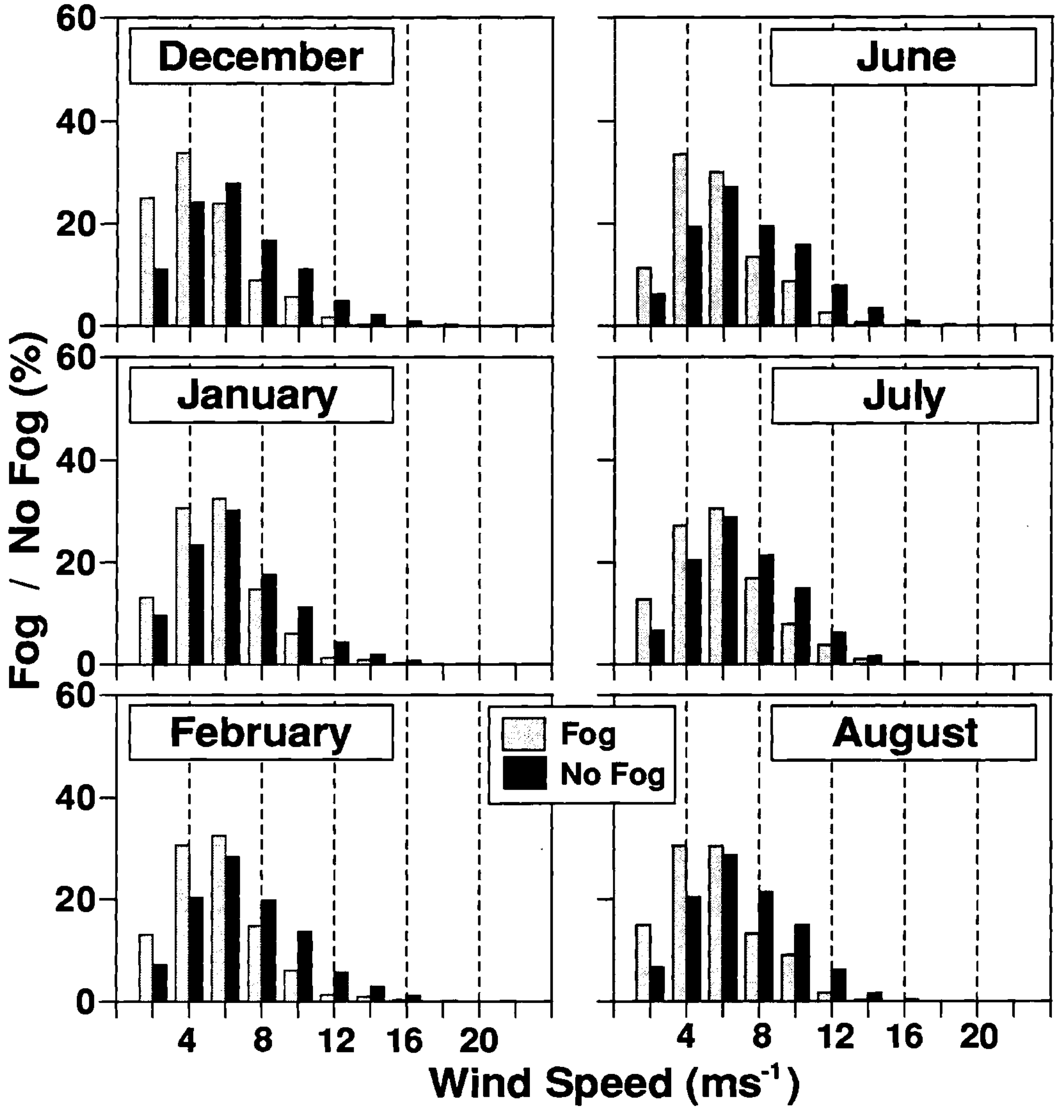


Figure 31. Distribution of Wind Speed for Fog and No Fog South Coast Region 7 (31-33N)(1949-1991)



2 ms^{-1} (7.2 *kph*) wind speed classes. The results were compared (Figures 28 through 31) for each month for the marine study regions.

Fog occurs in all wind speed classes, but most fog events occur at wind speeds below 4-6 ms^{-1} . For the winter months, wind speeds in northern Regions 1 and 2 (Figures 28 and 29) are more evenly spread and fog still occurs at speeds near 15 ms^{-1}. From the Southern California Bight (Region 5) southward to Region 7 (Figure 30 and 31), wind speeds during the occurrence of fog events are nearly all below 10 ms^{-1} with the highest percentage (approximately 30%) occurring between 2 and 4 ms^{-1}. In contrast, for "no fog cases," the fraction of observations with wind speeds greater than 6 *mk/s* is approximately twice that of the fog cases.

During summer (June-August), a pattern similar to that of the winter months is found in Northern California Regions 1 and 2 (Figures 28 and 29). However, the summer months indicate a tendency for increased fog during lower wind speed occurrence, with 28-30% of the summer fog cases having wind speeds between 4 and 6 ms^{-1} All regions show a few cases of fog with markedly high winds; for example there are fog occurrences with speeds of 14 ms^{-1} (50.4 *kph*) in the Bight (Region 5, Figure 30). The tendency for fog to occur under low winds in the Southern California Bight region may be the result of a mixing of particles that are trapped below the inversion base. This suggests that instead of an advection fog mechanism, fog forms due to the local marine environment (atmosphere and ocean). Alternatively, the diminished winds may also permit fog to persist once it is formed.

The fog records were also examined with respect to their association with wind direction without regard to the velocity. Wind directions were divided into octants (45 *degree* intervals), beginning with north (from -22.5 to 22.5), northeast (22.5 to 67.5), etc. Note that wind direction is defined as the direction *from* which the wind blows. Again, two populations were considered—observations for which fog was recorded and those for which no fog was recorded.

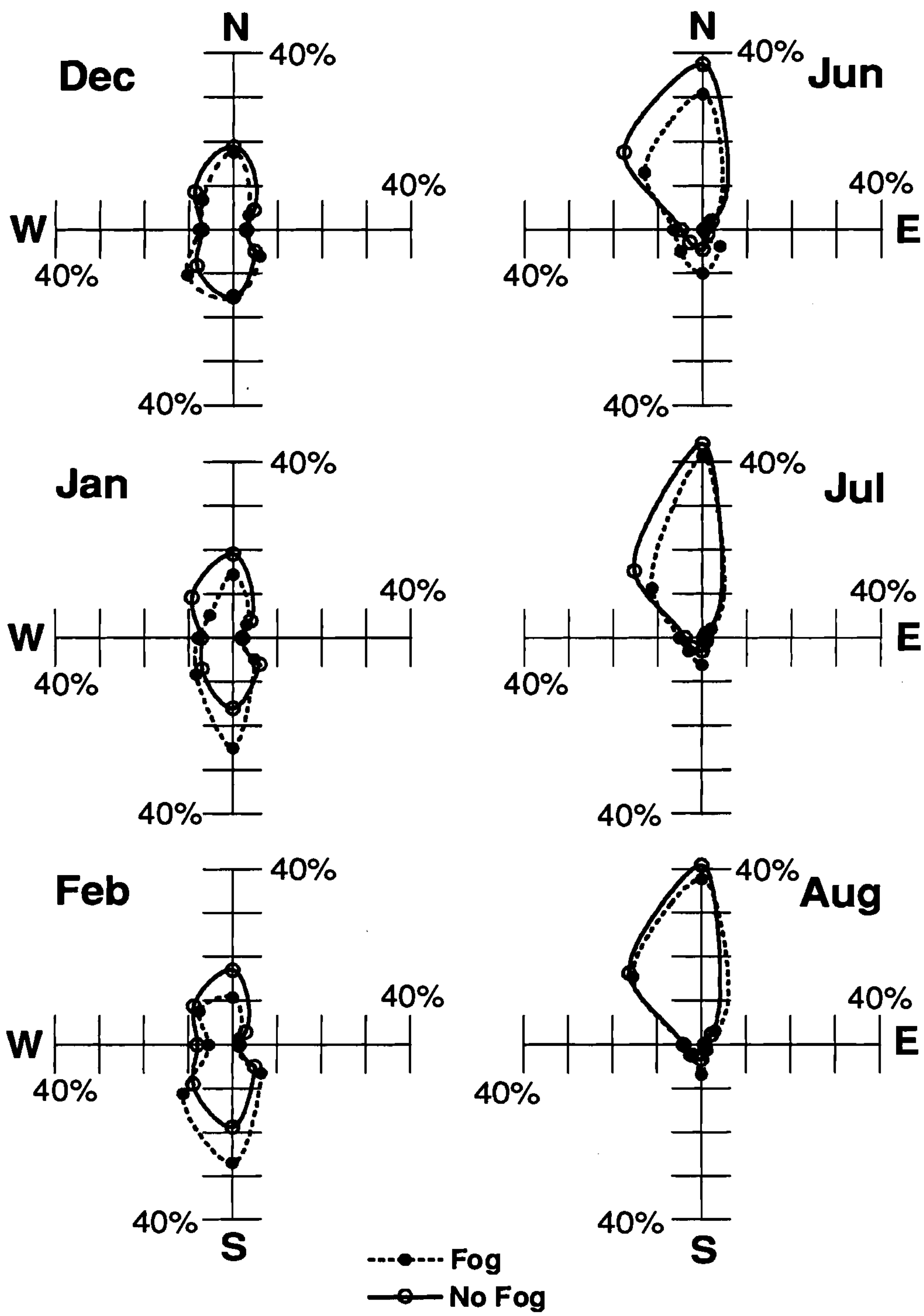
Figures 32 through 35 show the frequency of fog *vs.* no fog for eight wind directions, north through northwest. One of the first points illustrated by the charts is the prevalence, in all regions, of wind from a limited number of directions (the presence of "prevailing winds"),. This constraint to the directionality of the winds must be taken into consideration when evaluating the results.

Northern California (Region 1, Figure 32) has winds coming primarily from the north and south with a distinct decline in the number of occurrences as the wind direction approaches either east or west. Neither northerly or southerly winds appear to be particularly favored during the winter months (DJF), but northerly winds appear to predominate during the summer (JJA). This is consistent with the forces controlling wind during these periods.

The winter wet season is a time of rapidly changing atmospheric circulation as mid-latitude cyclones, with associated troughing (cyclonic wind) and ridging (anticyclonic wind), pass through the area. Summer, on the other hand, is controlled primarily by the semipermanent subtropical high pressure system (with persistent anticyclonic wind) found south and west of the California coast. The effects of large-scale circulation is discussed in *Section 7*. Here, however, we are only concerned with the effects of local circulation.

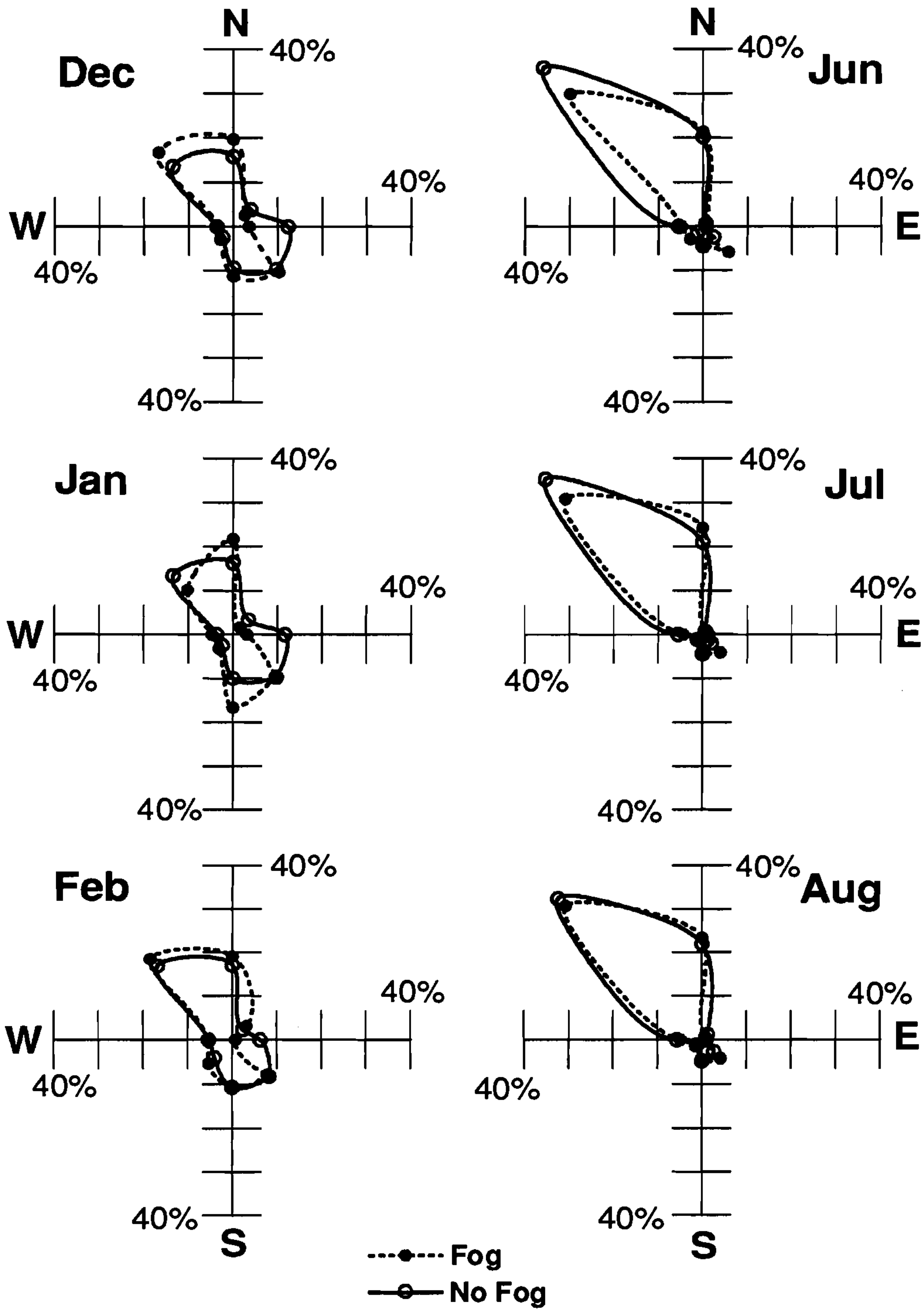
The prevailing winds in the other four regions (Figures 33 through 35) are consistent with those of Region 1, with certain exceptions. Summer winds in each of these regions display the dominance of the semipermanent high pressure system. The winter winds, however, show an increasing dominance by northerly wind as latitude decreases. This is probably a result of the decreasing frequency of mid-latitude

Figure 32. Percent Obs by Wind Direction for Fog and No Fog North Coast Region 1 (40-42N)(1949-1991)



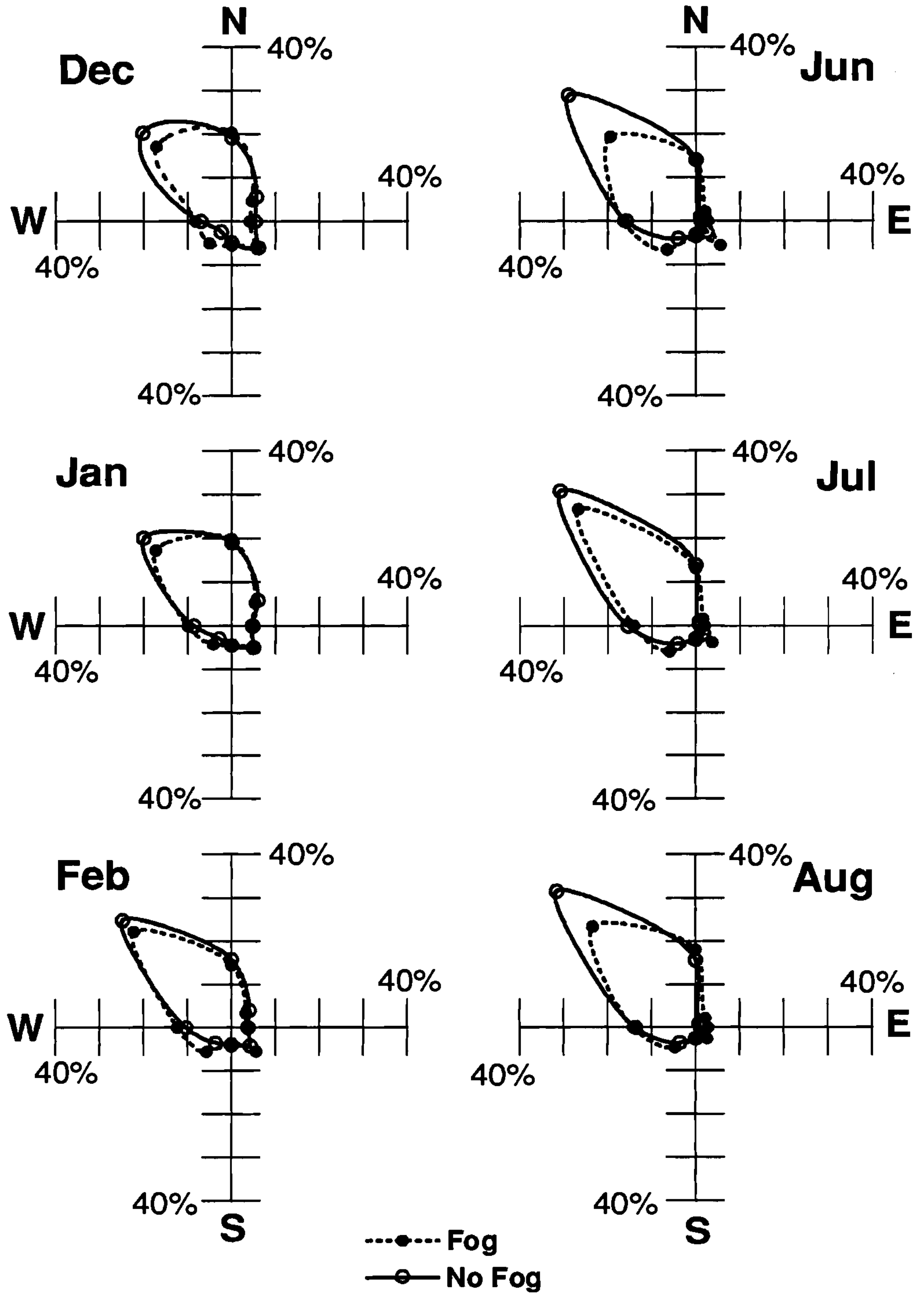
Wind direction on graphs is the direction FROM which the wind blows.

Figure 33. Percent Obs by Wind Direction for Fog and No Fog for North Coast Region 2 (38-40N)(1949-91)



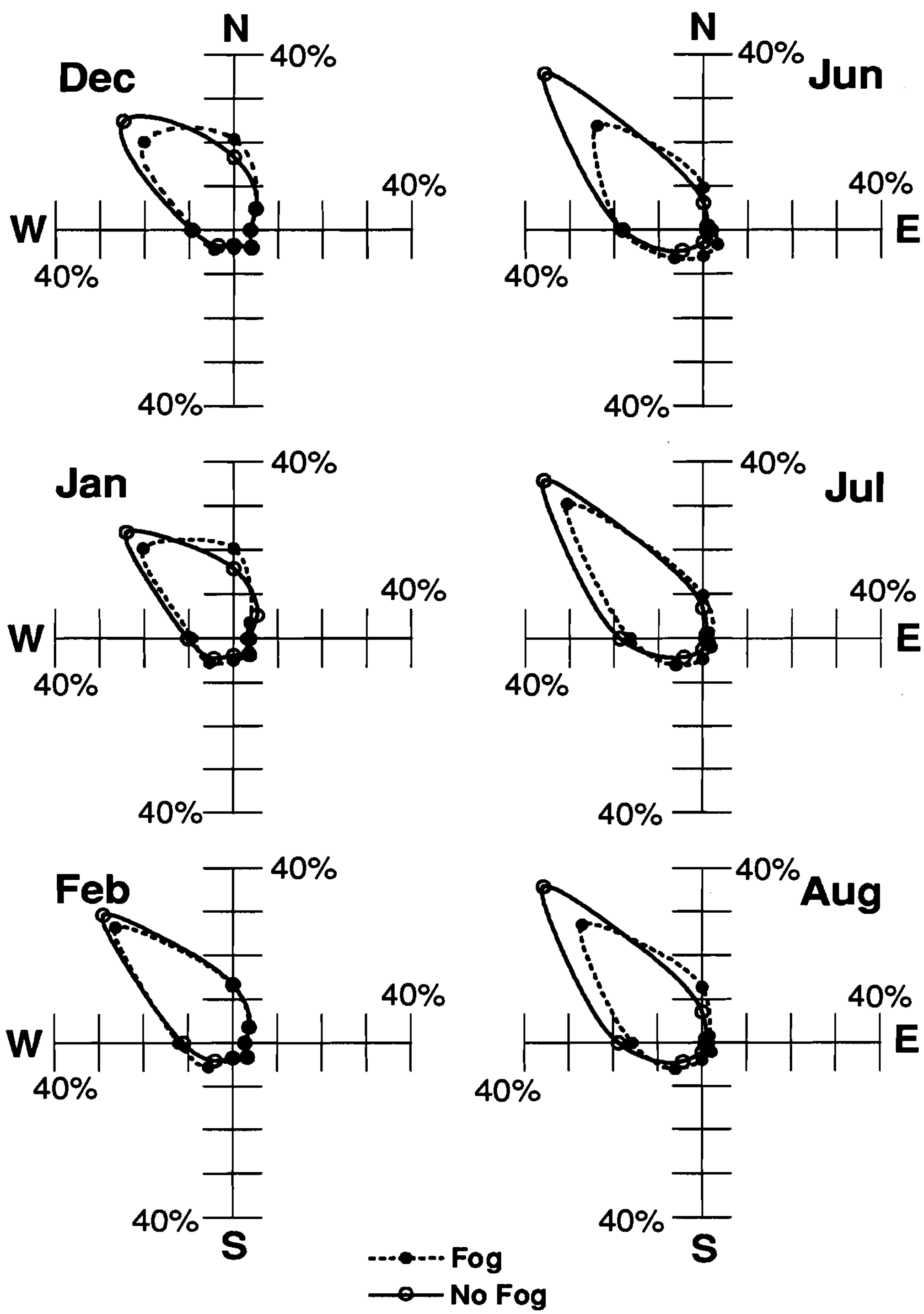
Wind direction on graphs is the
direction FROM which the wind blows.

Figure 34. Percent Obs by Wind Direction for Fog and No Fog South Coast Region 5 (33-36N)(1949-91)



Wind direction on graphs is the direction FROM which the wind blows.

Figure 35. Percent Obs by Wind Direction for Fog and No Fog South Coast Region 7 (31-33N)(1949-91



Wind direction on graphs is the direction FROM which the wind blows.

Figure 36a. Winter Wind Direction for ΔT Fog and No Fog North Coast Region 1 (40-42N) (1949-1991)

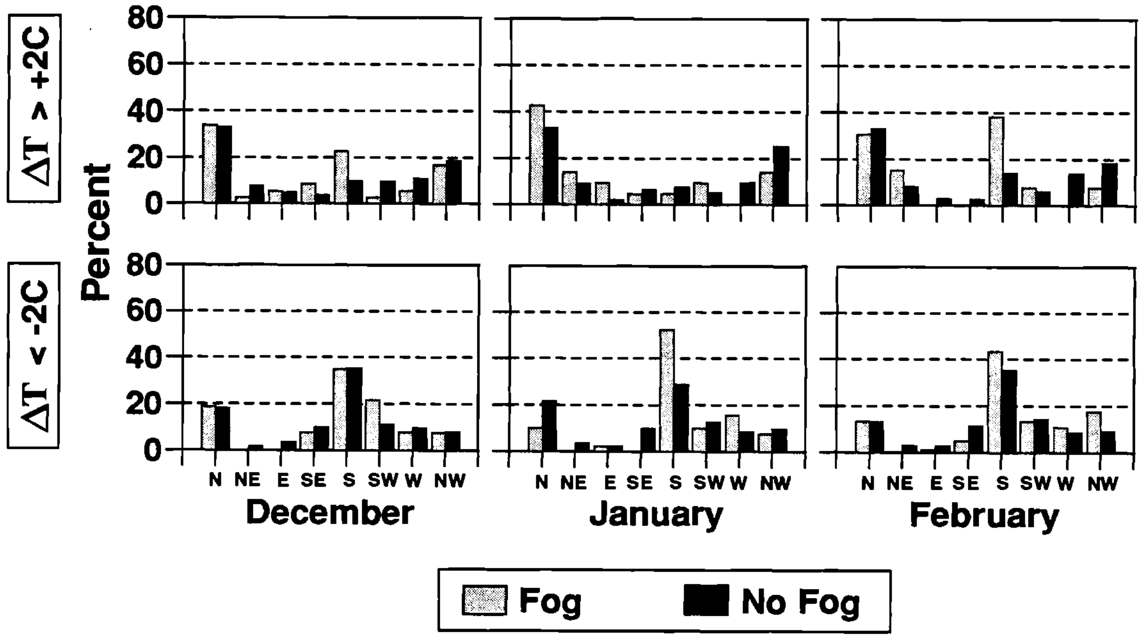


Figure 36b. Summer Wind Direction for ΔT Fog and No Fog North Coast Region 1 (40-42N) (1949-1991)

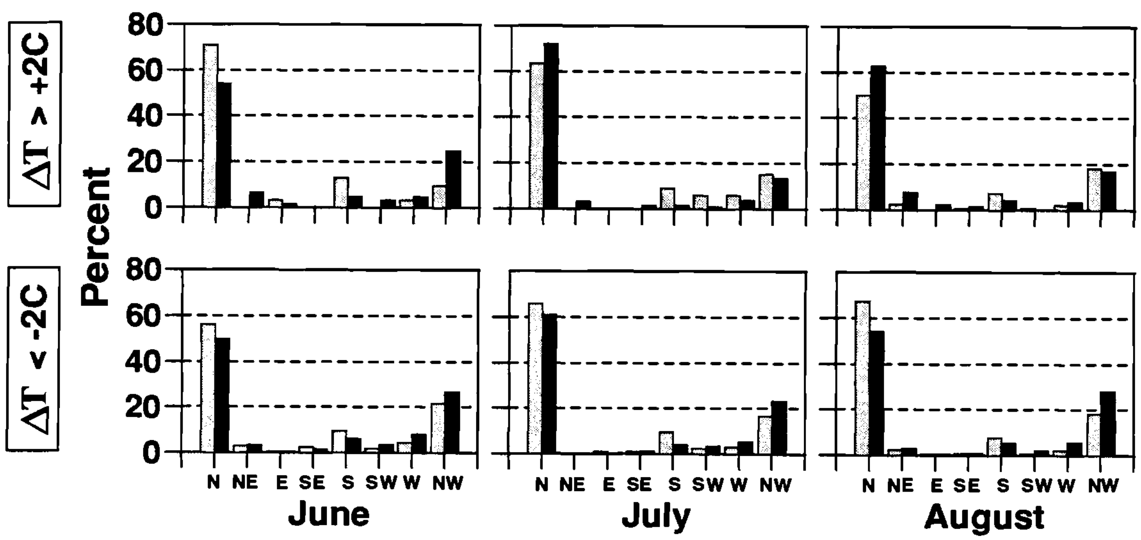


Figure 37a. Winter Wind Direction for ΔT Fog and No Fog Sourth Coast Region 5 (33-36N) (1949-1991)

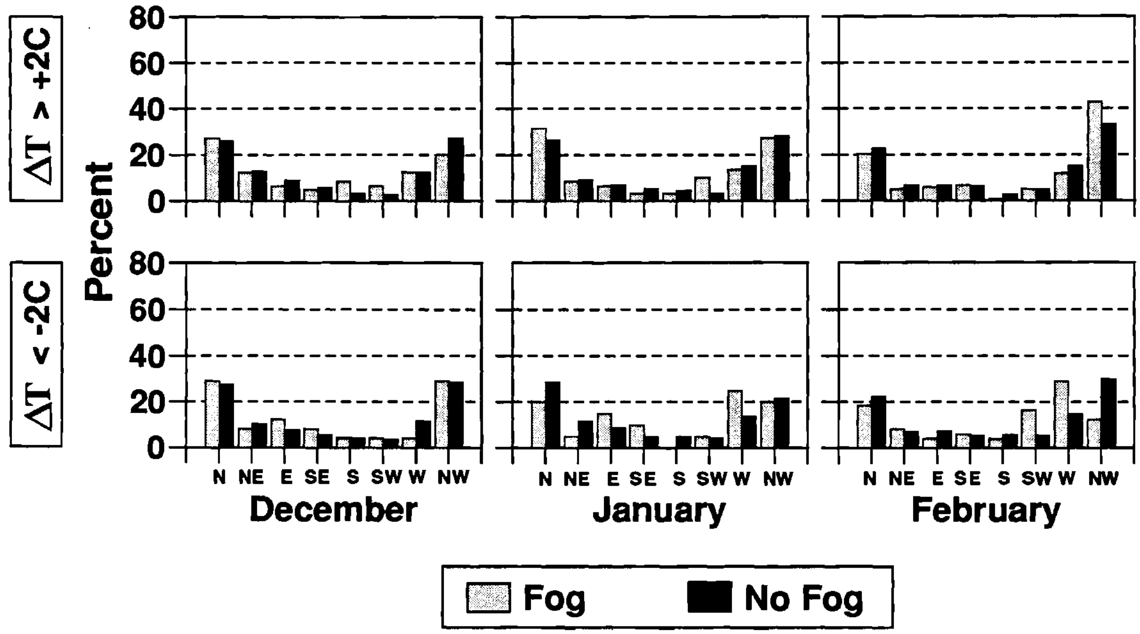


Figure 37b. Summer Wind Direction for ΔT Fog and No Fog South Coast Region 5 (33-36N) (1949-1991)

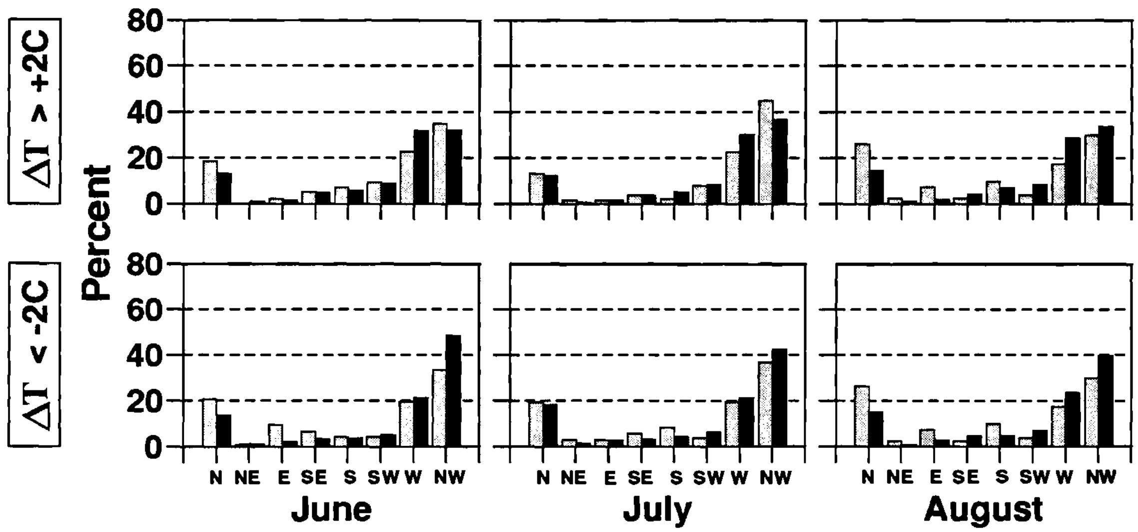


Figure 38. Wind Direction for ΔT Subsets Fog/No Fog North Coast Region 2 (38-40N) (1949-1991)

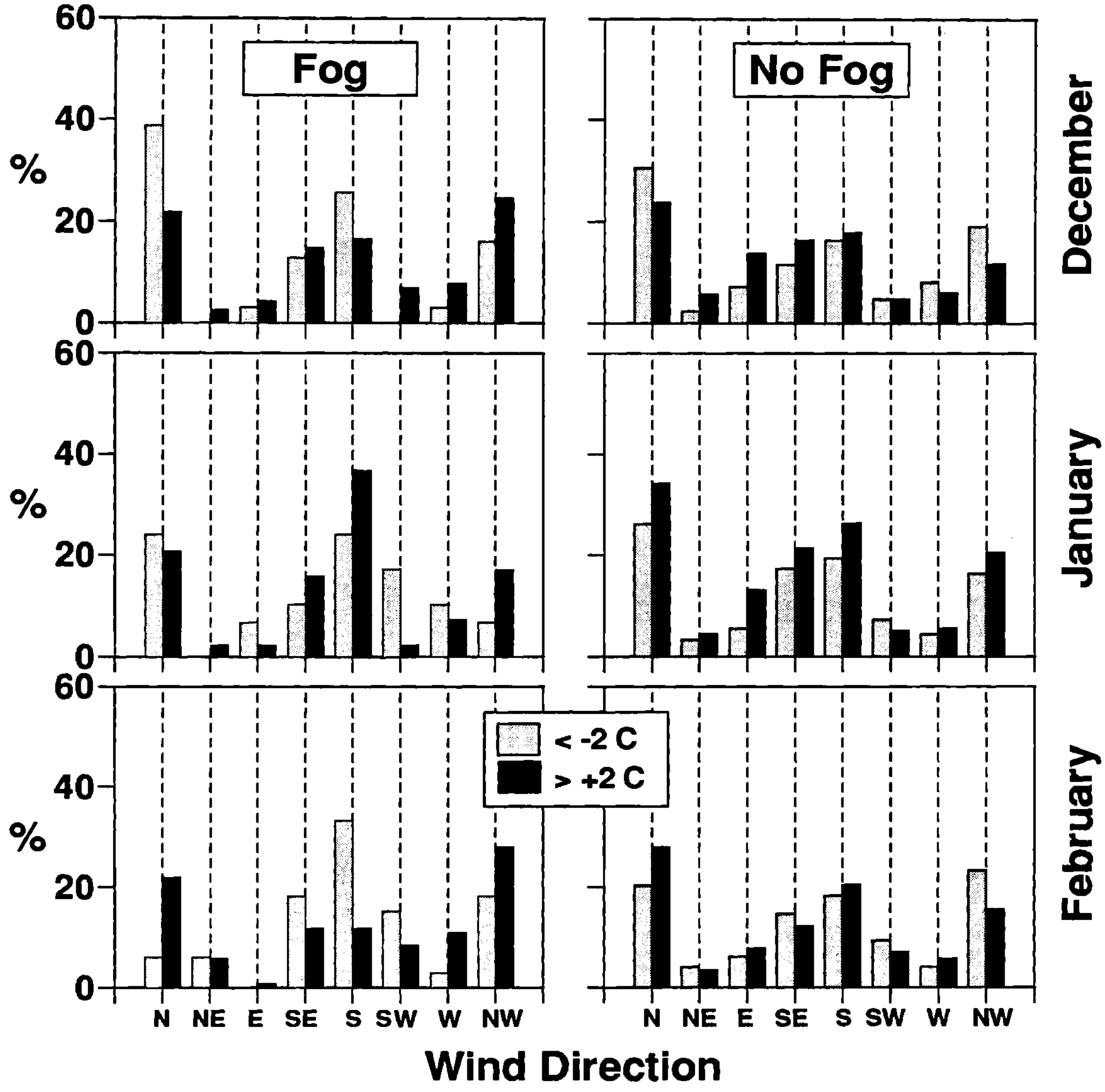
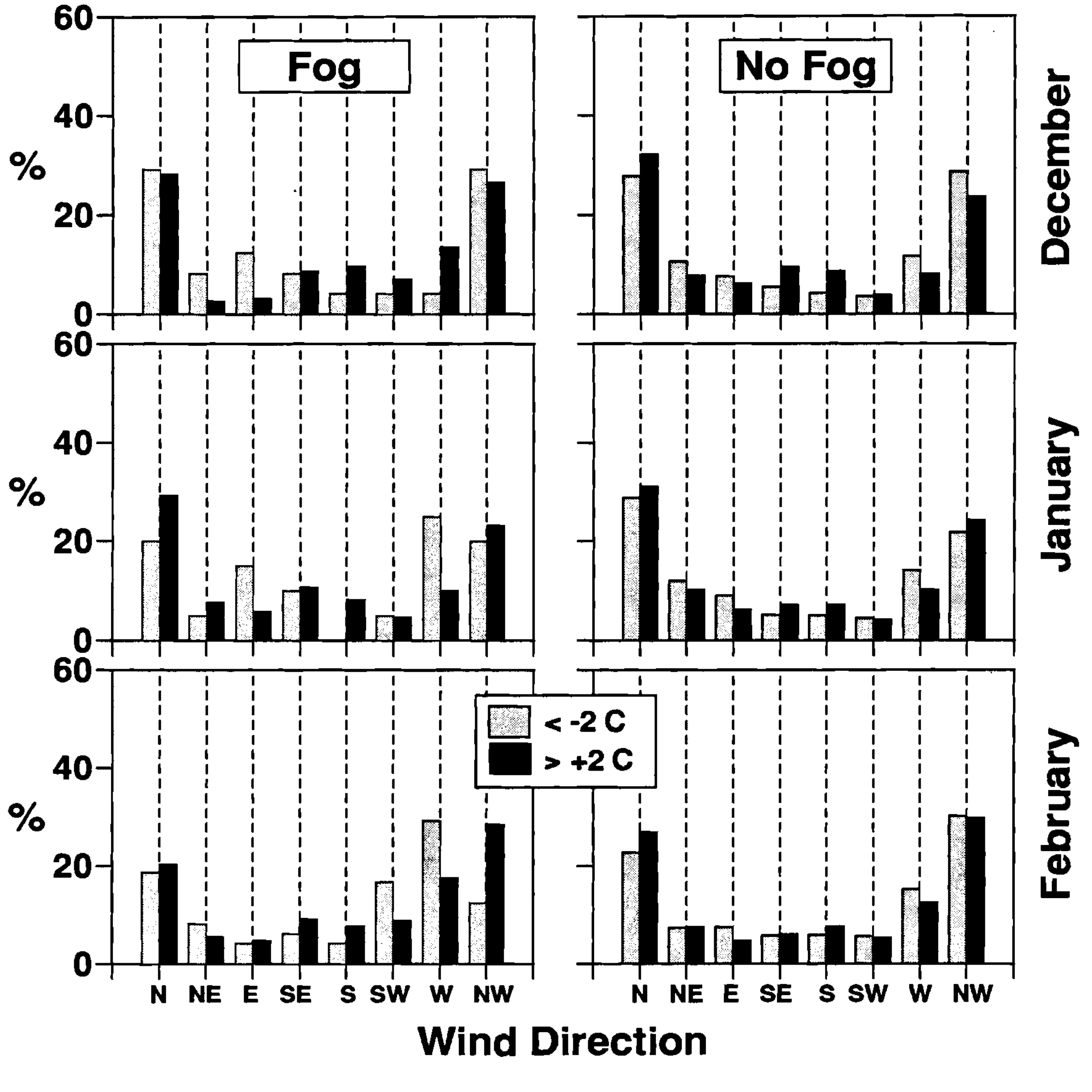


Figure 39. Wind Direction for ΔT Subsets Fog/No Fog
South Coast Region 5 (33-36N) (1949-1991)



cyclones as we approach the semipermanent high, which retreats to the south in winter, but never completely disappears. When we examine Southern California (Region 7), there is very little difference in the wind patterns between winter and summer.

The other important observation to make concerning the directionality of the wind in the study regions is the shift from north-south wind in the north (Region 1) to northwest-southeast wind in the south (Regions 5 and 7). The intervening area (Region 2) appears to be transitional between these two patterns. This change in directionality appears to be related to the coastal topography which runs north to south from the Oregon border to Cape Mendocino (~40°N, the southern boundary of Region 1), then swings around to the south-southwest from Cape Mendocino to Point Conception (~34°N and including Region 2), and finally southwesterly from Point Conception to the Mexican border (including most of Region 5 and all of Region 7).

Winter fog in the north (Region 1, Figure 32), expressed as the directional percentage of all winter observations, is favored by southerly winds. As latitude decreases (Regions 5 and 7), this pattern is weakened but never completely disappears. A similar pattern appears to exist in summer, but this happens only rarely because few southerly winds are observed during this period.

If the prevailing wind is directly from the north (as in Region 1), no northerly wind (northwest through northeast) favors the formation of fog. When the prevailing wind is from the northwest, however, there is a slight tendency for fog to outweigh no fog when the wind is directly from the north.

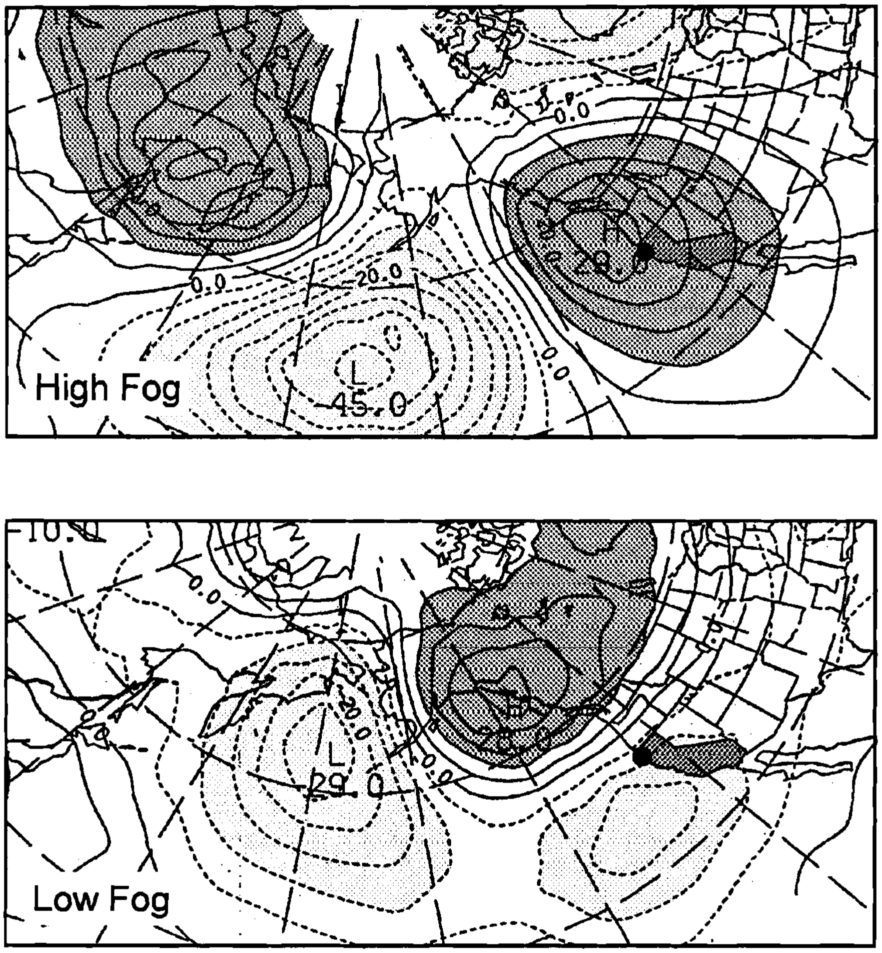
The remaining charts in this section (Figures 36-39), show a comparison between the occurrence of fog *vs.* wind direction for two classes of observations where the SST was at least 2°*C* warmer (ΔT is positive) or 2°*C* cooler (ΔT is negative) than the overlying air temperature. These differences are expressed as histograms. When the winter ΔT is positive in Region 1, the frequency of northerly winds increases and the frequency of southerly winds decreases. Northerly winds now tend to favor fog formation slightly. Westerly winds show a distinct drop in the percentage of fog occurrence. If ΔT is negative, southerly winds predominate, but the relative occurrence of fog doesn't change significantly. In summer, a negative ΔT is associated with a slight increase in fog occurrence, but otherwise shows little significant changes.

Positive ΔT in Region 5 winters has a slight increase in fog for northwesterly winds in February, but otherwise shows little significant change. Negative ΔT, however, shows a significant increase in fog for westerly winds. The only significant change during summer is an increase in the number of westerly wind observations (at the expense of the northerly and northwesterly observations) with "no fog" observations more common. An examination of winter positive *vs.* negative ΔT fog observations for four study regions (Figures 38 through 39) shows no coherent pattern.

7. Large-Scale Atmospheric Connections

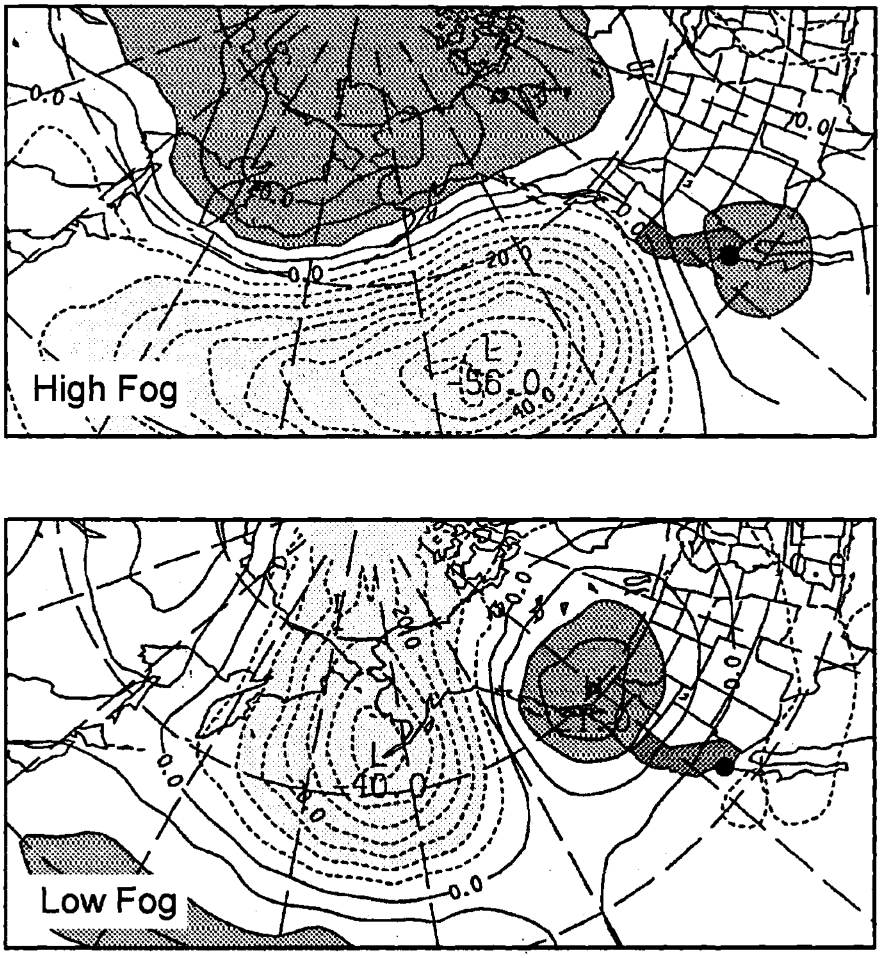
The strength of the association between fog and atmospheric circulation patterns is an important issue because such a link would provide a large-scale organization of fog occurrence. Composites of 700 *mb* height anomalies with high and low fog occurrence at several representative sites indicate that circulation does play a major role. As will be shown, strong composite circulation patterns accompany both daily and monthly fog anomalies during different seasons. The anomalous circulation patterns are consistent among nearby coastal sites, among nearby marine regions, and between coastal sites and nearby marine regions. That fog occurrence is mostly not a locally-driven process, is evidenced by the fact that circulation patterns have regional-basin scale anomalies over the West Coast and extend to strong upstream "teleconnections."

Figure 40. Composite 700mb Height Anomalies for the 25 Winter Months (DJF) with the Highest and Lowest Occurrence of Fog at Arcata, CA (1949-1990)



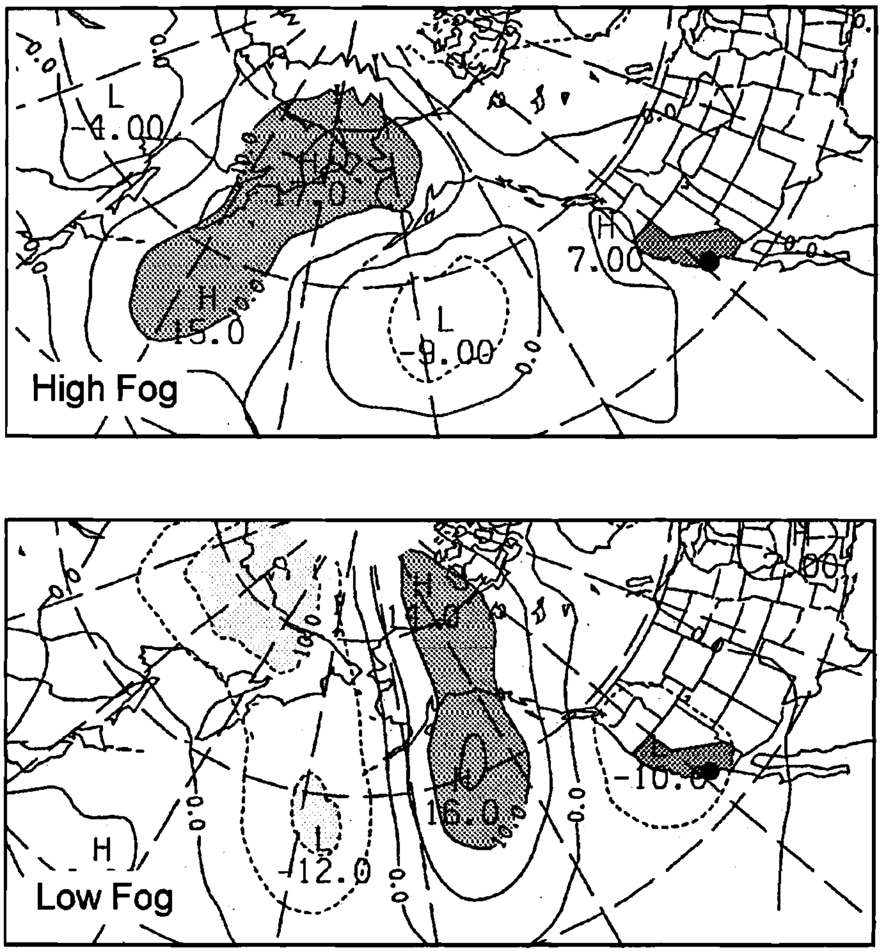
Positive anomalies are indicated by solid contour lines and dark gray shading. Negative anomalies have dashed contours and light shading.

Figure 41. Composite 700mb Height Anomalies for the 25 Winter Months (DJF) with the Highest and Lowest Occurrence of Fog at San Diego, CA (1949-1990)



Positive anomalies are indicated by solid contour lines and dark gray shading. Negative anomalies have dashed contours and light shading.

Figure 42. Composite 700mb Height Anomalies for the 25 Summer Months (JJA) with the Highest and Lowest Occurrence of Fog at Point Mugu, CA (1949-1990)



Positive anomalies are indicated by solid contour lines and dark gray shading. Negative anomalies have dashed contours and light shading.

7.1. Monthly Atmospheric Circulation Associated with High/Low Fog

The first set of circulation composites (Figures 40-42) is based on seasonal fog anomalies at selected California coastal stations. Seasonal composites were formed by averaging 700 *mb* height anomalies for the 25 months with the highest fog occurrence and for the 25 months with the lowest fog occurrence. These composites were repeated for each season to examine the circulation influence upon fog occurrence at the various stations. Regional averages of fog occurrence were constructed for the eight regions shown in Figure 2.

The anomalous circulation patterns were compared for the greatest winter (Dec.-Jan.-Feb.) fog occurrences for Arcata and San Diego, (Figures 40 and 41). Interestingly, the circulation patterns were very similar for all stations. Each pattern features positive 700 *mb* height anomalies along the California coast, indicating subsidence, a strong inversion, and a thin marine layer. Upstream, there are strong negative 700 *mb* height anomalies south of the Aleutian Island chain and positive anomalies to the northwest near Kamchatka.

For the summer months (June-July-August), a similar circulation pattern to that of winter appears at stations such as Alameda, Point Mugu and San Diego, although with much smaller anomalies present (Figure 42 is an example for NAS Point Magu). Anomalies appear smaller for the summer period because the summer variability of the 700 *mb* height is much less than in winter. The relationship between high fog occurrence and positive height anomalies evidently operates through the establishment of a more stable coastal marine layer, probably due to enhanced subsidence.

The low fog case for the coastal stations was also examined. At most locations, there are negative height anomalies (low pressure) in the region, with positive anomalies (high pressure) to the north (see Arcata, Figure 40). In this case, the low fog pattern is one of diminished westerly flow (marine influence) but the low pressure also appears to indicate a thicker, less stable boundary layer.

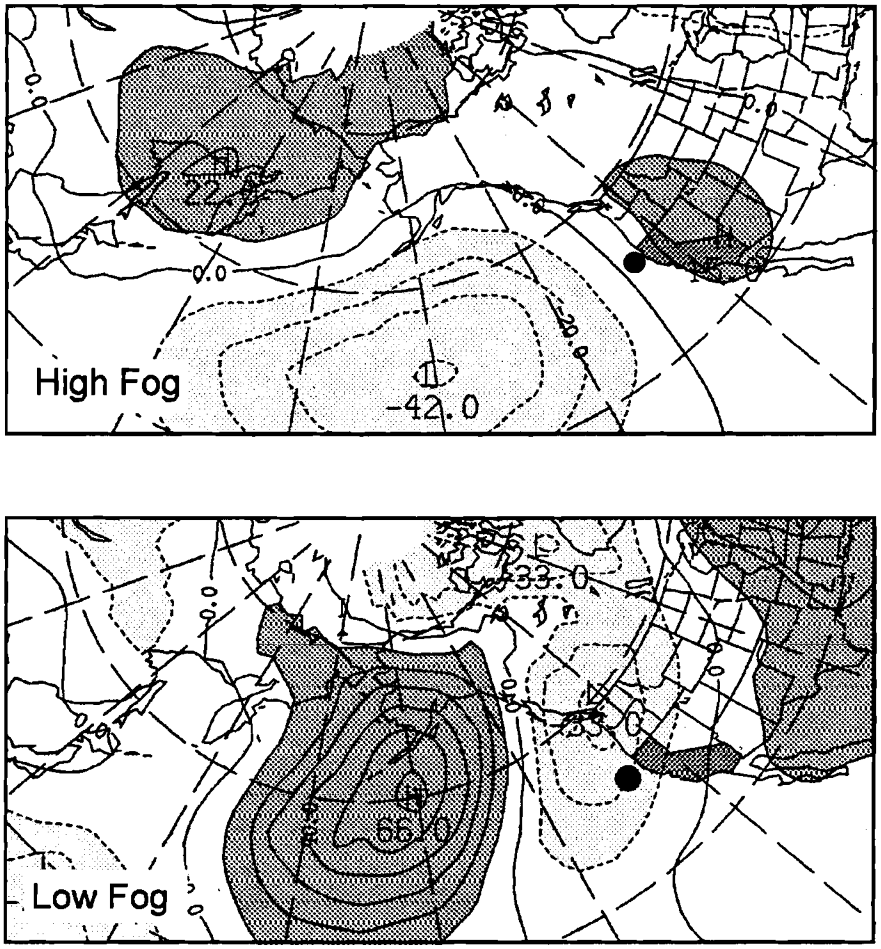
Turning to the marine regions, the circulation patterns for high fog occurrence are nearly identical to those for the high fog cases at the coastal stations. For winter months with the least fog occurrence at the marine regions, the negative 700 *mb* height anomalies are shifted north and are somewhat weaker (Figures 43 through 45). This pattern indicates an increased southwesterly flow and a thicker more unstable boundary layer. During summer, positive 700 *mb* height anomalies are present over the coastal region, similar to Point Mugu but much weaker (not shown here). This low summer fog circulation pattern indicates that a much stronger westerly flow predominates over the coastal region. This decreases stability in the marine boundary layer with increased atmospheric mixing, and less moisture in the lower marine boundary layer, so fog does not develop.

7.2. Daily Atmospheric Circulation

Composites of daily 700 mb height associated with fog events at individual coastal stations were constructed to determine if heavy coastal fog tends to develop systematically over several days. To qualify as a heavy fog day, a station was required to have fog recorded in at least 6 of its 8 three-hourly reports. Evolution of a fog event is examined by identifying the peak day of fog occurrence. To form the composites, such events were averaged over the period of record for the 25 days with highest occurrence in a given month. In cases where there were several days of heavy fog, the first day of this "run" was taken as day 0. Several cases of synoptic scale fog events are exhibited in *Appendices B* and *C*.

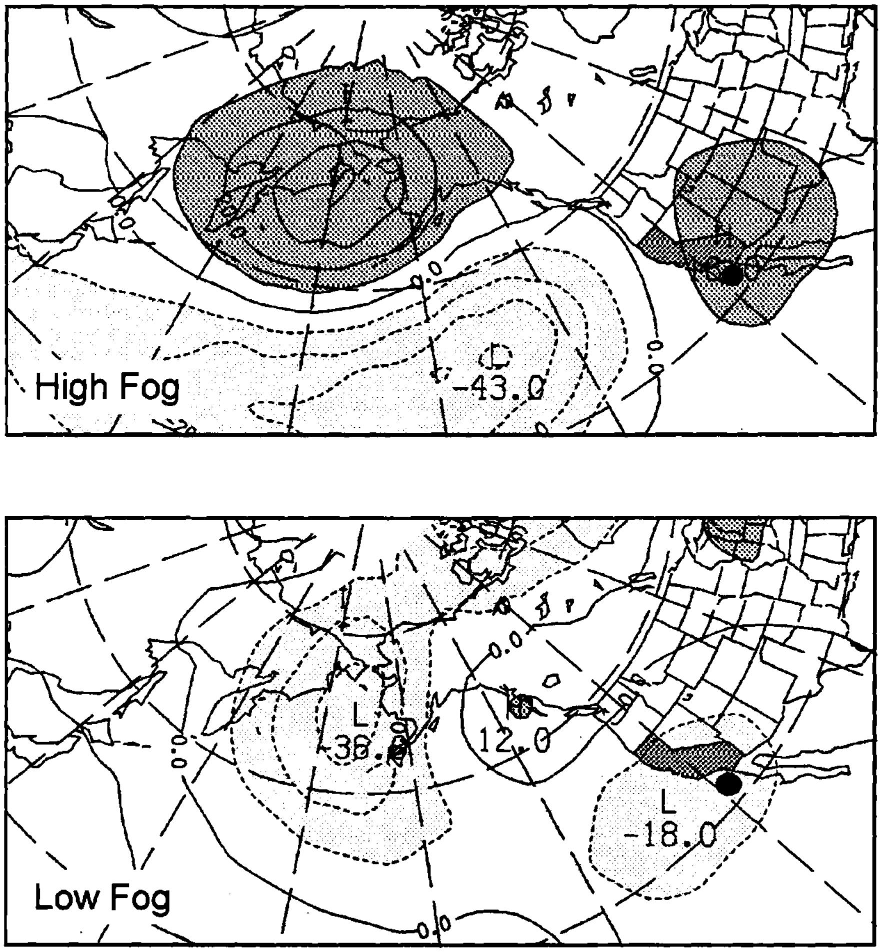
These composites were stratified by month; for example, only January days were taken together. Composites of 700 *mb* height anomalies were constructed for 4 days prior to the peak occurrence, through two days after it. Results of the daily circulation composites for a high fog sequence are very

Figure 43. Composite 700mb Height Anomalies for the 25 Winter Months (DJF) with the Highest and Lowest Occurrence of Fog in North Coast Region 1 (1949-1990)



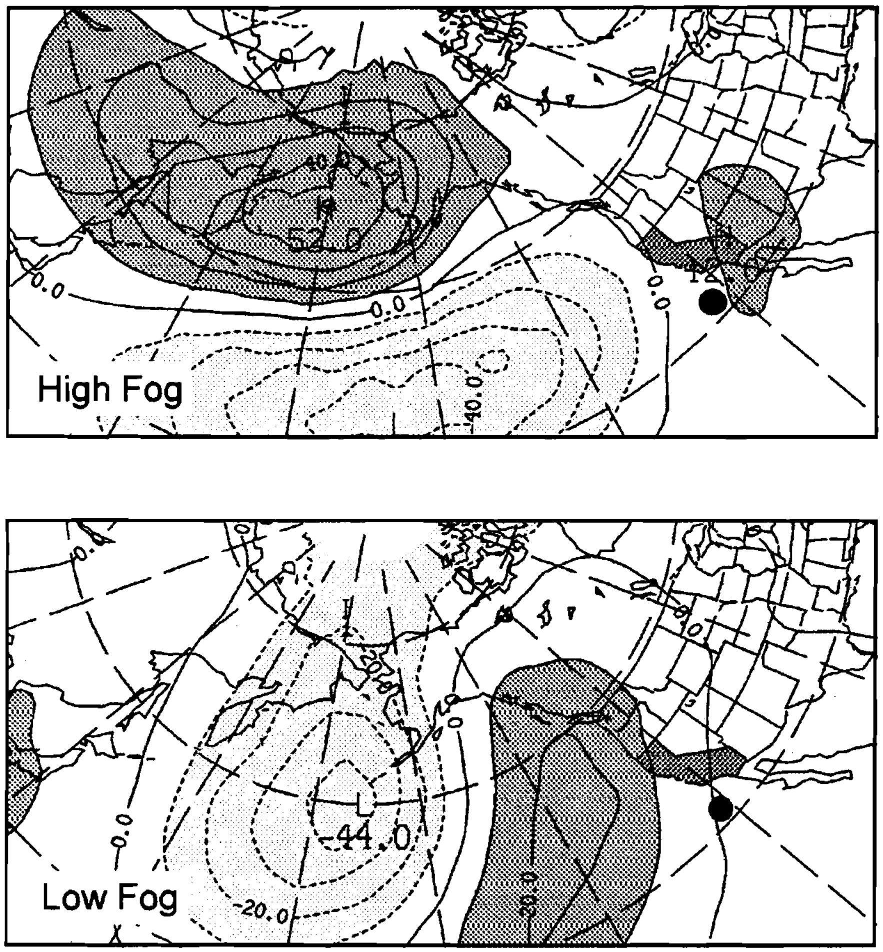
Positive anomalies are indicated by solid contour lines and dark gray shading. Negative anomalies have dashed contours and light shading.

Figure 44. Composite 700mb Height Anomalies for the 25 Winter Months (DJF) with the Highest and Lowest Occurrence of Fog in South Coast Region 7 (1949-1990)



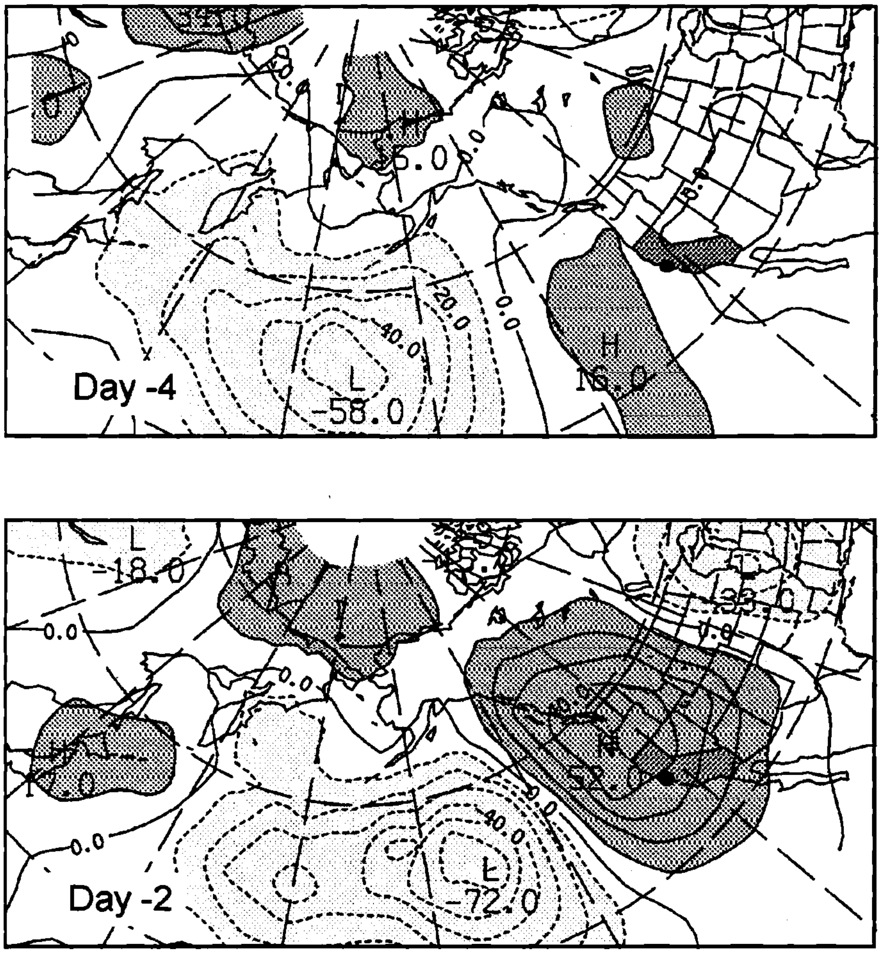
Positive anomalies are indicated by solid contour lines and dark gray shading. Negative anomalies have dashed contours and light shading.

Figure 45. Composite 700mb Height Anomalies for the 25 Winter Months (DJF) with the Highest and Lowest Occurrence of Fog in Offshore Region 8 (1949-1990)



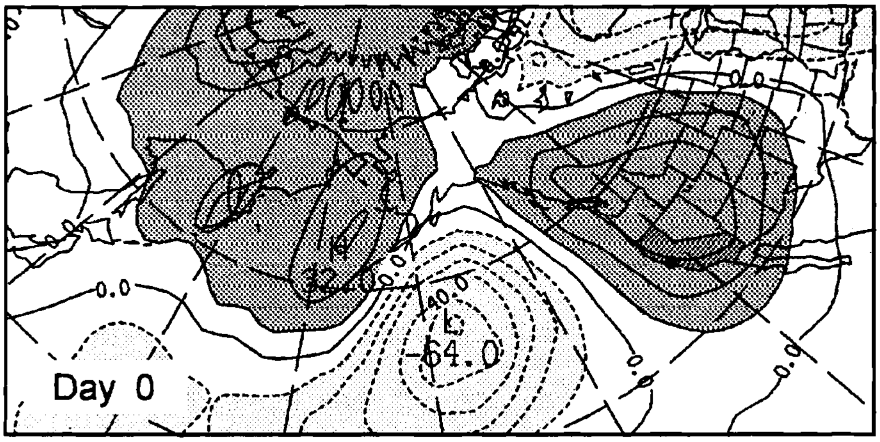
Positive anomalies are indicated by solid contour lines and dark gray shading. Negative anomalies have dashed contours and light shading.

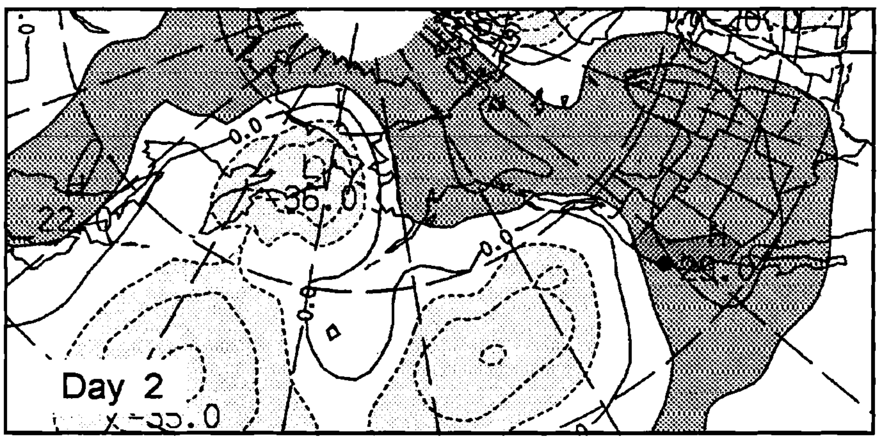
Figure 46a. Composite 700mb Height Anomalies for Day -4 and Day -2 Prior to Peak Fog Occurrence Days in San Francisco, CA (1949-1990)



Positive anomalies are indicated by solid contour lines and dark gray shading. Negative anomalies have dashed contours and light shading.

Figure 46b. Composite 700mb Height Anomalies for the Peak Fog Occurrence Day (Day 0) and Day +2 in San Francisco, CA (1949-1990)





Positive anomalies are indicated by solid contour lines and dark gray shading. Negative anomalies have dashed contours and light shading.

similar to the patterns for high seasonal fog, but illustrate how the fog-producing circulation develops systematically over a period of about one week. Figures 46a and 46b show a typical sequence for large-scale atmospheric circulation for the December fog evens occurring in San Francisco. A station with a seasonal maximum in the month of December, San Francisco shows that positive 700 *mb* height anomalies have developed over the California coast 4 days prior to the onset of heavy fog (day zero). Coincidentally, negative 700 *mb* height anomalies have developed to the south of the Aleutian Island chain on day -4. These features strengthen on day -2 and persist through day two after peak occurrence. Similar patterns (not shown) with strong anomaly centers occur in association with heavy fog at other stations.

Since the circulation patterns associated with fog development are strong, it is almost certain that other weather elements have an accompanying anomalous signature. Daily surface air temperature anomalies across the United States (for the high fog event detailed above) were also constructed (Figures 47-49). The composites are shown for day -3, day 0, and day 3. A positive temperature anomaly pattern occurs from the West Coast to the Midwest. Largest temperature anomalies are not found at the coast, but further east over the Rocky Mountain states, extending south to Arizona. There are negative anomalies downstream from the Midwest to the East Coast. This temperature pattern is consistent with a ridge (positive 700 *mb* height anomalies) over the West and a trough (negative 700 *mb* height anomalies) over the Southeast.

Other cases examined beside the San Francisco case contained similar evolutions. Each of these cases showed early development of fog (beginning from four to two days prior to peak occurrence), a strong pattern of positive and negative anomalies (as discussed) on day zero, and persistent fog for as much as four days after peak occurrence. Surface air temperature anomalies across the United States were consistent with the circulation pattern, with widespread warm conditions developing over much of the west. Also, it is not surprising that with these large-scale circulations, there are very strong ties between the coastal stations and marine regions. Figure 50 is a comparison of San Francisco December high fog days, with Northern California's (Region 2) high winter fog days. Note the similar placement and strength of the positive and negative height anomalies. This was also consistent with other stations and regions, such as San Diego and Point Mugu (not shown here).

8. Spatial Patterns of Marine and Coastal Fog

8.1. Seasonal Fog Distribution

It is important to determine how spatially coherent the occurrence of fog is along the California coast. To begin this investigation, the marine data was considered. From a compilation of seasonal fog observation totals over the period of record (1949-1991), an average for each one degree grid square was calculated to examine the climatological seasonal background. The resulting long-term climatology reveals the spatial distribution of fog over different seasons along the West Coast.

The seasonality of the spatial distribution elucidates the seasonal cycles of the various marine regions and those of the coastal stations portrayed in *Section 5*. In general, these maps (Figure 51 a-d) reveal low fog in spring and high fog in summer, with intermittent high occurrences in fall and winter. The spring period is marked by low fog occurrence with only one small region in the Southern California Bight exceeding 10%. It is noteworthy that the annual minimum of fog occurrence in Spring coincides with coolest SST along the California coast, again confirming that other factors than sea surface temperature operate.

The greatest marine fog occurs in summer, with a maxima extending from well north of

Figure 47. Composite Daily Surface Air Temperature Anomalies (C) for Peak December Fog Occurrences at Arcata, CA (1949-1990)

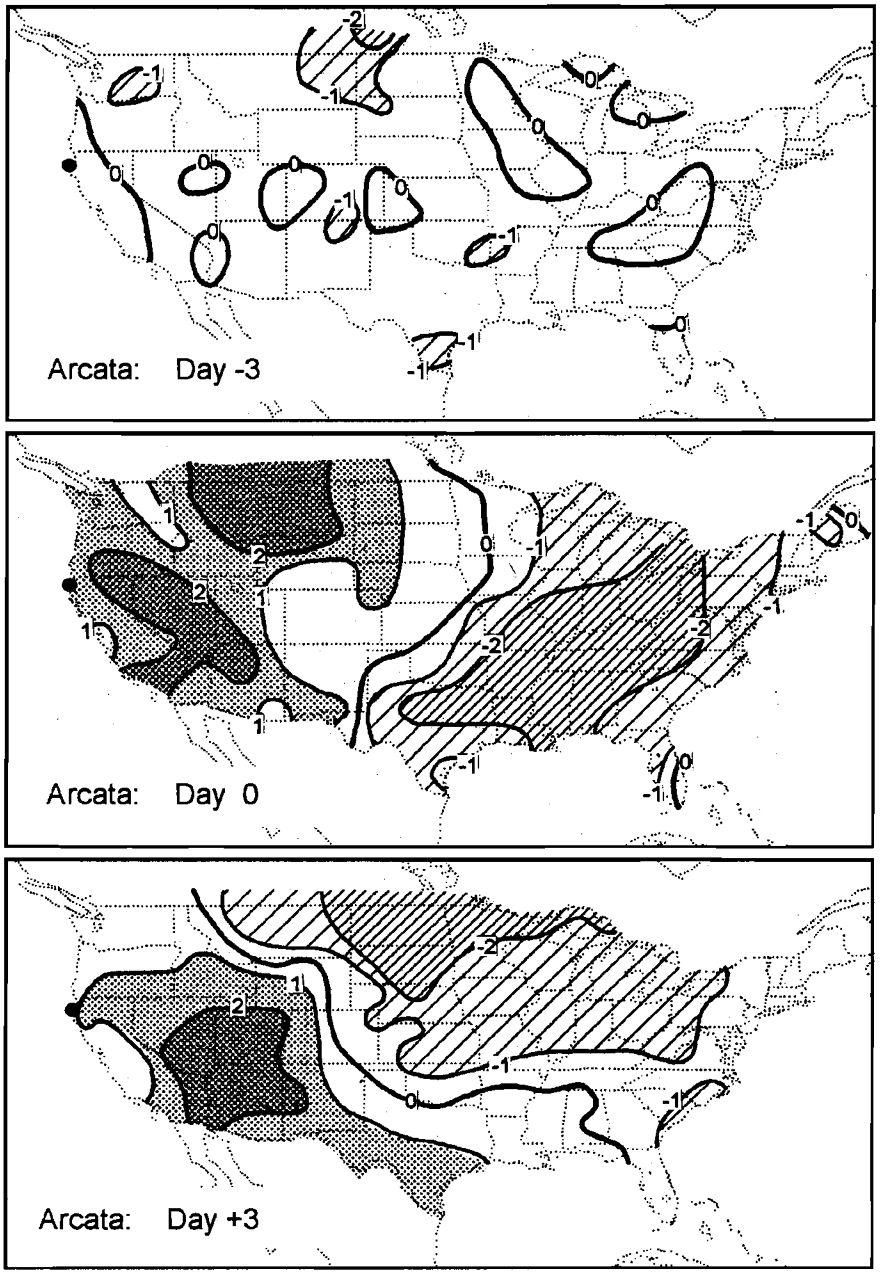


Figure 48. Composite Daily Surface Air Temperature Anomalies (C) for Peak December Fog Occurrences at San Francisco, CA (1949-1990)

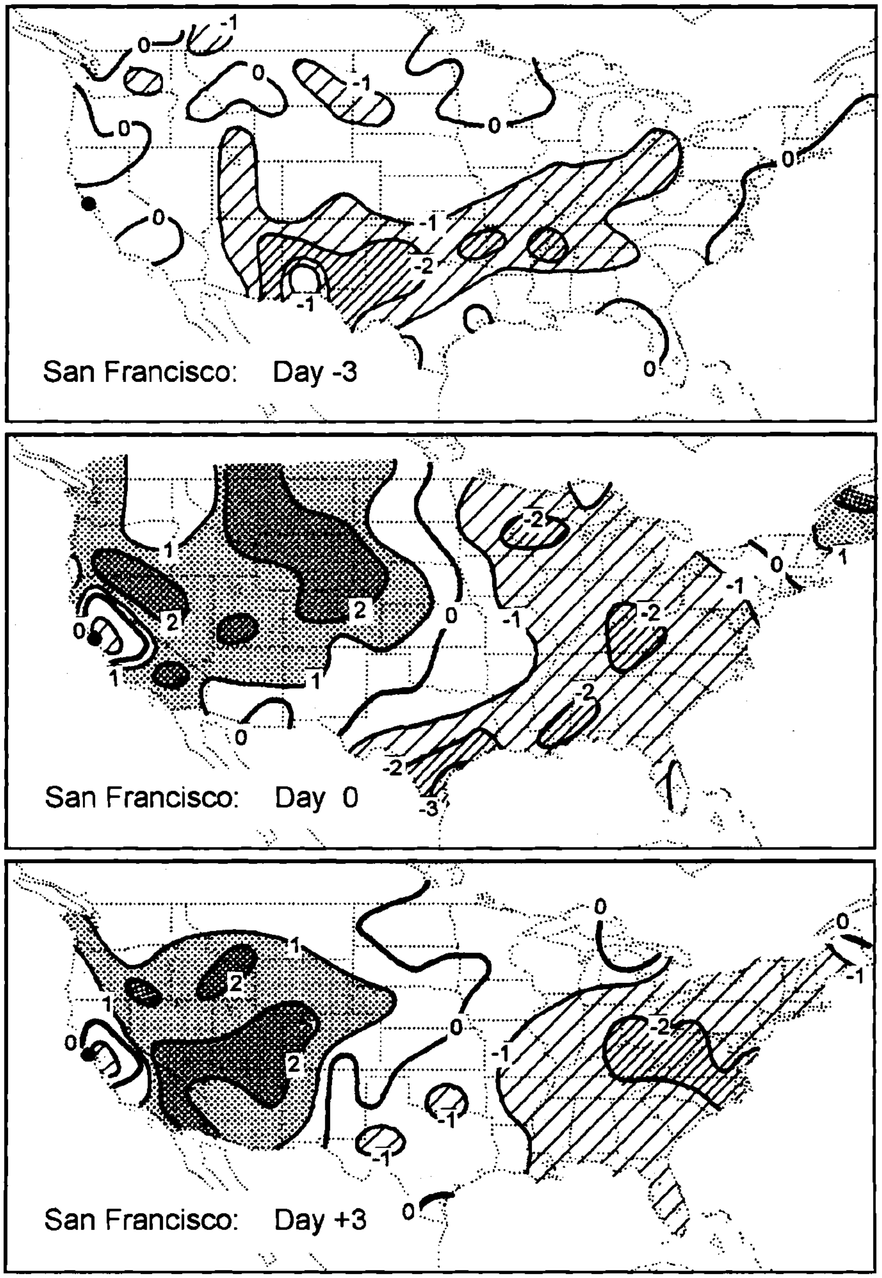


Figure 49. Composite Daily Surface Air Temperature Anomalies (C) for Peak December Fog Occurrences at San Diego, CA (1949-1990)

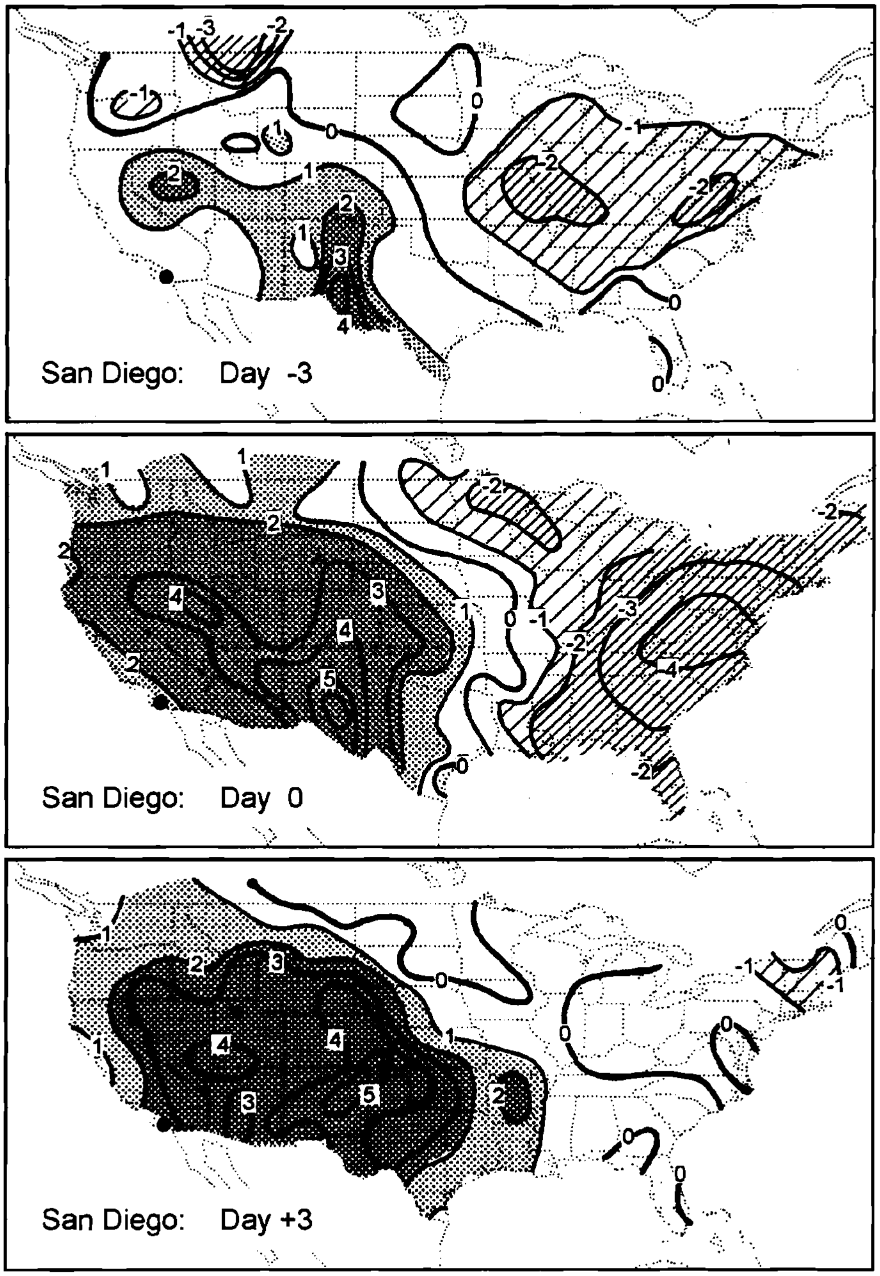
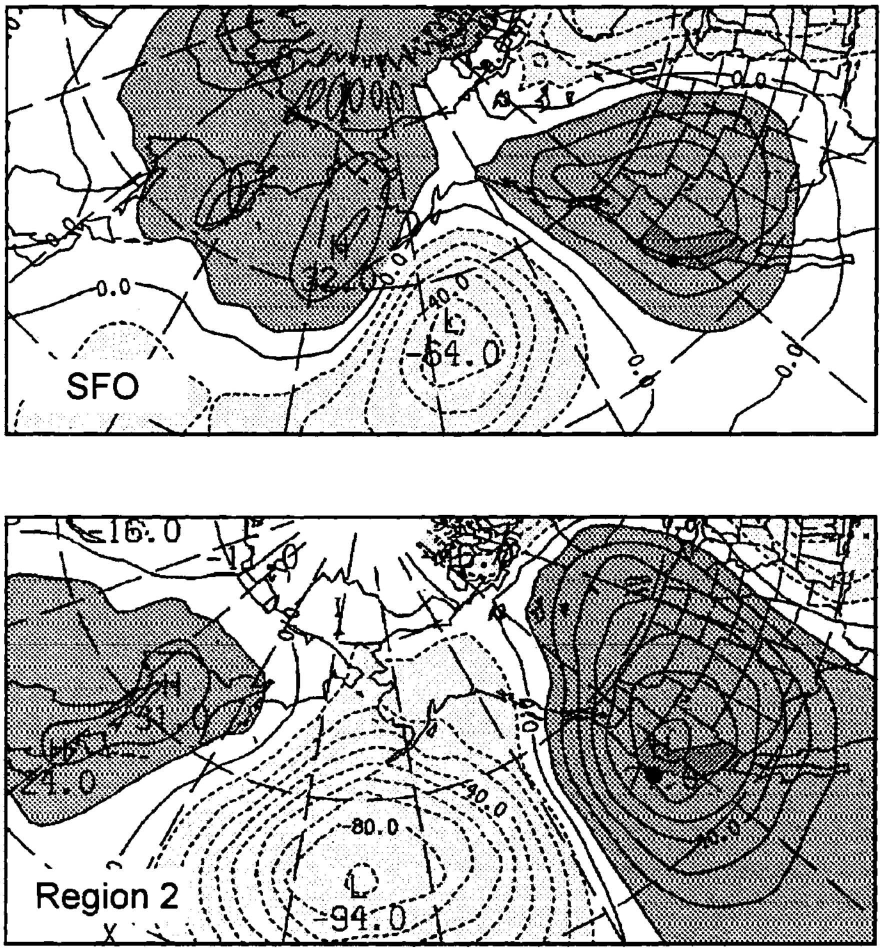


Figure 50. Composite 700mb Height Anomalies for the Peak Fog Occurrence Days in San Francisco, CA and North Coast Region 2 (1949-1990)



Positive anomalies are indicated by solid contour lines and dark gray shading. Negative anomalies have dashed contours and light shading.

California to the northern part of the Southern California Bight region near latitude 34°N. Summer fog occurrence reaches 30% along the Central Coast. Fall and winter values are not as high, but the duration of maxima is longer in Southern California. Peak occurrence reaches 26% at 33°N in the Southern California Bight.

8.2. Spatial Coherence of Monthly Fog

Next, the spatial coherence of monthly anomalies at the marine regions and the coastal regions was examined. The monthly fog anomalies in the marine regions show a higher coherence during the winter months (Table 3), except for extreme Northern California (Region 1) which has fairly low correlations with all other regions. Region 2 and Region 3 correlate very well for all months, with a July peak at 0.72; the Central Coast (Region 3) also correlates well in winter with the neighboring offshore area (Region 4) and offshore of the Bight (Region 6). The offshore Southern California Bight (Region 6), correlates in the winter to Region 7, Southern California, and in the winter/spring closer inshore in the Bight (Region 5). Southern California (Region 7) correlates strongly with the Bight area during December through March and in June, but is more weakly correlated in spring, late summer, and fall. Somewhat surprisingly, the fog occurrence of Southern California, Region 7, correlated rather weakly with that of the adjacent offshore Region 8.

Table 3. Correlations of Monthly Fog Occurrences Between Marine Regions, 1949 to 1991.

Region 1 (40-42°N) vs. Other Marine Regions

Region	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
2	.49	.54	.59	.35	.37	.36	.32	.54	.41	.27	.17	.64
3	.39	.52	.61	.00	.08	.42	.36	.54	.06	.21	.11	.29
4	.33	.61	.56	.06	.24	.28	.20	.36	.17	.41	.15	.54
5	.16	.44	.56	.21	.11	.33	.23	.39	.04	.48	-.03	.32
6	.05	.28	.38	.18	.36	.33	.54	-.06	.19	-.06	.06	.14
7	-.15	.22	.48	.37	.09	.12	.11	.11	.41	.27	-.01	.21
8	-.11	.10	.31	.05	-.19	.13	-.02	.29	.11	.37	-.10	.28

Region 3 (36-38°N) vs. Other Marine Regions

Region	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
1	.39	.52	.61	.00	.08	.42	.36	.54	.06	.21	.11	.29
2	.50	.63	.70	.64	.48	.55	.72	.56	.57	.57	.59	.36
4	.54	.76	.85	.35	.22	.40	.35	.09	.33	.47	.59	.78
5	.59	.74	.90	.64	.40	.50	.63	.47	.42	.19	.59	.67
6	.21	.56	.68	.51	.22	.36	.37	-.05	.30	.47	.59	.34
7	.23	.31	.71	.27	.50	.45	.29	.13	.18	.40	.31	.36
8	.14	.51	.76	.20	.16	.32	.17	.03	.15	.19	.37	.35

Region 7 (31-33°N) vs. Other Marine Regions

Region	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
1	-.15	.22	.48	.37	.09	.12	.11	-.11	.41	.27	-.01	.21
2	-.06	.41	.47	.47	.34	.30	.33	-.05	.24	.02	.45	.13
3	.23	.31	.71	.27	.50	.45	.29	.13	.18	.40	.31	.36
4	.17	.28	.56	.30	.30	.28	.21	.26	.26	-.05	.45	.27
5	.33	.45	.64	.38	.38	.32	.00	.35	-.02	.25	.63	.35
6	.80	.71	.75	.44	.34	.68	.26	.40	.35	.34	.41	.61
8	.21	.38	.58	.23	.14	.25	.20	.49	.14	.34	.56	.26

Correlations between monthly fog anomalies at coastal stations (Table 4) are somewhat spotty—probably owing to local influences. Nonetheless, these correlations and, especially the foghorn series in *Appendix D*, reveal regional spatial coherence along the coast at 100-300 *km* scales.

Table 4. Correlations of Monthly Fog Occurrences Between California Coastal Stations, 1949 to 1990.

Alameda vs. Other Coastal Stations

Stations	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Arcata	.18	.34	.42	.34	.30	.30	-.10	.29	.50	.63	-.04	.47
San Francisco	.71	.64	.89	.33	.34	-.04	.34	.02	.43	.76	.77	.71
Moffet Field	.78	.69	.81	.25	.37	.30	.29	.27	.65	.86	.62	.69
Santa Barbara	.24	.14	.49	.67	.27	.28	.40	.11	.48	.59	.56	.45
Point Magu	.32	.49	.42	.33	.31	.30	.54	.21	.54	.61	.59	.51
San Nicolas	.07	.14	.27	.05	.25	-.23	.04	.15	.31	.76	.21	.24
San Clemente	.09	.66	.54	.60	.38	.08	.05	.14	.46	.30	.32	.45
Miramar	.22	.50	.31	.13	.12	-.05	-.03	.18	.44	.57	.47	.41
San Diego	.38	.64	.33	.00	.20	.34	.07	.31	.41	.56	.53	.50
North Island	.28	.72	.48	.29	.28	.25	.27	.22	.40	.54	.53	.55

Point Mugu vs. Other Coastal Stations

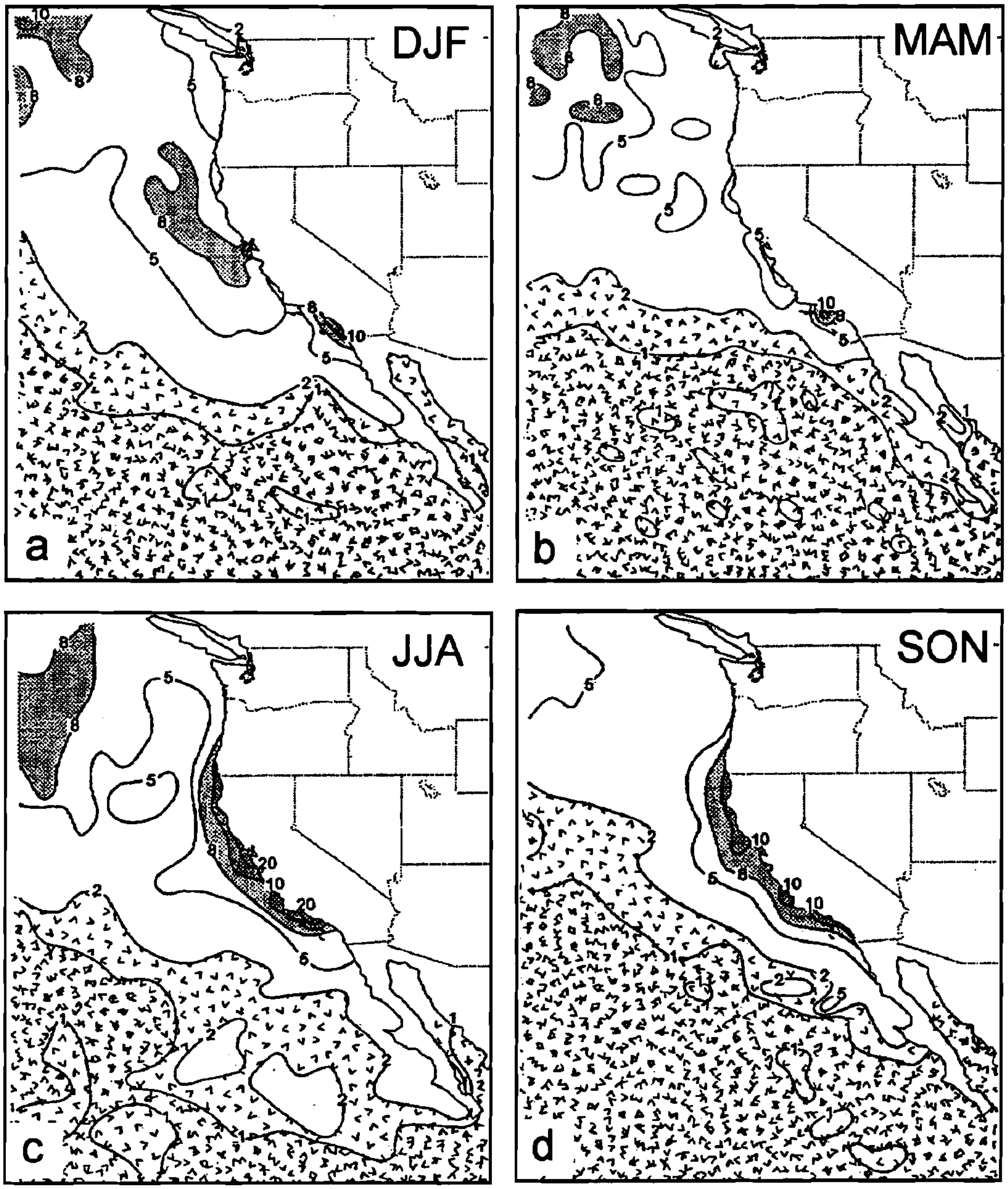
Stations	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Arcata	.23	.16	.56	.27	.20	.32	.15	.06	.25	.58	.07	.55
San Francisco	.37	.50	.44	-.02	-.21	-.05	.13	-.08	.28	.58	.07	.55
Alameda	.32	.49	.42	.33	.31	.30	.54	.21	.54	.61	.59	.51
Moffet Field	.12	.35	.60	.32	.31	.14	.11	-.11	.13	.45	.38	.42
Santa Barbara	.86	.88	.84	.73	.92	.91	.78	.79	.78	.86	.91	.91
San Nicolas	.63	.62	.78	.55	.63	.55	.50	.54	.36	.67	.58	.66
San Clemente	.80	.59	.60	.61	.34	.00	.04	.17	.33	.36	.52	.67
Miramar	.84	.75	.72	.47	.48	.23	.01	.36	.40	.78	.75	.82
San Diego	.84	.73	.72	.57	.44	.44	.07	.42	.15	.81	.69	.83
North Island	.85	.69	.77	.40	.37	.46	.32	.49	.37	.81	.73	.83

North Island vs. Other Coastal Stations

Stations	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Arcata	.24	.37	.52	.49	.31	.13	-.18	.11	.26	.57	.00	.53
San Francisco	.30	.54	.46	.15	.19	.09	-.05	-.04	.02	.43	.56	.60
Alameda	.28	.72	.48	.29	.28	.25	.27	.22	.40	.54	.53	.55
Moffet Field	.07	.56	.54	.09	.39	-.03	-.04	.06	.14	.43	.28	.53
Santa Barbara	.67	.53	.80	.46	.27	.32	.30	.34	.07	.80	.77	.70
Point Mugu	.85	.69	.77	.40	.37	.46	.32	.49	.37	.81	.73	.83
San Nicolas	.63	.34	.66	.41	0	.26	-.18	.20	.05	.67	.57	.71
San Clemente	.75	.73	.89	.74	.40	.03	.19	.45	.19	.67	.46	.72
Miramar	.91	.79	.82	.78	.41	.41	.35	.52	.45	.80	.85	.89
San Diego	.93	.92	.84	.83	.69	.76	.68	.74	.81	.92	.92	.93

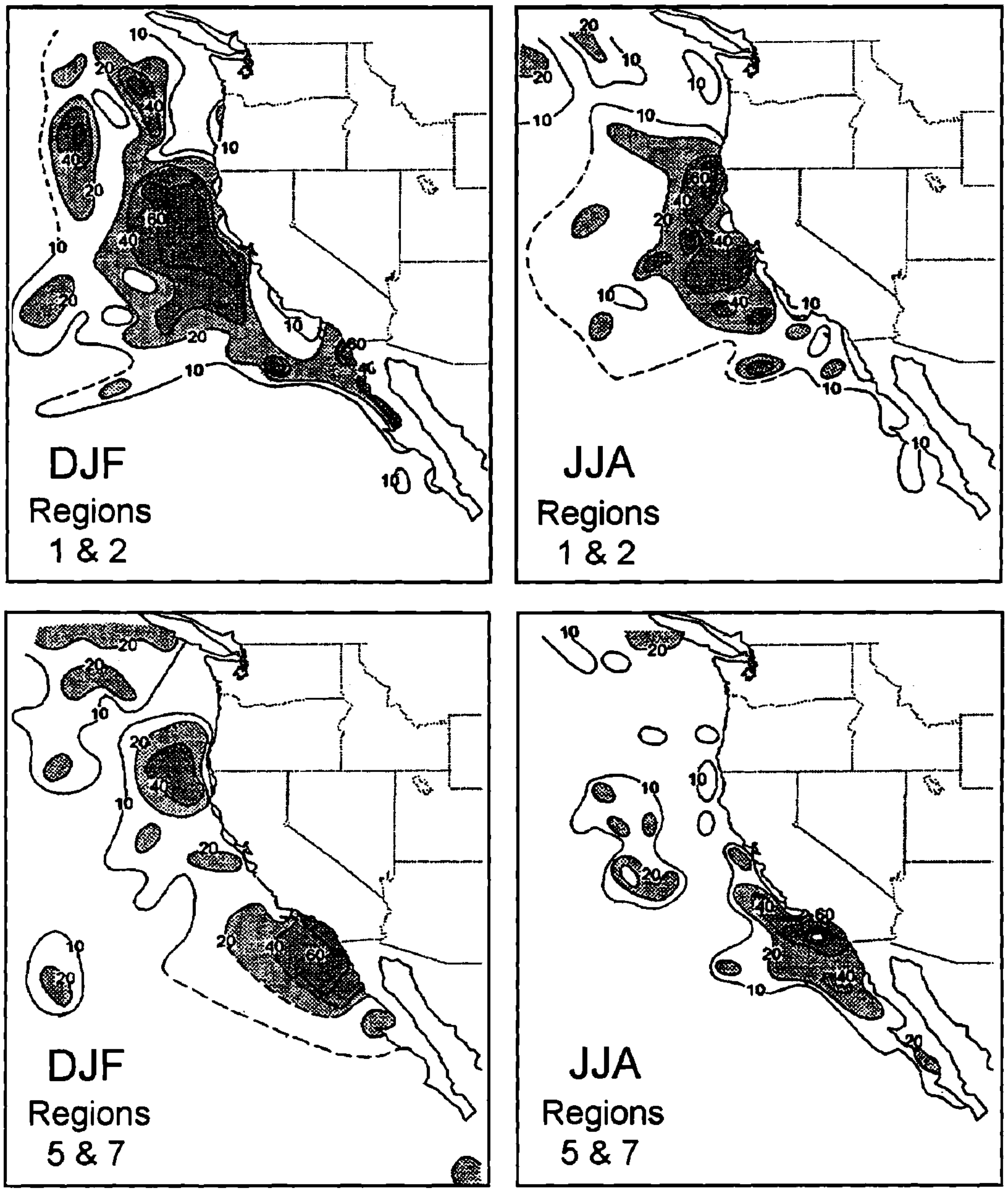
Examining the relationships between the coastal stations and marine regions, we find the positive correlations to be somewhat lower and the negative correlations somewhat higher (Table 5). Arcata correlated in winter with Regions 2 and 3, to the southwest. Santa Barbara correlated highly with Regions 5, 6, and 7 in the winter/spring

Figure 51. Seasonal Climatology of Fog Occurrence (in percent) for Winter (DJF) through Fall (SON) for the Study Area (from COADS)



Fog occurrence greater than 8% is indicated by dark gray shading.
Fog occurrence less than 2% is indicated by the random "V" pattern.

Figure 52. Composite Occurrence of Fog (in percent) Over the Eastern North Pacific Ocean on Days with Coastal Fog Occurrence Greater than 30 Percent



Fog occurrence greater than 20% is indicated by light gray shading, greater than 40% by medium gray, and greater than 60% by dary gray.

but very low in mid-summer. San Clemente had a high correlation with all regions in February and March, generally ranging between 0.53 and 0.84. High correlations are found between North Island and adjacent regions to the north and west (Regions 5 through 7), especially in the winter months.

Table 5. Correlations of Monthly Fog Occurrence Between Coastal Stations and Marine Regions, 1949 to 1990.

Arcata vs. Marine Regions

Region	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
1	.57	.40	.45	.35	.25	.29	.41	.35	.48	.52	.35	.32
2	.48	.46	.73	.36	.41	.49	.44	.31	.44	.38	.65	.49
3	.44	.59	.65	.27	.51	.48	.32	.22	.28	.48	.44	.69
4	.37	.58	.70	.33	.07	.19	-.04	.15	.24	.58	.36	.71
5	.31	.40	.68	.32	.37	.19	.20	-.01	.07	.38	.25	.59
6	.37	.51	.46	.19	.28	.21	.19	-.01	.27	.27	.31	.28
7	.27	.41	.46	.54	.45	.24	.02	.03	.19	.19	.24	.43
8	.11	.25	.46	.29	.14	.10	-.33	.11	.12	.16	.35	.43

Santa Barbara vs. Marine Regions

Region	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
1	-.32	-.23	.56	.37	.36	.34	.05	.33	.43	.43	-.03	.24
2	.04	.12	.66	.59	.29	.11	.13	.13	.26	.22	.10	.18
3	.31	.20	.49	.38	.36	.39	.43	.35	.30	.27	.15	.48
4	.32	.11	.58	.06	.38	-.07	.31	.51	.29	.22	.41	.45
5	.51	.32	.61	.63	.17	.31	.42	.44	.09	.33	.53	.40
6	.65	.54	.51	.55	.52	.23	.02	.16	.30	.40	.13	.59
7	.69	.50	.36	.49	.39	.29	-.14	.28	.43	.45	.46	.49
8	.41	.46	.33	.15	.10	.15	.21	.43	.48	.01	.29	.43

North Island vs. Marine Regions

Region	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
1	-.07	.23	.51	.27	-.07	-.06	-.07	.07	.21	.33	-.10	.27
2	-.13	.29	.69	.55	.27	.28	.06	0	.05	.23	.18	.35
3	.18	.39	.69	.29	.40	.31	.11	0	.03	.37	.32	.34
4	.10	.42	.73	.22	.11	.32	.13	.01	.25	.29	.39	.41
5	.41	.51	.73	.40	.12	.32	.04	.23	-.02	.47	.57	.46
6	.47	.51	.62	.51	.09	.58	.23	.17	.29	.45	.15	.65
7	.56	.51	.59	.68	.47	.71	.40	.50	.29	.48	.42	.49
8	.18	.49	.39	.08	.46	.42	.14	.15	-.08	.22	.46	.32

8.3. Daily Fog Distribution

Turning to daily events, an interesting question is the spatial extent of an individual event. Examining size in composite fashion for two target regions shown in Figure 52, showed that fog can be quite prevalent for a few hundred kilometers along the coast when a fog event is present in one locality of the target regions, further suggesting that mechanisms of large-scale atmospheric circulation may routinely assist in local fog development.

On a daily scale, some fog events were noted as persistent in some local areas but not even present in others, or appearing a few days apart. Over a 12-day period from 20 October to 31 October 1990, fog events were compared at four stations along the California coast (Table 5). At Arcata, one fog count (out of the eight possible) was observed on 21 October followed by heavy fog days on 22 and 23 October. However, no fog was observed these days at NAS Alameda, NAS Point Mugu, or NAS North Island.

During the next few days, fog was observed at North Island and Point Mugu, with heavy events on 27 October at Point Mugu and 26 and 28 October at North Island. Arcata also showed persistent fog on 26 October but none the following day. Fog was observed for only a few hours at Alameda on these days. For the remainder of the month, fog persisted at North Island and Arcata, but was not observed at Alameda and dissipated by 28 October at Point Mugu. This case shows the somewhat spotty nature of fog events from Northern to Southern California (Table 6).

Table 6. Number of daily fog observations taken at coastal stations from 20 October 1990 to 31 October 1990. Maximum number per day is 8.

DAY	20	21	22	23	24	25	26	27	28	29	30	31
Arcata	0	1	8	7	2	2	7	0	5	0	2	3
Alameda	0	0	0	0	0	0	2	2	0	0	0	1
Pt. Mugu	0	0	0	0	0	1	3	7	4	4	0	0
North Is.	0	0	0	0	1	3	5	3	6	5	5	3

In another case study, the same four stations were studied for the period from 14 to 27 December 1989 (Table 7). No fog was observed on 14 December, but then appeared at 3 of the 4 stations the next day. It was locally persistent at Arcata and North Island, the northern and southernmost stations, but was observed only for a few hours at NAS Alameda and not at all at Point Mugu.

The persistent fog event shifted to Alameda on 19 October, lasting until 23 October, while fog basically dissipated from 19 October to 24 October at Arcata, only two hundred fifty miles to the north. Notice the shift in persistent fog events between stations that occasionally occurs. Other time periods show fog occurring at all stations up and down the coast (Table 7).

Table 7. Number of daily fog observations taken at coastal stations from 14 December to 27 December 1989. Maximum number per day is 8.

DAY	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Arcata	0	4	8	6	0	5	2	0	0	0	7	2	2	5
Alameda	0	3	3	5	1	7	8	6	8	8	3	2	1	4
Pt. Mugu	0	0	0	0	0	0	0	2	2	0	0	0	2	5
North Is.	0	2	5	5	3	0	1	4	3	1	2	3	4	3

9. Summary and Conclusions

Fog is a prevalent meteorological condition along the California coast with considerable temporal and spatial variability. In this study, four decades of historical weather reports are used to better describe and understand this variability. Two primary data sets were employed: a set of coastal station three-hourly observations from 1949-1990, and marine surface weather observations obtained from COADS 1949-1991. An auxiliary set, the hours of operation of foghorns at seasonal light stations *(Appendix D)*, was only available for 15 years (1950-1964) but is valuable for filling a void in coastal observations along Northern and Central California, as well as those between the coastal ocean and the San Francisco Bay. These data combine to produce a comprehensive picture of the variability of coastal and marine fog. However, some stations and regions in this study do contain changes in fog occurrence over time that are not well understood. These could be artifacts from changes in observational methodology or instrumental problems. Data representing the boundary layer thickness, stability, and inversion height were not employed for this study. Only surface marine data were used and consisted of the following variables: air temperature, SST, ΔT (SST-air temperature), wind direction and speed.

California coastal stations can be grouped into two general climatological patterns of fog: a winter maximum/summer minimum, or a spring-summer maximum/late winter-early spring minimum. Those seasonal climatological extremes have a widespread signature along the California coast. Stations with a summer maxima include Arcata, Santa Barbara, San Nicolas Island, and San Clemente Island. Stations with a winter fog maximum include San Francisco, Alameda, and San Diego. This behavior is elucidated by the foghorn data collection. Virtually all of the Pacific coastal foghorn records exhibit a summer maximum. The transect of foghorn sites entering the San Francisco Bay illustrates how the fog pattern changes from a summer maximum outside the Bay to a winter maximum inside with a mixed regime at intermediate sites in the space of approximately 10 km.

The amplitude of the annual fog cycle varies considerably among the coastal stations. For San Francisco Bay stations, the amplitude ranges from near 0% in summer to over 15% frequency of fog in winter observations. For Arcata, along the Northern California coast, the annual range is from less than 15% in winter to 45% in summer. The Southern California stations have similar patterns of variability but a smaller range with monthly maxima about 10%. The causes of these two dominant seasonal patterns are linked to local physiography. Sites with land-borne radiational cooling tend to have winter fog maxima, while those dominated by coastal marine exposures tend to have summer fog maxima.

The seasonality of fog displayed by the coastal stations is repeated in the marine observations. The marine observations show similar patterns of seasonal variability, with higher ranges in fog occurrence off the Northern California coast and much less variability along the Southern California coast. Such seasonal variability is nearly identical to the California coastal stations, suggesting that the two regions share common fog producing mechanisms. Offshore regions have an annual cycle of fog similar to the coastal fog regions, but have a lower amplitude. The ship observations reveal how fog tends to cluster near-shore along the coastal waters.

Besides the annual cycle, there is considerable variability over synoptic to interannual time scales. That there is a high degree of coherence of individual month's anomalies between stations along the California coast and the various data sets is evidence supporting the reality of this variability.

Associations of marine fog with local conditions such as wind speed and direction, sea surface temperature, and the sea-air temperature difference (ΔT) were examined. Results are not clear cut, suggesting that *(a)* different processes take place in fog development at different times and, *(b)* the production of fog is not governed by purely local conditions.

Previous case studies suggest that high winds would inhibit fog occurrence. This was confirmed—most fog reports occurred with wind speeds of 6 ms^{-1} or less. However, higher wind speeds were found to co-exist with fog occurrence in the Southern California Bight and other regions. with some marine fog present at relatively high speeds (greater than 10 ms^{-1}). Wind directions forced by the large-scale circulation cause some variability throughout the West Coast regions.

The importance of cooler sea surface temperatures (SSTs) in the formation of West Coast fog is a commonly held belief, but this influence is not universally supported by the marine data. Indeed, though higher occurrences of fog are favored by cooler than normal SST at some regions during particular seasons, other cases have experienced a significant number of fog events during warmer than average SST. A more likely scenario is that fog will be more prevalent when the ocean temperature is cooler than the air temperature (i.e. negative ΔT). This association of fog with cool relative temperatures occurs in most regions. However, there are also cases when fog co-exists with large positive ΔTs.

Thus, local observations suggest three possible scenarios for the fog phenomena. In some cases, it appears that local conditions such as SST, ΔT and wind direction, are suited to producing fog with diminished wind speeds and a sea surface cooler than the overlying air. In other cases, it appears that fog affects the local weather, so that air temperature relative to SST is low, and no systematic wind patterns exist. Finally, in a number of cases, the overall weather pattern that produces fog may also affect the other local weather conditions so that associations between fog and parameters such as wind and fog may both be effects of the larger scale patterns and not the cause and effects. Comparison of the population of surface weather parameters associated with fog to those that occur when fog is not present clearly indicate that on the whole, "fog weather" elements other than visibility are distributed quite closely to the climatological norms—evidence suggesting that fog development does not require exceptional local changes.

Monthly fog anomalies have a fairly high degree of coherence along the California coast. Stations such as those in the Southern California Bight region, separated by less than 300 *km*, vary together. This coherence was present among and between time series from three different types of data: surface airways reports from coastal stations, marine fog from ship weather reports, and the frequency of coastal foghorn operations. Correlations between coastal stations and the marine regions are weaker, but tend to exhibit onshore-offshore spatial coherence. This coherence occurs in the monthly data in spite of there being considerable spatial structure over synoptic scales. Daily case studies indicate that individual fog events are often quite patchy.

Even though the associations between fog and local conditions are not clear cut, there is a strong influence by the large-scale atmospheric circulation. In general, favorable conditions for fog have high pressure directly over the West Coast with a strong low pressure center upstream, south of the Aleutian Islands. This circulation pattern produces atmospheric subsidence which evidently provides optimum local conditions (Leipper, 1994) that result in fog along the California coast. Another regional large-scale by-product of this fog circulation pattern is the occurrence of positive surface air temperature anomalies over most of the Western United States. Coastal fog has a quasi-hemispheric signature which develops rather systematically over several days (typically at least four) and often persists for several more. These synoptic influences are also reflected in longer monthly or seasonal time periods, where the circulation patterns associated with heavy seasonal fog resemble those for synoptic events. Coastal and marine fog are linked to similar circulation patterns. Also, on seasonal scales there are rather bold anomalous circulation patterns that inhibit the development of fog; these patterns are nearly opposite from those that favor heavy fog.

With identified atmospheric circulation patterns favoring formation of fog, further investigation of these patterns should improve predictability of fog at longer leads (4-5 *days*). Some potential avenues to forecast fog development include: circulation forecasts could be coupled with local and regional data such as the marine weather parameters employed here, and possibly with remotely sensed imagery.

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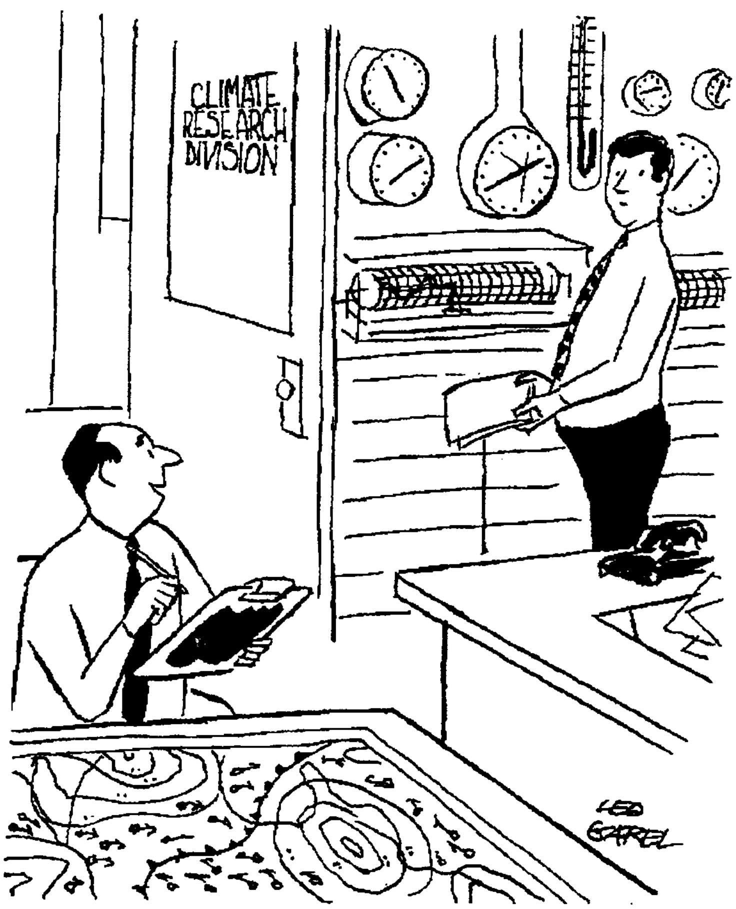

"I figure there's a 40% chance of fog, and a 10% chance we know what we're talking about."

Adapted from a cartoon by Leo Garel in the *Wall Street Journal.*

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Appendix A

Surface and Marine Weather Observation Methodologies

There are two primary sources of data used in this study: (1) surface observations at coastal and island stations along Coastal California (aviation weather or "surface airways" reports) and (2) open ocean surface ship observations (marine weather reports). Aviation weather reporting criteria consider visibility to be obstructed when it is less than seven statute miles. On the other hand, marine observations report fog only if the visibility is reduced to less than one kilometer. Any obstruction due to suspended water droplets where the visibility is equal to or greater than one kilometer is categorized as mist. Present weather categories most likely to obstruct visibility are precipitation (liquid, freezing, and solid), blowing dust or sand, haze, and fog. This great difference between the visibility thresholds of the two weather reporting systems is due to the velocities of the respective modes of transport.

Ships typically travel at 10-20 knots (nautical miles per hour) or 18-37 kph (kilometers per hour). At 15 knots (28 kph) a ship travels one kilometer in just over two minutes. Aircraft operating close to the surface (below 3 km) typically travel at 150-250 knots or 275-460 kph. So, in the same two minutes, an airplane moving at 200 knots (370 kph) would travel 6.7 nautical miles (12.3 km). Thus, in terms of response times (but not distance) the aviation and marine criteria are essentially equivalent.

The following excerpts are the operational definitions of fog and some applicable observing considerations from the National Weather Service handbooks for surface airways and marine weather observing. The numbers at the beginning of each section are the paragraph reference numbers.

Surface Airways Fog Observation Instructions

From: *Surface Observations* (NWS, 1973)

CHAPTER A7. ATMOSPHERIC PHENOMENA

2.2.11 Fog, Ground Fog. A visible aggregate of minute particles of water (droplets) based at the earth's surface, which reduces horizontal visibility. ----High relative humidity accompanies fog. In Aviation observations, this hydrometeor is reported as Fog when it hides more than half of the sky or extends upward into existing cloud layers. Otherwise it is reported as Ground Fog. Ground Fog is termed shallow when it does not restrict visibility (less than 6 feet in depth).

3.6 Reporting Obstructions to Vision. Include obstructions to vision in the body of a report only if prevailing visibility is reduced to less than 7 miles and the obstruction is present at the station. If the visibility is reduced to less than 7 miles by an obstruction at a distance from the station the phenomenon is described in Remarks.

Maritime Fog Observation Instructions

From: *Marine Surface Weather Observations* (NWS, 1991)

CHAPTER 2 - GENERAL OBSERVING PRACTICES

2.4 Points to Remember While Observing

d. Visibility - The absence of suitable objects generally makes it infeasible to observe visibility from ships as accurately as at land stations. Make use of targets on the radar screen. On long ships, when visibility is low, objects of known distances onboard should be used. In coastal areas, the appearance of landmarks can be used as a guide. In the absence of other objects, use the appearance of the horizon or mentally sub-divide the known distance to the horizon. At night, the appearance of navigation lights gives a useful indication of the visibility.

CHAPTER 3 - SHIP'S SYNOPTIC CODE WITH OBSERVING INSTRUCTIONS

3.5 Precipitation and Weather Data Indicators, Cloud Base Height, and Visibility

Visibility at Sea

Estimating visibility requires that you see an object clearly enough to identify it. If the object, for instance a ship held on radar at 6 miles, is an indistinct visual shadow, the visibility is less than 6 miles. Conversely, if the same ship had a sharp outline with little or no blurring of color, the visibility would be greater than 6 miles. An object that is blurred and indistinct, but still identifiable, is just about at the limit of visibility. Blurring and reduced visibility in the stack gas area downwind of the ship should be disregarded as this is a local condition caused by the ship and will soon change after the passage of the ship.

3.11 Present and Past Weather Groups, and Indicator

Fog and Shallow Fog. A visible aggregate of minute water particles (droplets) which are based at the earth's surface. The difference between a cloud and fog is that a cloud has a base above the surface.

a. Fog (code 40-49) reduces horizontal and vertical visibility and may extend over a sizable area. Fog is reported when the depth of the phenomena is greater than approximately 10 meters (33 feet) at sea.

b. Shallow fog has little vertical extent, normally less than 10 meters (33 feet), and reduces visibility horizontally, but to a lesser extent vertically. The stars may often be seen by night and the sun by day. This is a local phenomena usually formed by radiational cooling of the air. It is often patchy, forming first over cooler surface water areas.

c. When fog is present and the occurrence does not clearly fit the definition of shallow fog, the phenomenon will be reported as fog.

Table 3.19 Present Weather Codes in Priority Order, (ww)

ww = 40-49 Fog or Ice fog at the time of observation

ww		
49	Fog, depositing rime, sky invisible	
48	Fog, depositing rime, sky visible	
47	Fog or ice fog, sky invisible	has begun or has become thicker
46	Fog or ice fog, sky visible	during the preceding hour
45	Fog or ice fog, sky invisible	no appreciable change during
44	Fog or ice fog, sky visible	the preceding hour
43	Fog or ice fog, sky invisible	has become thinner during the
42	Fog or ice fog, sky visible	preceding hour
41	Fog or ice fog In patches	
40	Fog or ice fog at a distance at the time of observation, but not at the station during the preceding hour, the fog or ice fog extending to a level above that of the observer	

ww = 20-29 Precipitation, fog, ice fog, or thunderstorm at the station during preceding hour but not at the time of observation

ww	
28	Fog or ice fog

ww = 00-19 No precipitation, fog, ice fog (except for 11 and 12), duststorm, sandstorm, drifting or blowing snow at the station* at the time of observation or, except for 09, during the preceding hour

ww		
12	More or less continuous	shallow fog or ice fog at the station, whether on land or sea, not deeper than about 2 meters
11	Patches of	on land or 10 meters at sea
10	Mist (also called light fog)****	

* The expression "at the station" refers to a land station or a ship.

**** The visibility restrictions on ww = 10 shall be 1,000 meters or more. The specification refers only to water droplets and ice crystals. For ww = 11 or 12 to be reported, the apparent visibility shall be less than 1,000 meters

Sea Haze Over La Jolla Cove, San Diego, California

This photograph illustrates normal visibility conditions when neither mist nor fog are present in the Southern California Bight region. Visibility is unrestricted operationally and such conditions fall into our "no fog" category, but sea haze is present. Notice how the view of La Jolla gets progressively "grayer" as the distance increases from the upper left of the photograph to the upper center. Sea haze is a "lithometer" composed of microscopic salt particles. Both fog and mist are "hydrometers" composed of minute water droplets.

Photograph by L.G. Riddle, date unrecorded.

Appendix B

Synoptic Scale Coherence of Coastal Fog

To examine the synoptic (hourly to daily) scale coherence of coastal fog. To do this, we asked two questions: (1) Can the occurrence of fog at one location be used as a predictor of fog at a second location? (2) Can the occurrence of coastal fog be used as a predictor of fog in the offshore regions?

To address these questions, we selected five UTC days (from 00:00 to 23:59 UTC) with known fog occurrence at coastal stations and for which satellite imagery was available. We then compared the synoptic situation (as given in the *Daily Weather Maps* series from the Climate Analysis Center), the surface airways (land) weather reports, and the Volunteer Observing Ship (marine) weather reports. These five cases are shown on the following 5 pages.

All usable marine reports are displayed as a circle and observation time (Note: "Z" is operationally synonymous with "UTC"). If weather was reported and fog was present, the circle is filled. If weather was reported and no fog was present, the circle is open. If weather was omitted (as not being significant) and the visibility was ≥ 5.4 km, the "circle" is replaced by an open square. We found no cases where the weather was omitted and visibility was < 5.4 km.

Surface airways stations are displayed on the weather maps if there were a sufficient number of reports (minimum: 12) available to determine whether fog had been present during the UTC day. If fog was carried as a restriction to visibility or in the remarks section (e.g., "FOG BANK W") of at least one observation, the station circle is filled. If no fog was reported, the circle is open.

From the five cases, the following conclusions can be drawn:

Fog is patchy at synoptic scales. The occurrence of fog at one location does not preclude a nearby station from being clear of fog. See the May 23, 1994 and August 1, 1994 cases as examples. However, there is much evidence of regional coherence during most of the cases studied. It appears that fog would be the rule in these cases with some clear areas as allowed by local microscale circulation. It is interesting to note that a frontal system or surface trough was offshore of Washington-Oregon in 4 of the 5 cases examined.

Coastal fog is not a reliable indicator of fog occurrence in the marine regions. This supports the results from the overall marine fog climatology that, while having similar month to month fog distributions, the marine regions have significantly reduced fog frequency.

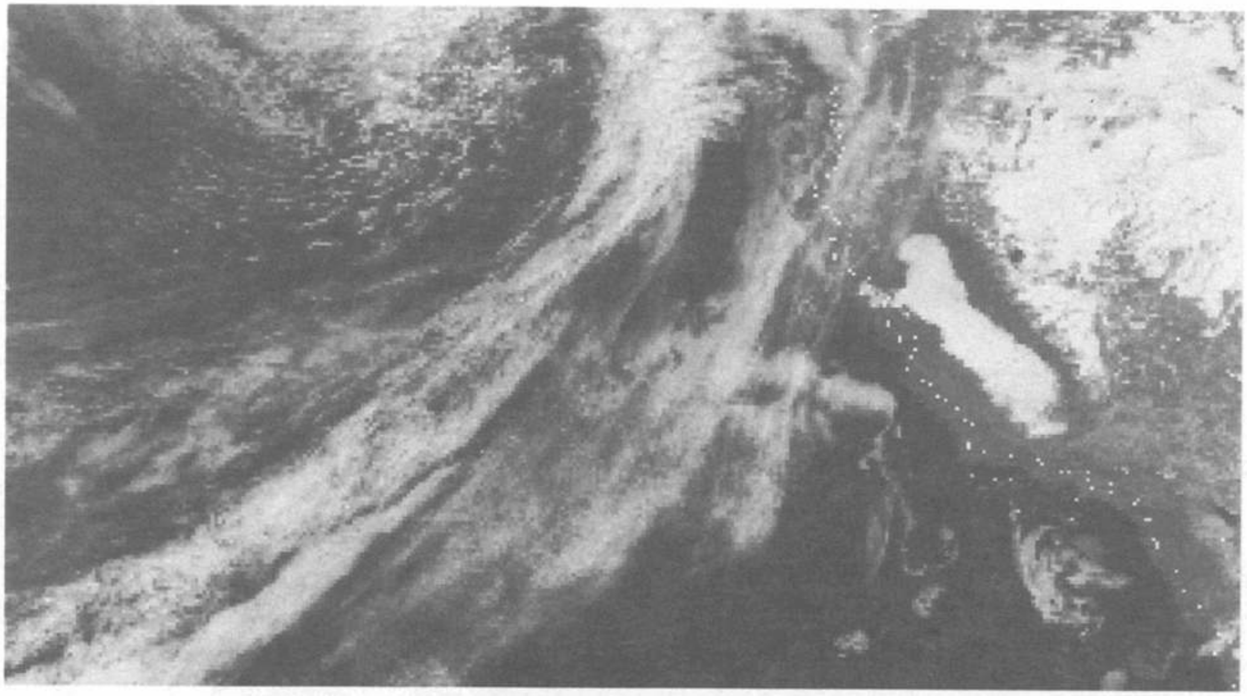


Figure B.1a

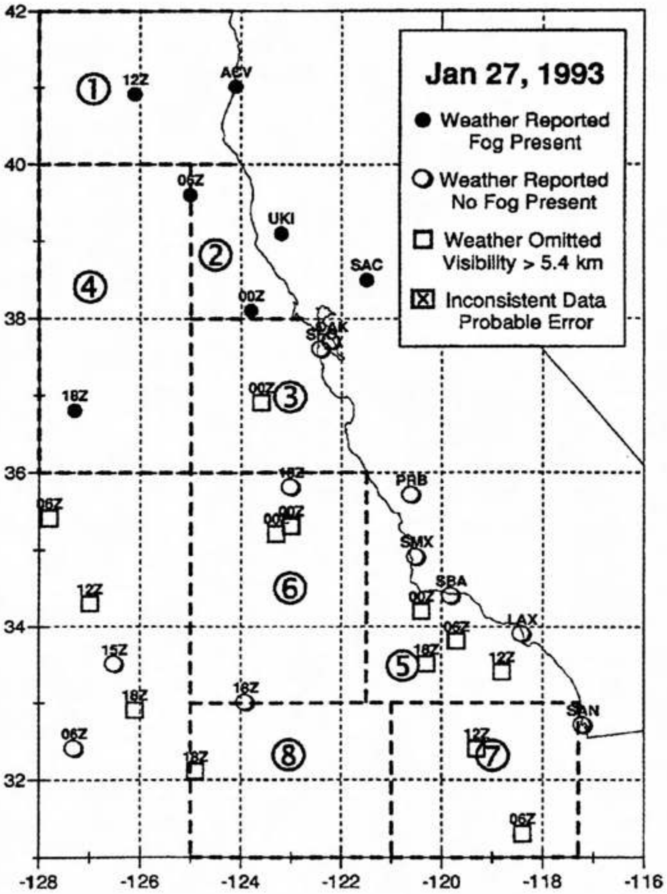


Figure B.1b

January 27, 1993

Situation: A cold front was approaching coastal Oregon. A warm front was passing over the Puget Sound area. A surface high pressure system occupied the Great Basin.

Analysis: Fog was reported in marine regions ①, ②, and ④ (depicted on the maps as rectangular regions delineated by heavy dashed lines) as well as all of the land stations north of the Bay Area. The Central Valley shows extensive fog. The Bay Area and all marine regions and land stations to the south were fog free. Fog was regionalized and confined to the pre-frontal area of Northwestern California. There was fog found in both airways and marine weather reports.

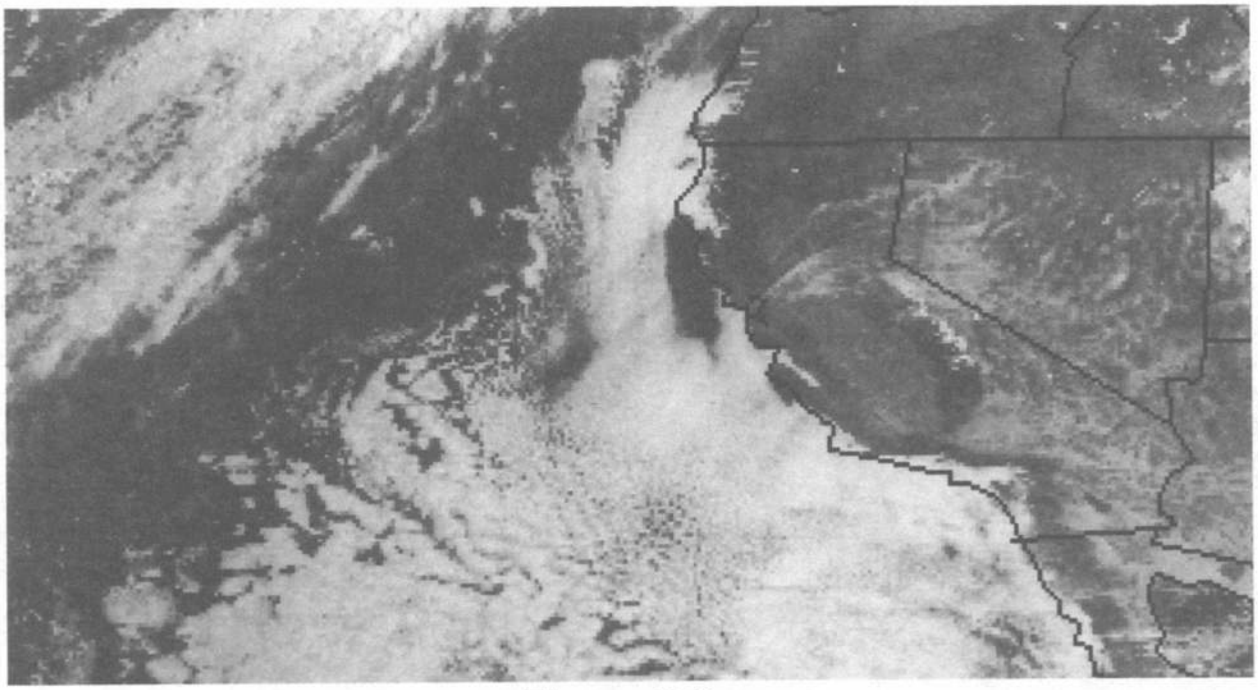


Figure B.2a

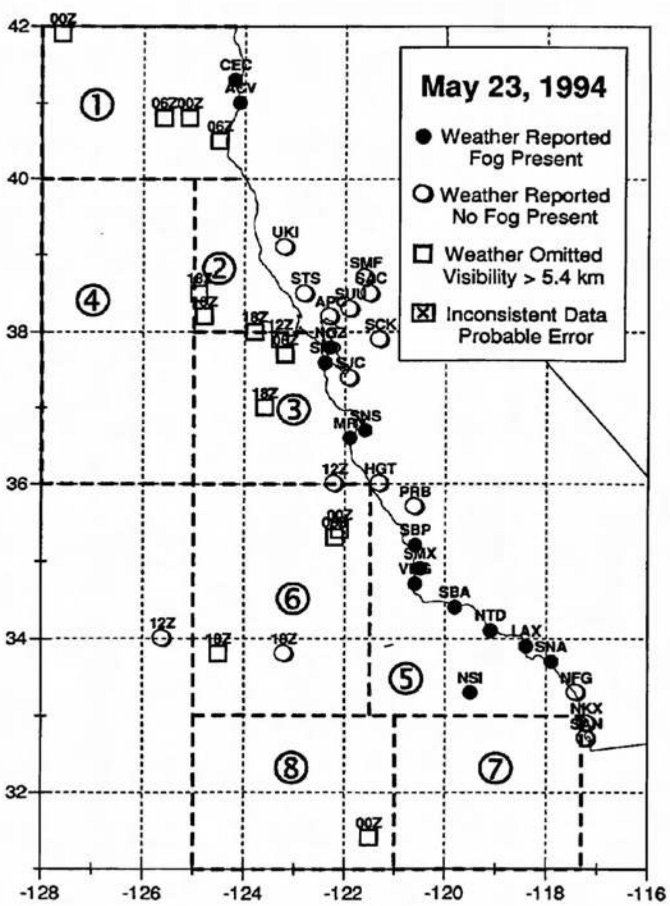


Figure B.2b

May 23, 1994

Situation: There was a weak frontal system to the northwest, well out to sea. There was a weak frontal system and surface wave in the Inter-mountain West. A thermal low was centered over the northern Sea of Cortez.

Analysis: Extensive stratus clouds existed from Oregon south to Baja California, with localized open areas from Cape Mendocino to Point Reyes and from Monterey (MRY) south to San Luis Obispo (SBP). Salinas (SNS) and the Salinas Valley were fogged in. There was extensive fog from San Nicolas Island (NSI)-Santa Ana (SNA) north to SBP. Fog was reported in the Monterey Bay area and in the San Francisco Bay area. There were no reports of fog being observed in any of the marine study regions.

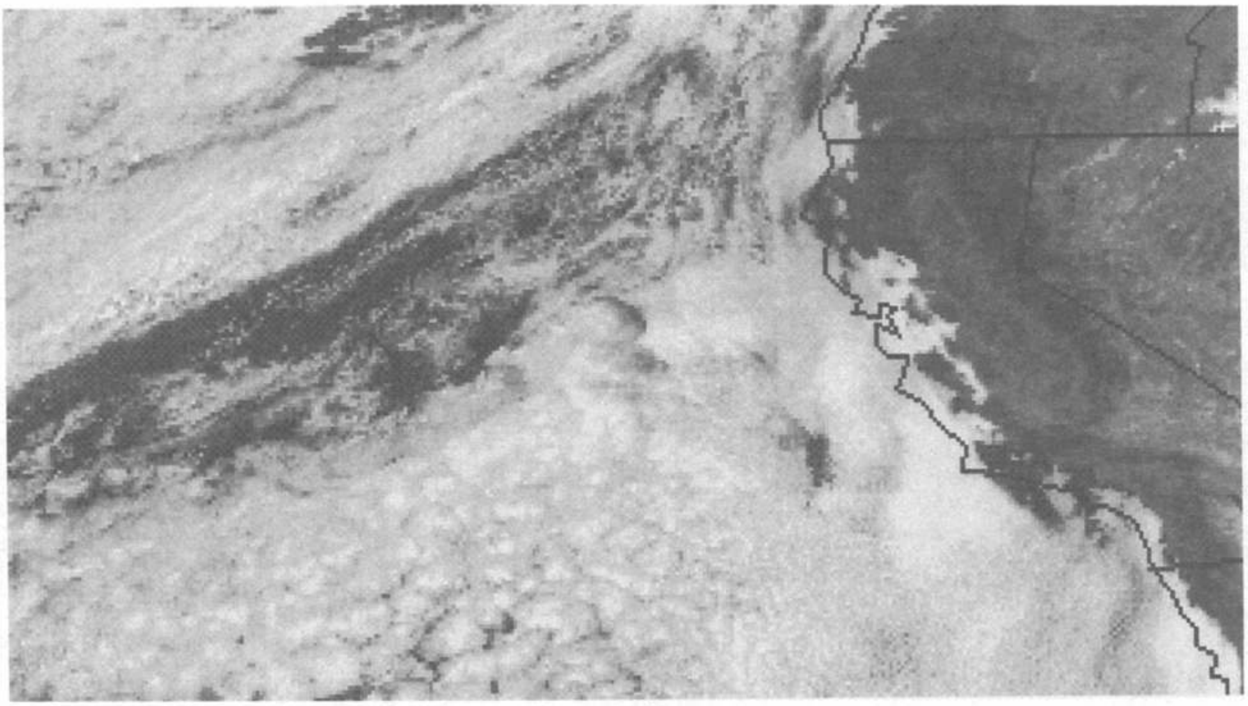


Figure B.3a

August 1, 1994

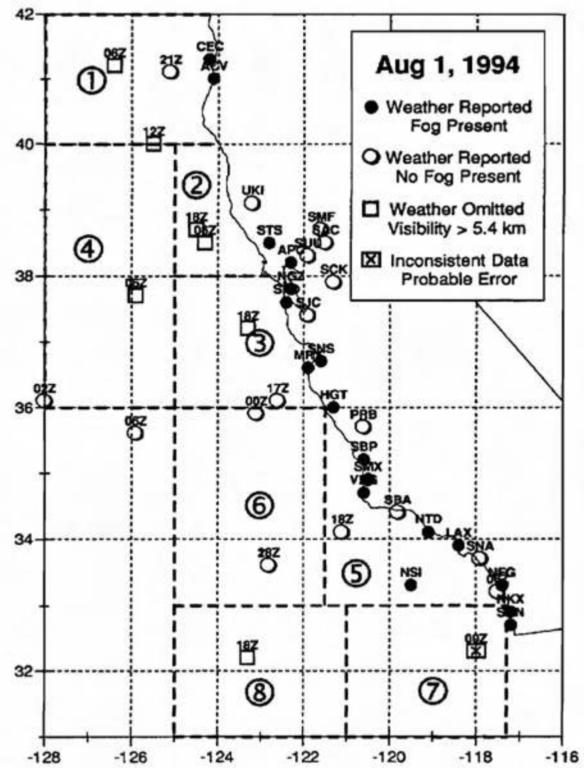


Figure B.3b

Situation: A surface trough was approaching the Puget Sound region. There was a diffuse high pressure system in the Great Basin and a thermal low near Yuma, Az.

Analysis: Extensive, but patchy, stratus clouds along the coast from Oregon to Baja California. Open area existed near Santa Barbara (SBA) and SNA in Southern California, Paso Robles (PRB) in Central California, and Ukiah (UKI) in Northern California. There is much fog in the Salinas, Santa Clara, Napa, and Russian River Valleys. The Central Valley is fog-free and there were no reports of fog from the marine regions.

This case contains the only "Inconsistent Data" encountered in this study. There was a marine report near Baja California of intermittent heavy snow (present weather code 74), which would be unusual in Baja in August. If the 74 is transposed to 47, the report would then be fog of increasing intensity. Fog is consistent with the temperature, dewpoint, and visibility given in the report and the satellite imagery. However, this would be the only marine fog report in any other season than mid-winter.

Note: The continental outline is not reliable from this case forward. The GOES 7 satellite had used up most of it's steering fuel (compressed gas) and had started to wobble.

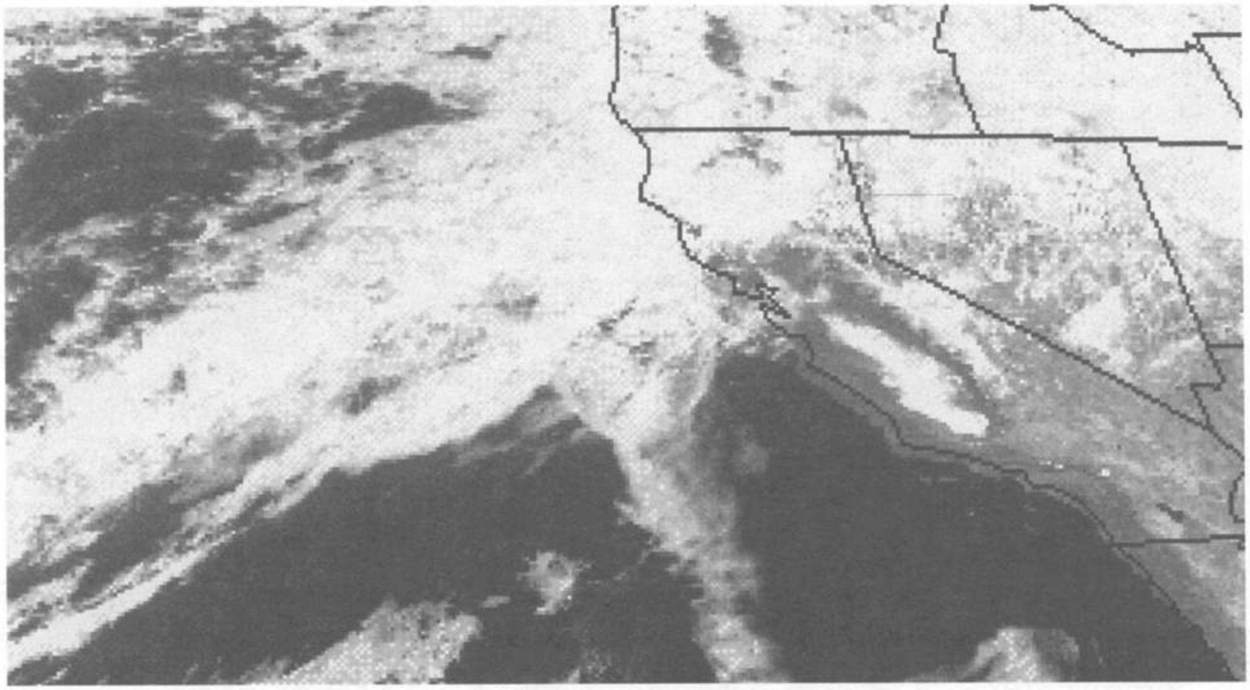


Figure B.4a

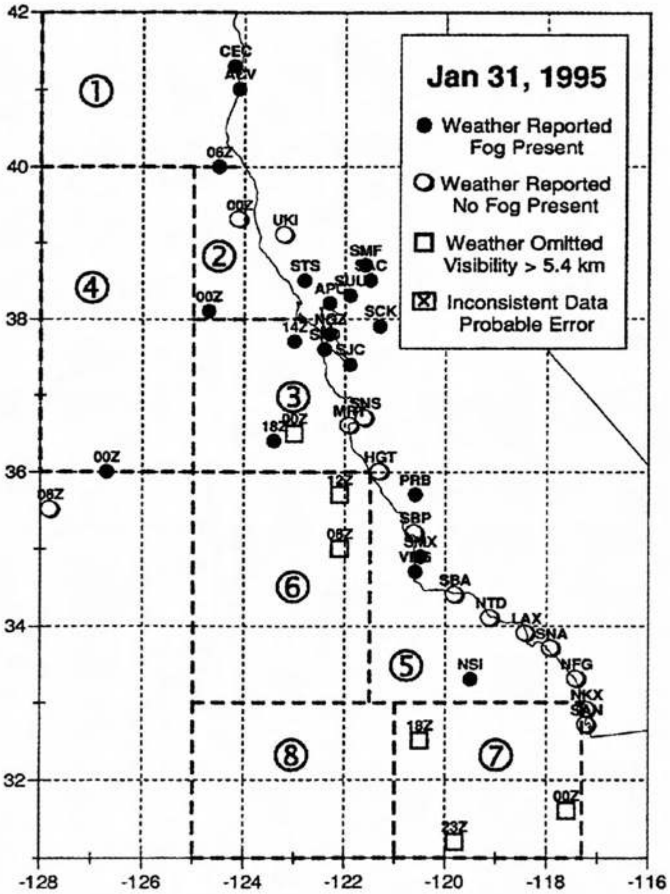


Figure B.4b

January 31, 1995

Situation: A cold front was pushing on-shore in Northern California. There was warm frontal activity in the Puget Sound region. A high pressure system was located over the Four Corners region.

Analysis: This was a clearly defined frontal system. Southern California (except for San Nicolas Is.) was fog free south of Point Conception. There was some localized morning fog at Vandenberg AFB (VBG), Santa Maria (SMX), and Paso Robles (PRB) but not at San Luis Obispo (SBP). The Bay Area and San Joaquin (South Central Valley) were extensively fogged in and the Sacramento Valley had some fog. The North Coast of California was foggy (it is interesting to note that Crescent City (CEC) and Arcata (ACV) had fog reported in all of the case studies). Fog was reported in the four northern marine regions (①, ②, ③, and ④).

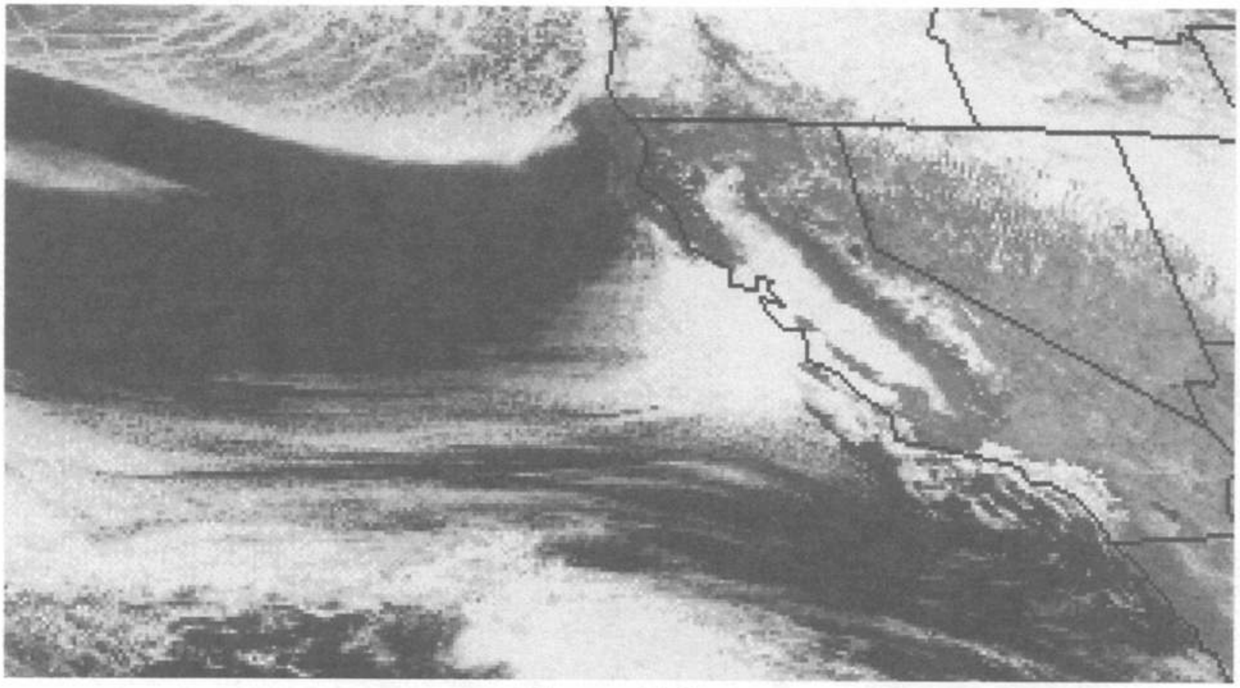


Figure B.5a

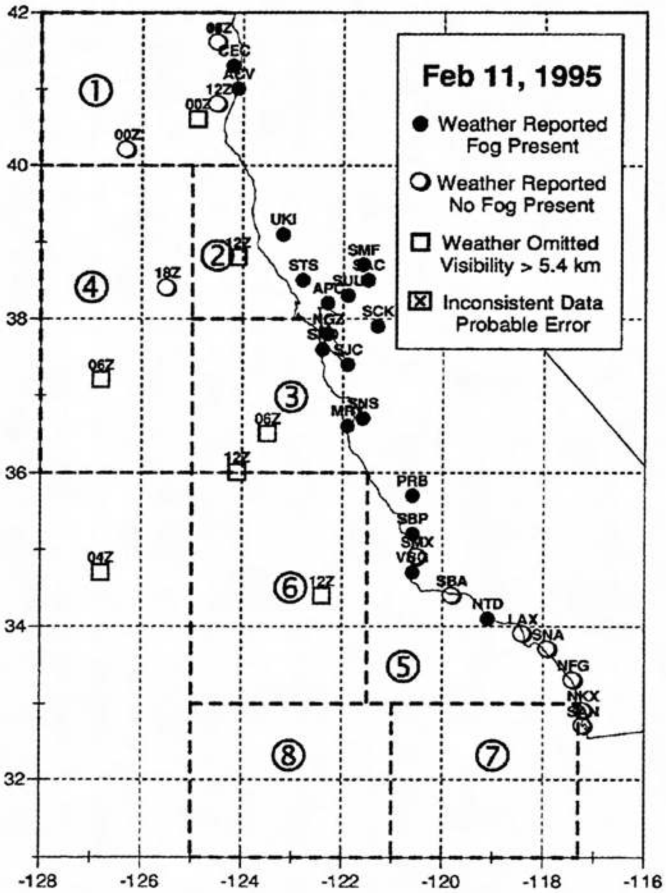


Figure B.5b

February 11, 1995

Situation: This was an unusual case. A low-latitude surface low and associated front had passed through Southern California about six days prior to this event. There was a persistent cut-off upper level low to the southwest and a cut-off upper level high to the northwest. A stationary front ran from Washington State to a surface wave (low) in the Four Corners region.

Analysis: Patchy local coastal fog existed at Point Mugu (NTD) and Central California (VBG, SBP, and PRB but not SMX). The Bay Area and the entire Central Valley are foggy. Occasional fog was observed at all of the airways stations north of the Bay Area.

Appendix C

Santa Ana Fog

This is an attempt to evaluate the Leipper (1948) model of fog development during the end of a Santa Ana episode in Southern California and the coherence of these fog episodes throughout the rest of California.

Leipper's model says that, as long as the Santa Ana persists (winds in the lower 2-3 km of the atmosphere are from the north through east), condition by determining the low level winds (surface to 700 mb or approximately the lowest 3 km of the atmosphere) as reported in the San Diego (NAS Miramar) radio wind sonde (rawinsonde) observations.

Figure C.1 is the rawinsonde (upperair) temperature (solid curve), dew point (dashed curve), and wind observations (wind barbs) for

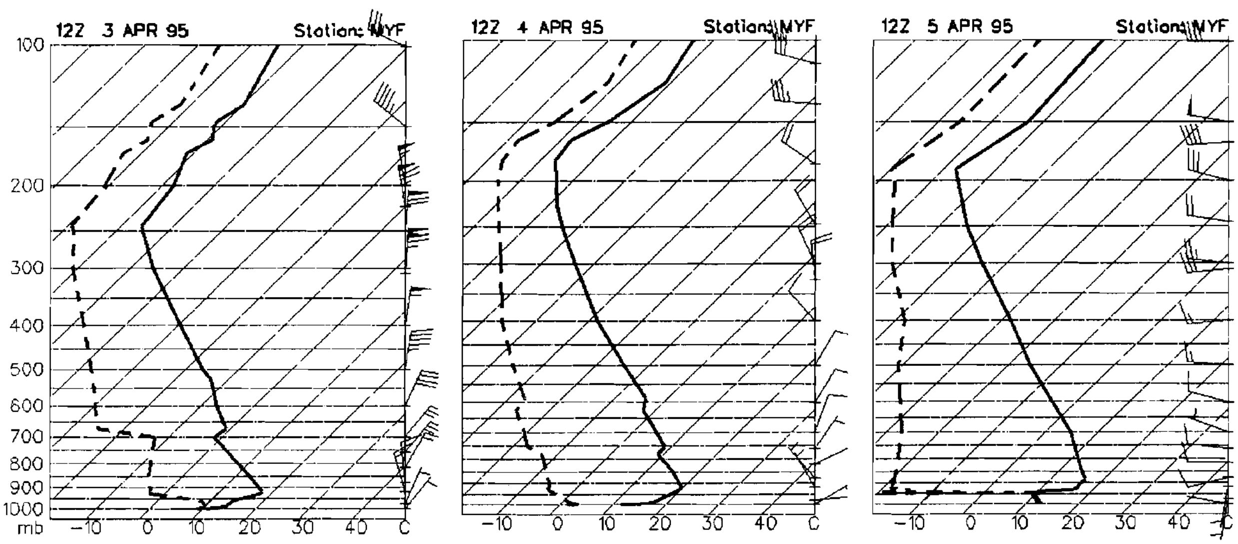


Figure C.1

the lower atmosphere will continue to dry out and fog will not be observed at San Diego. But, as soon as the Santa Ana winds cease, the marine layer (cool, moist air beneath a low level temperature inversion) will form rapidly. The air in the marine layer will become very moist very quickly and fog will occur. Saturation is not necessary for fog to occur.

We examined a series of three days of data (observations and imagery) at the end of a Santa Ana wind episode in the Southern California Bight. We confirmed the Santa Ana 12:00 UTC for three days covering the end of a Santa Ana episode (April 3-5, 1995). The greater the separation between the temperature and the dew point curves, the drier the air at that level. Notice that, as long as the surface to 700 mb winds are from the north or east, the air in the lower atmosphere gets drier. However, when the winds back westerly, the marine layer reforms (although the air above the inversion continues to dry).

Figure C.2 is the 19:00 UTC visible light images from GOES 7. In the April 3 image,

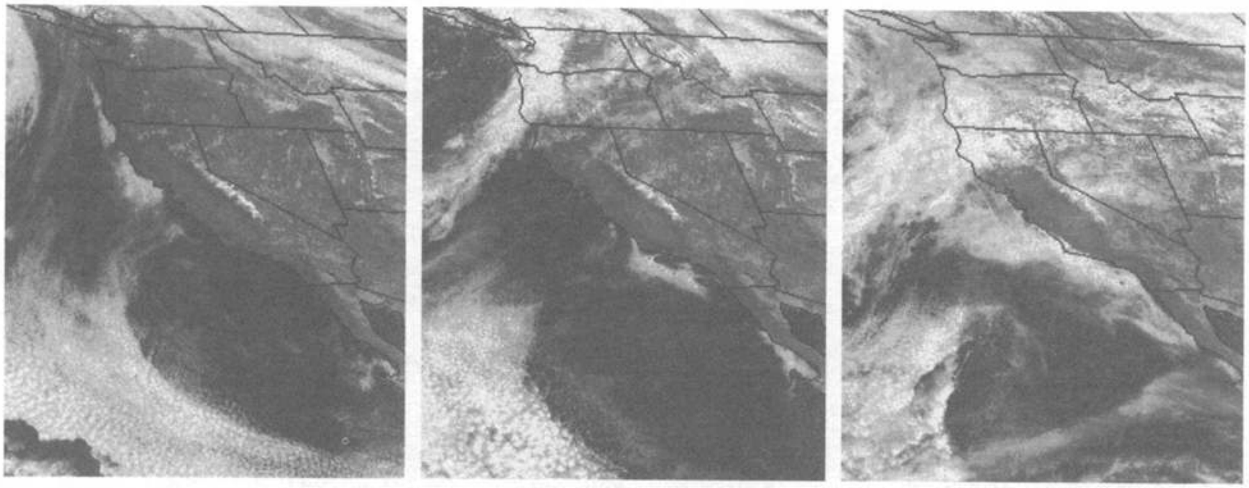


Figure C.2

there is patchy coastal low stratus from Point Reyes north to Oregon. The coast is clear of clouds from the San Francisco Bay Area south to Baja California. In the April 4 image, a frontal system is moving on shore in the Northwest. The thick stratus has disappeared from Northern California, but has appeared from above Point Conception south into the Channel Islands. Low stratus has started to form off Baja California. Most of the Southern California Bight stations are still stratus free. On April 5, most of coastal California is covered by low stratus clouds. This is consistent with Leipper's model and the rawinsonde observations.

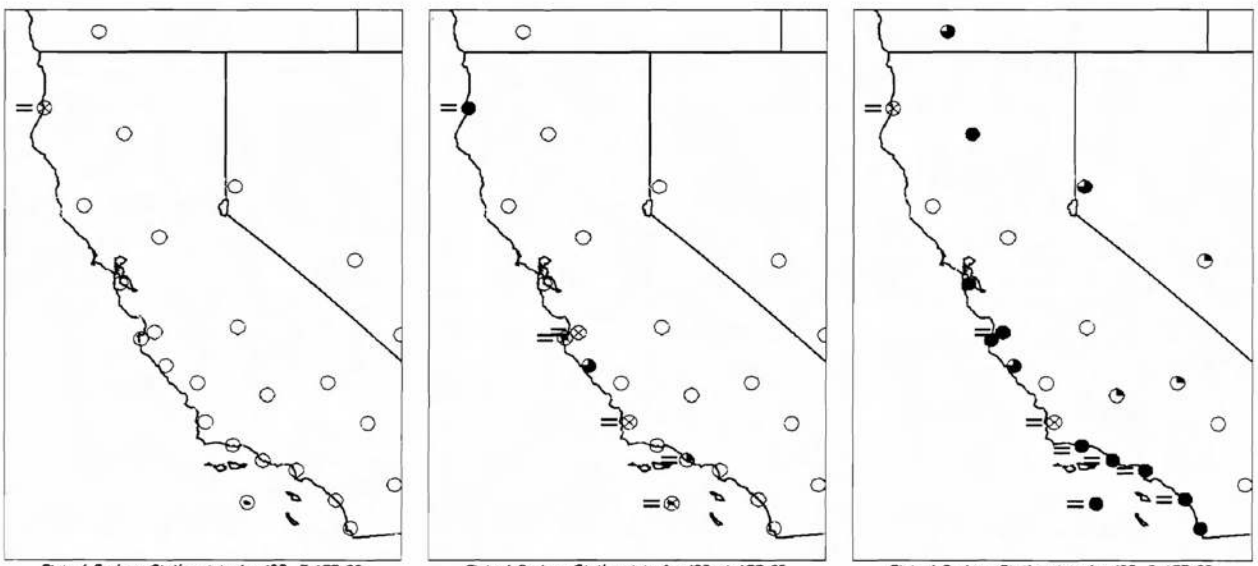


Figure C.3

Figure C.3 is the present weather observations for 12:00 UTC (or 13:00 UTC for stations not starting operations before then) for the three study days. The station circles show the locations of the stations. The interior of the circles depict the sky conditions at the time of observation. Open circles show clear skies or scattered clouds. A quarter filled circle is partly cloudy. A three quarters filled circle is mostly cloudy. Filled shows overcast cloud conditions. The X'd circles indicate that sky conditions could not be observed due to poor visibility. The "=" symbol indicates fog was occurring at the station. These weather charts are consistent with the satellite imagery shown above.

surface winds are calm. Also notice that fog does not persist very long after the surface winds start at sunrise and that the surface airmass never reaches saturation. The highest the humidity ever gets is less than 85 percent.

Leipper's model accurately predicted fog occurrence throughout the Southern California

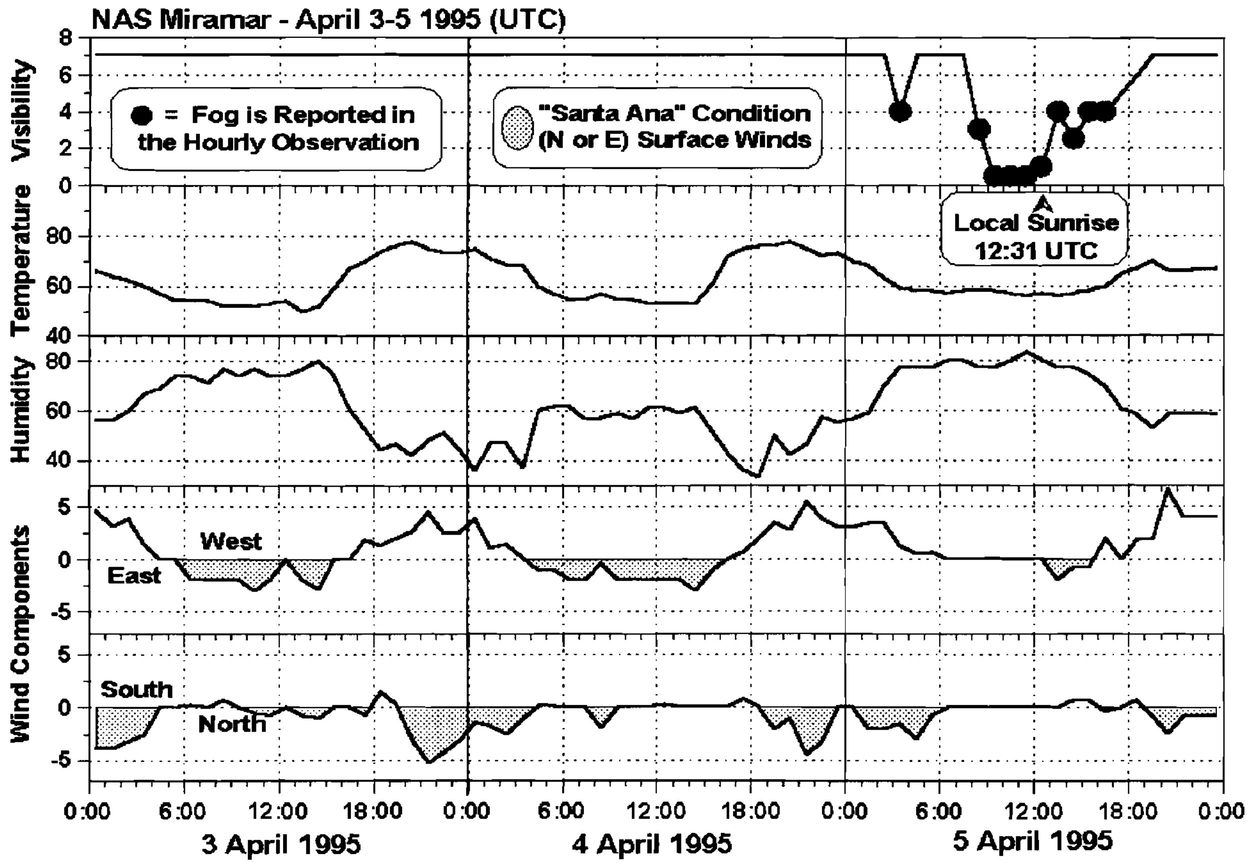
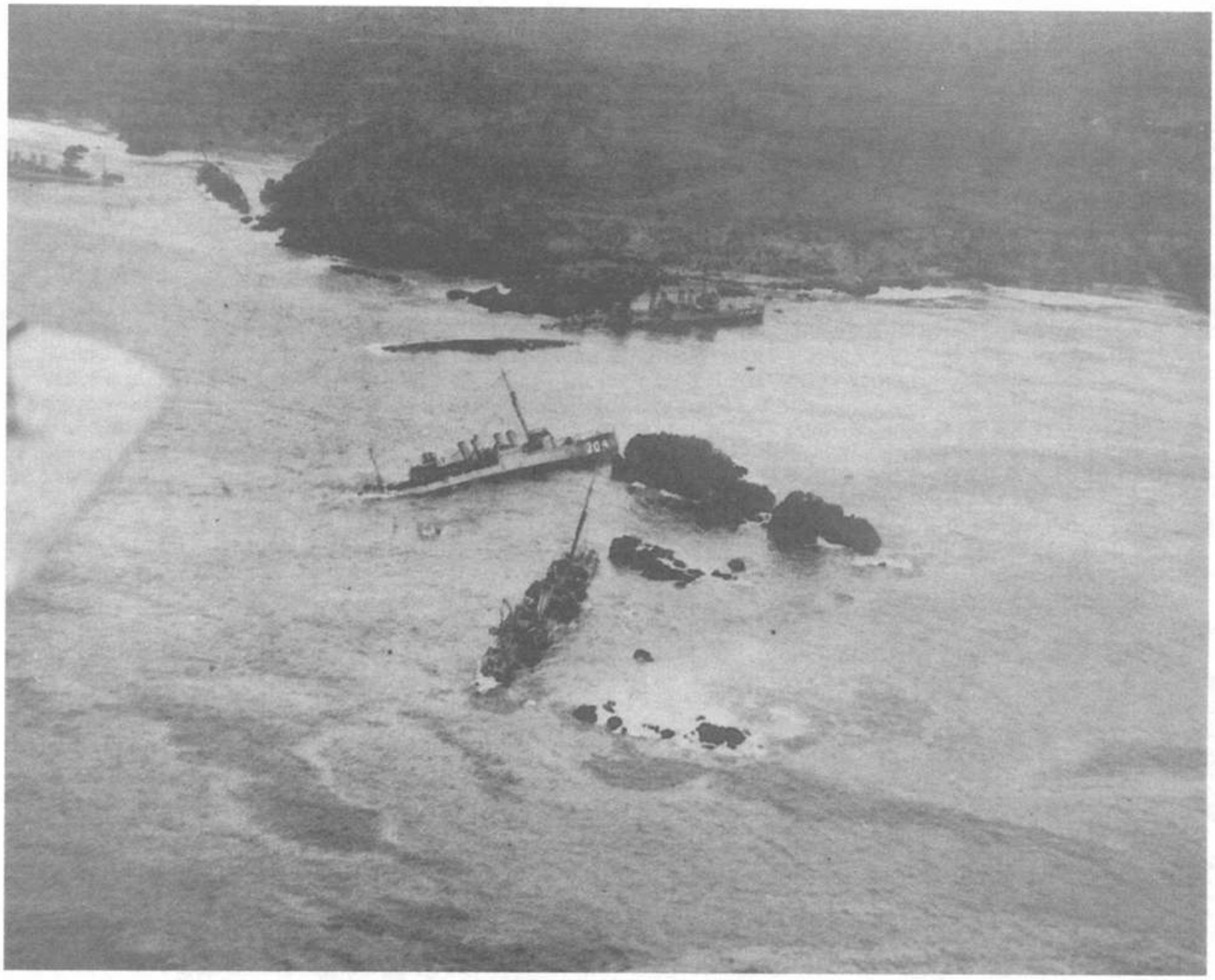


Figure C.4

Figure C.4 is 72 hours of observations at NAS Miramar (closest station to the rawinsonde site) during the end of the Santa Ana. Periods of Santa Ana condition surface winds are gray shaded on the wind component curves. Fog reports are indicated by black dots on the visibility curve. Notice that no fog is reported until after the upperair winds have backed (shifted counter-clockwise) to the west. The heaviest fog is not observed until the local

Bight. The soundings show a very thin marine layer during the onset of fog, along with light winds. Based on the spatial coherence of fog during this episode, the use of Leipper's San Diego model north of Point Conception is probably valid, but should be re-evaluated using the Vandenberg AFB (VBG) and Oakland (OAK) rawinsonde observations.



Point Honda Disaster

On September 8, 1923 the U.S. Navy Destroyer Squadron Eleven, less four vessels, left the *San Francisco Light Ship* at 8:30 a.m. for San Diego. Around 11 o'clock the squadron was aligned in standard formation with *Pigeon Point Light* on the port beam some 1 mile distant. The speed was about 20 knots. After some simple tactical exercises, in the afternoon, the squadron was formed in column. Visibility while not great, did not interfere with the exercises.

At 8:50 p.m., after checking his position on the chart, the Squadron Commander decided to change course to 090° to make the approach to Santa Barbara Channel. The course change was made at 9 p.m. and 5 minutes later the ***Delphy*** stranded on *Point Pedernales* (known locally as *Point Honda*). The Squadron Commander immediately sent warning signals to the vessels astern but, due to the configuration of the coastline, the outlying rocks and the fact that the ships were in formation, six other vessels were suddenly stranded on a rocky promontory at night. The lives of 800 officers and men were in peril. A total of 23 lives were lost and more would have died except for the high degree of discipline and morale in the squadron. The seven vessels were declared total wrecks and later sold as hulks. In the historic photograph above notice the wing of the biplane at left.

--adapted from the *Mariners Weather Log, Vol. 34, No. 3, Summer 1990*

The last sentence of the first paragraph implies that fog (with visibility < 1 *km*) was not present, but that mist probably was and may have been a contributor. September is a heavy fog month along the Central California Coast with fog present in 13% of the observations in Marine Region 3 (near *Pigeon Point*) and increasing to 15% in the vicinity of *Point Pedernales* (just north of *Point Arguello* in Figure D.1).

Appendix D

Supplementing Weather Observations with Foghorn Operation Records

One of the major problems we encountered in this study was the lack of coastal surface airways weather stations in the Central and North Coast areas. We were unable to locate any stations sited on or near the coast between Santa Barbara and Arcata. Even in the San Francisco Bay area, we were only able to obtain records for stations significantly inland from the open ocean. We are confident these records do exist (e.g., Vandenberg AFB, San Luis Obispo, Monterey, Salinas, etc.), but we were not able to obtain them.

A novel data set that does provides a measure of the variability of fog in this area is the number of hours of foghorn operation from U.S. Coast Guard light stations along the West Coast. We obtained a 15 year (1950-1964) record of the hours of foghorn operation at several (37) stations along the West Coast from Gunner Roden, who collected this data in the 1960's. There are 30 stations located along the California coast, and those are the ones that are reported on here (Figure D.1).

The reported number of foghorn operation hours for each month were converted to a monthly frequency of occurrence by dividing those hours by the total number of hours for that month. The time series of monthly fog occurrence for all of the California light stations are shown in Figures D.2a through D.4b. To test the fidelity of these data against the two conventional data sources employed throughout this study (coastal surface airways weather observations and marine weather observations), the seasonal climatology and the monthly-interannual variability of the foghorn data were compared against nearby stations/regions having records of the conventional data.

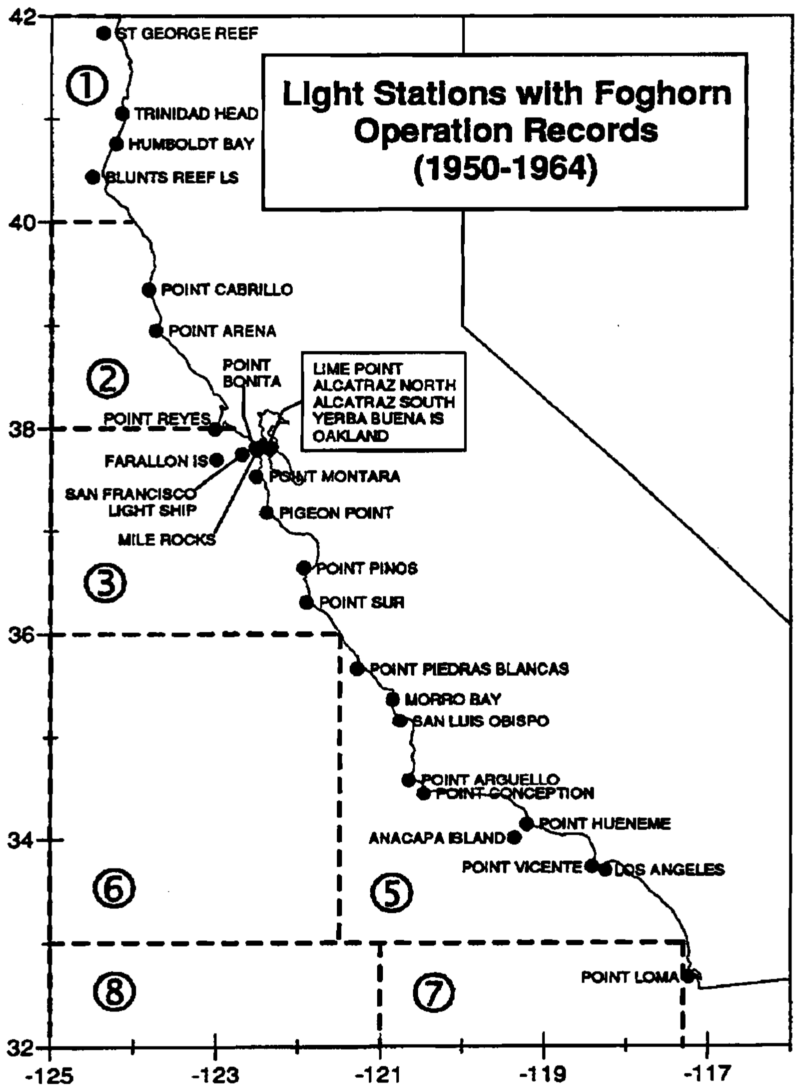


Figure D.1

Monthly Hours of Foghorn Operation (1950-1964)
Saint George Reef to Point Cabrillo

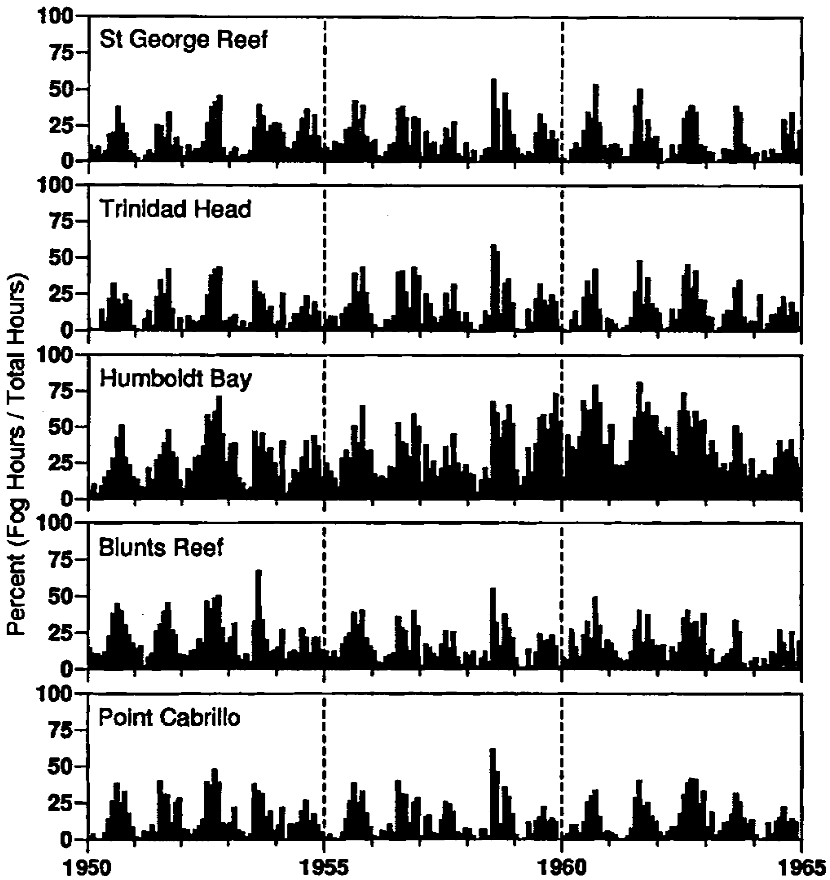


Figure D.2a

Monthly Hours of Foghorn Operation (1950-1964)
Point Arena to the Farallon Islands

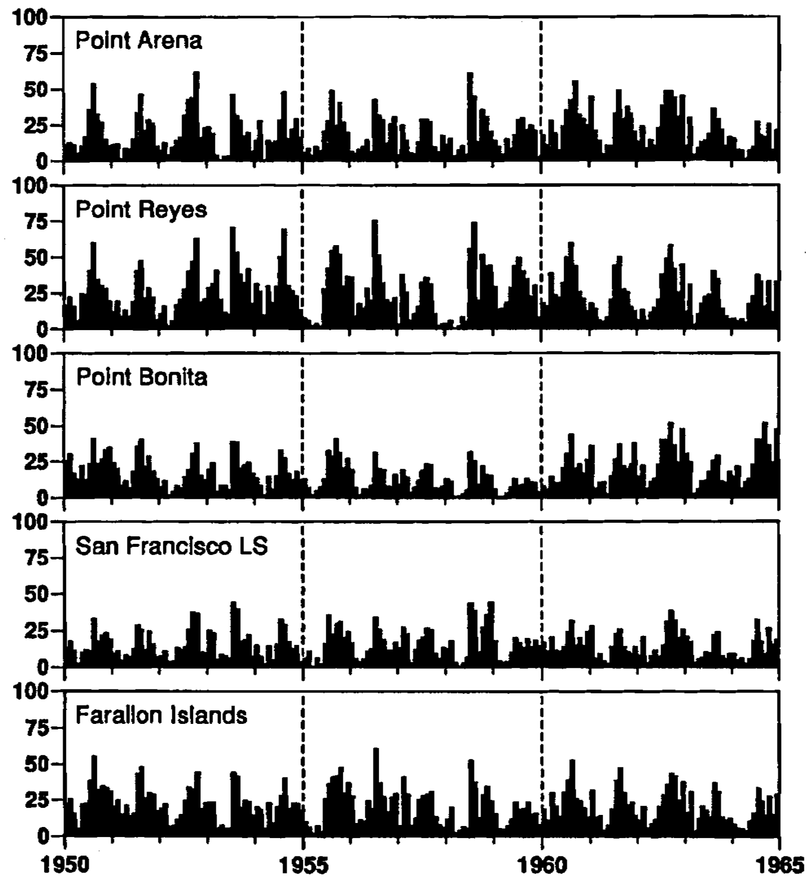


Figure D.2b

Monthly Hours of Foghorn Operation (1950-1964)
San Francisco Bay Area

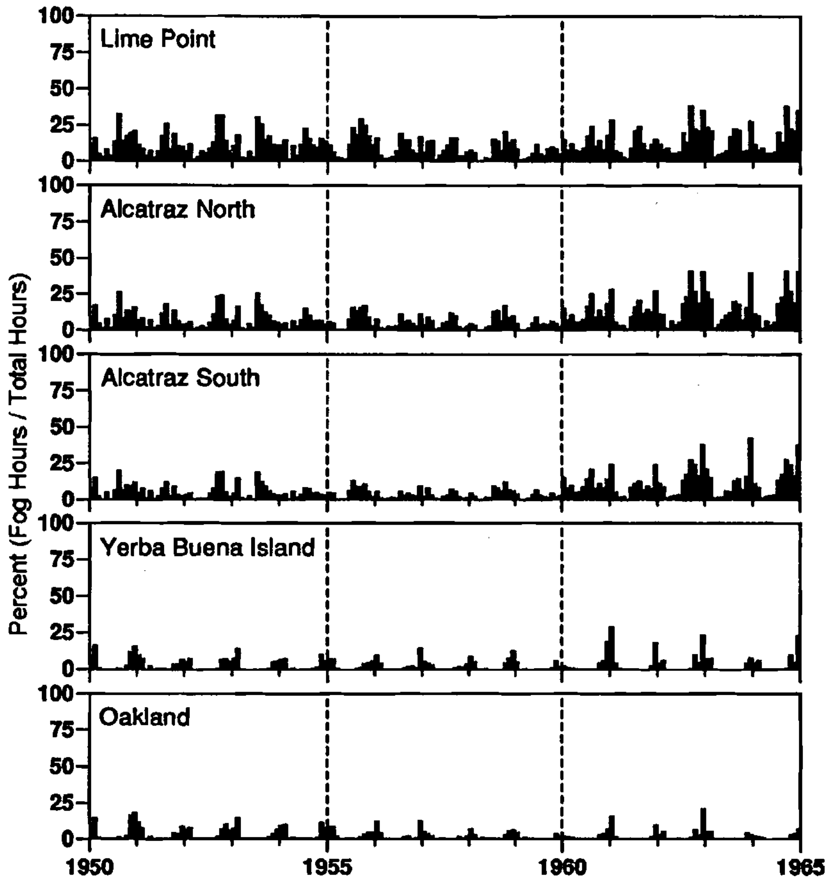


Figure D.3a

Monthly Hours of Foghorn Operation (1950-1964)
Mile Rock to Point Sur

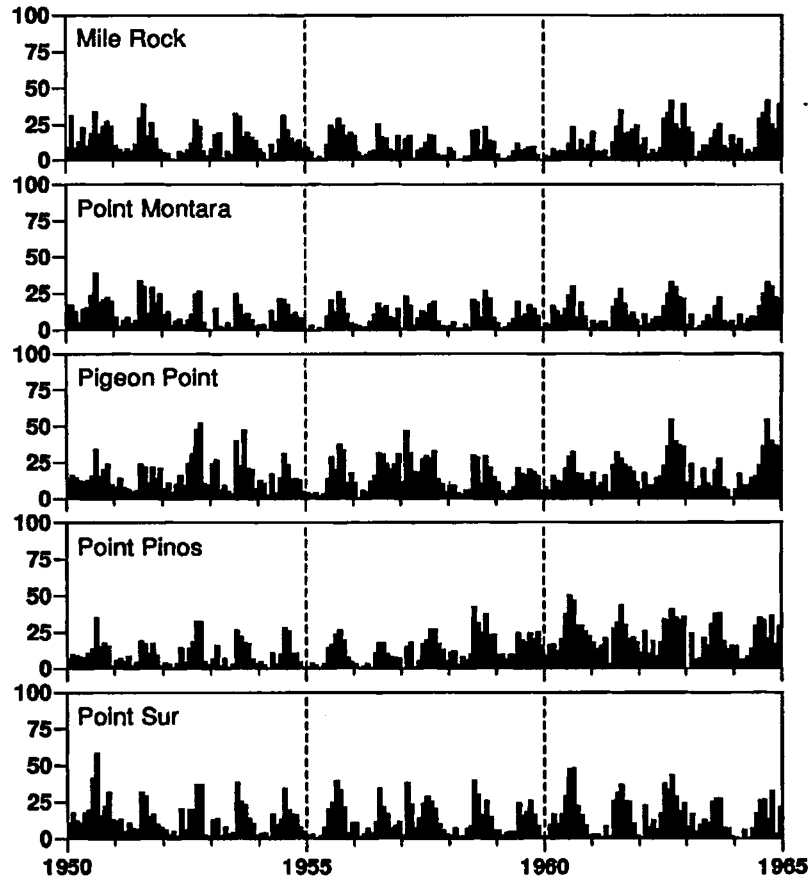


Figure D.3b

Monthly Hours of Foghorn Operation (1950-1964)
Point Piedras Blancas to Point Conception

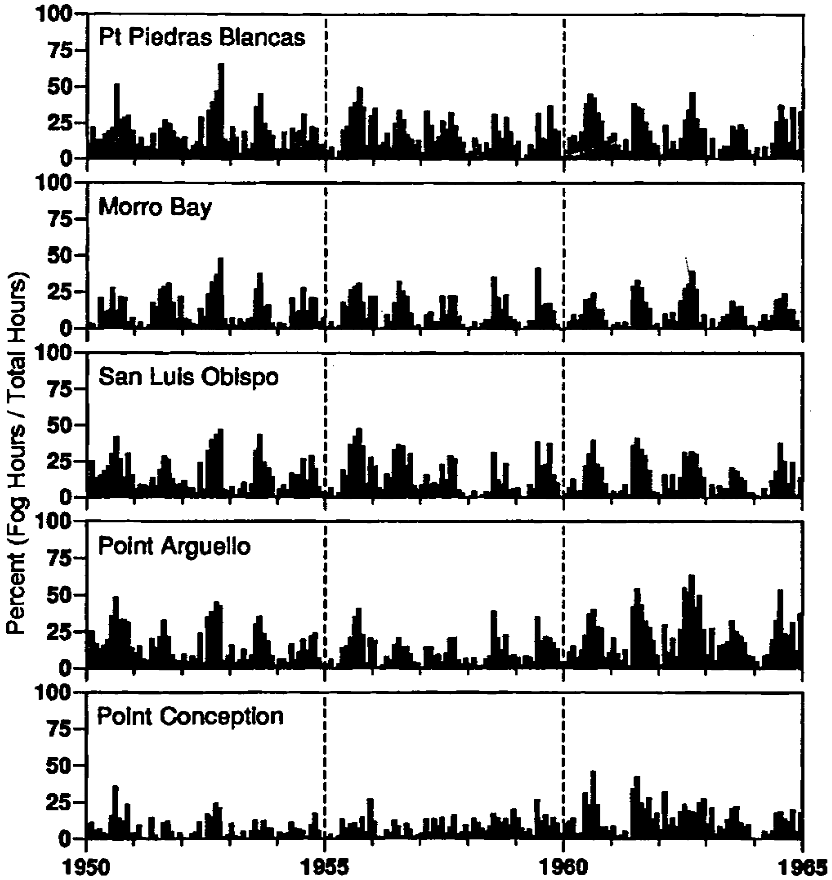


Figure D.4a

Monthly Hours of Foghorn Operation (1950-1964)
Point Hueneme to Point Loma

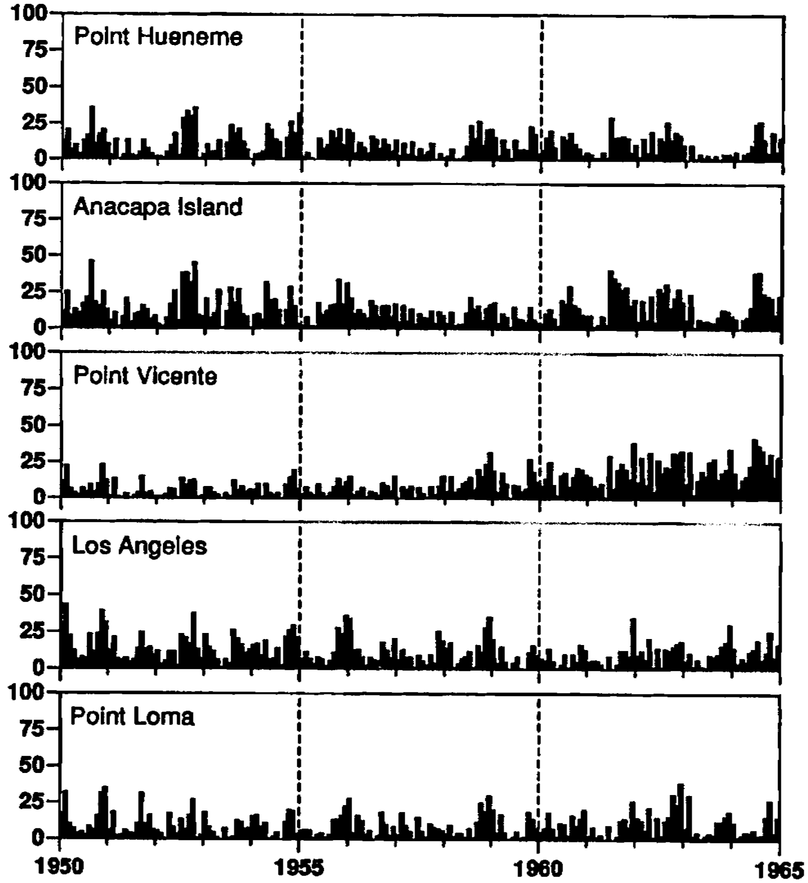


Figure D.4b

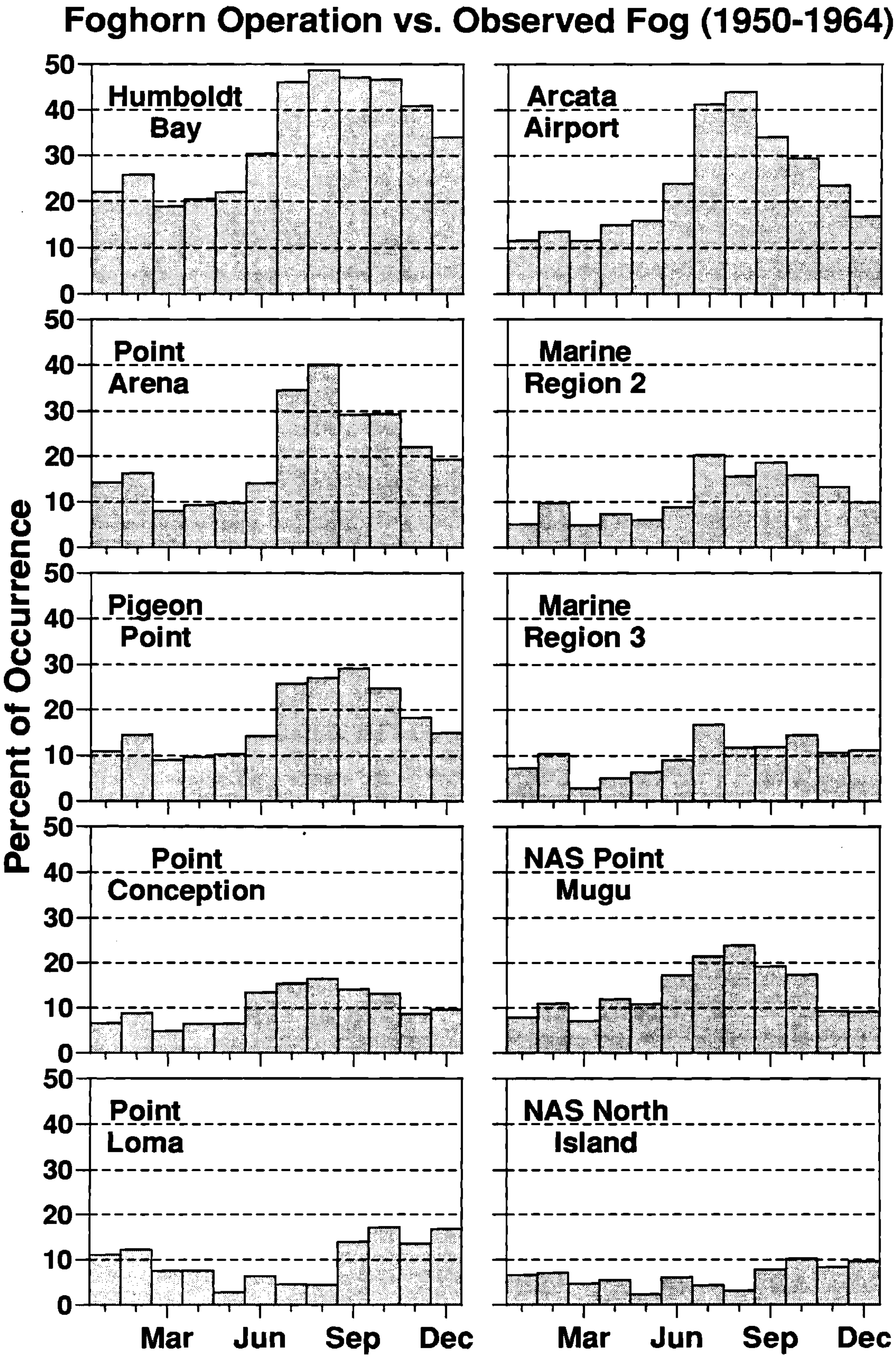
The climatology of several foghorn records along the California coast, from Humboldt Bay southward to Point Loma is plotted in Figure D.5 (left). For comparison, nearby records from the conventional data are also plotted in Fig D.5 (right). These plots show that the foghorn data are very consistent with the conventional data, with good agreement between the magnitude of the annual cycle and the timing of annual maxima and minima. The magnitude of fog occurrence is quite like the coastal airport fog occurrence and significantly less than that of the marine regions. But, as with the airport-marine regions, in comparing the time series of foghorn frequency with that of nearby fog frequency, there is a great degree of common variability. Note that the annual cycle at most stations is readily apparent; most of the coastal stations exhibit warm season maxima, while those inside San Francisco Bay (Figure D.7) contain a strong winter maximum.

Figure D.6 compares the time series of three light station foghorn records with the fog occurrence at nearby surface airways stations. Once again, the variability of the foghorn records is very similar to that of the airport weather observations, with a great deal of agreement in the monthly and interannual variability of foghorn frequency at nearby stations over the 15 year record.

Interestingly, the foghorn data reveal much more clearly the transition between the seasonality of fog in the coastal and landward locations of the San Francisco Bay (Figure D.7). Outside of the Bay, at Point Bonita and Mile Rocks, there is a pronounced summer maximum in fog; this is consistent with airways stations such as Arcata and Santa Barbara and with the various marine regions along the north and central coast (Regions 2 and 3). Traversing inside the Bay (Figure D.8), the seasonal maxima rapidly changes to a winter maxima and a summer minimum, as at Yerba Buena Island and Oakland; this is consistent with NAS Alameda and San Francisco. Also, for these inner locations, the overall frequency of fog is considerably lower than that along the outside, indicating how the coastal fog regime is rapidly overwhelmed by the coastal land environment. Interestingly, intermediate foghorn sites in between the coastal and landward extremes have a hybrid signal with vestiges of both the summer and winter maxima (Lime Point and the two Alcatraz Island records).

We are attempting to expand the foghorn records, but have encountered several problems. First, there are no manned light stations left in California. The light stations have all been unmanned since 1971-1972. They are controlled either by automatic strobe light visibility sensors, nearby installations whose primary responsibilities lie in other areas (e.g., some foghorns are controlled by harbor masters), or are run continuously if there are no people nearby (e.g., on the buoys that have replaced the light ships) (van Houten, 1995).

The U.S. Coast Guard (Pojar, 1995) has said that foghorn operation records for the periods before and after our existing records (pre-1950 and 1965-1972) should be in the light station log books. The National Archives (Suitland, MD) has some log books from the 1870s through the 1920s (around the time the National Lighthouse Service was transferred to the U.S. Coast Guard) and most of the log books from the 1920s to the mid-1950s. The log books from the mid-1950s to the end of the manned lighthouse era (ca. 1972) are still in the custody of the Coast Guard and are located in regional records centers.



Foghorn Operation vs. Observed Fog (1950-1964)
Percent of Occurrence
50
40
30
20
10
0
Humboldt Bay
Arcata Airport
Point Arena
Marine Region 2
Pigeon Point
Marine Region 3
Point Conception
NAS Point Mugu
Point Loma
NAS North Island
Mar
Jun
Sep
Dec

Figure D.5

Comparison of Monthly Hours of Foghorn Operation and Surface Airways Observed Fog (1950-1964)

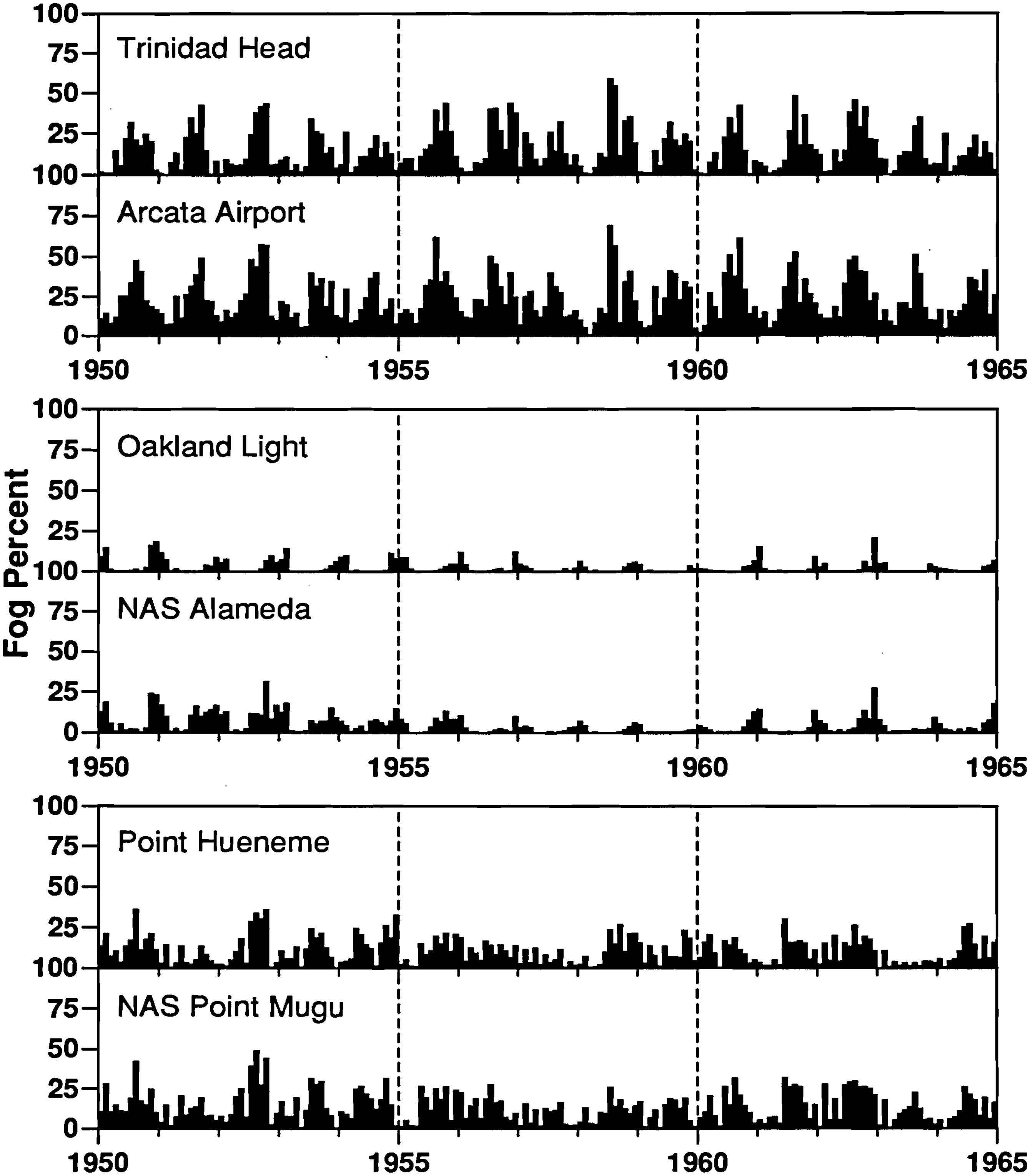


Figure D.6

Foghorn Operation in the San Francisco Bay Area (1950-1964)

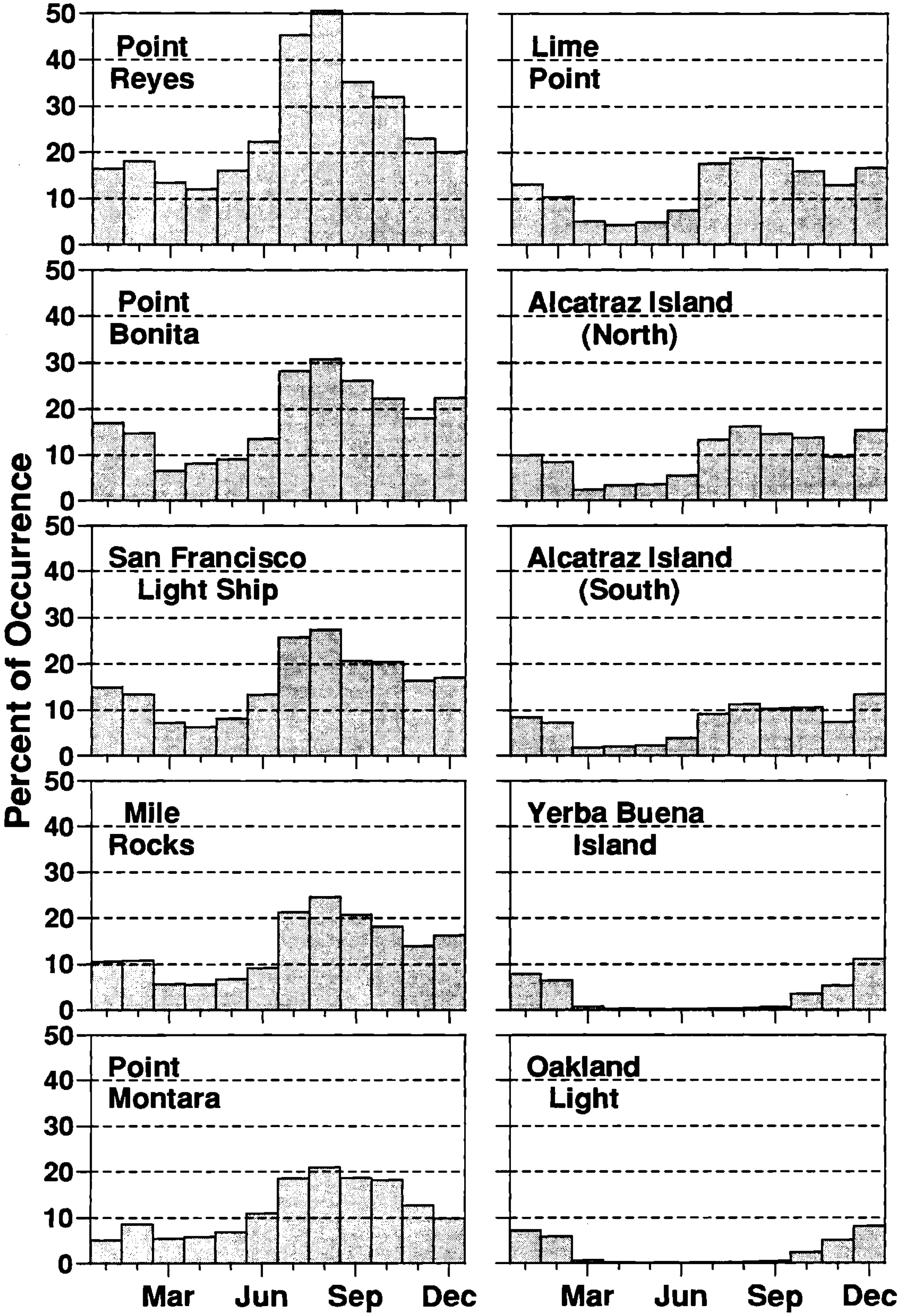
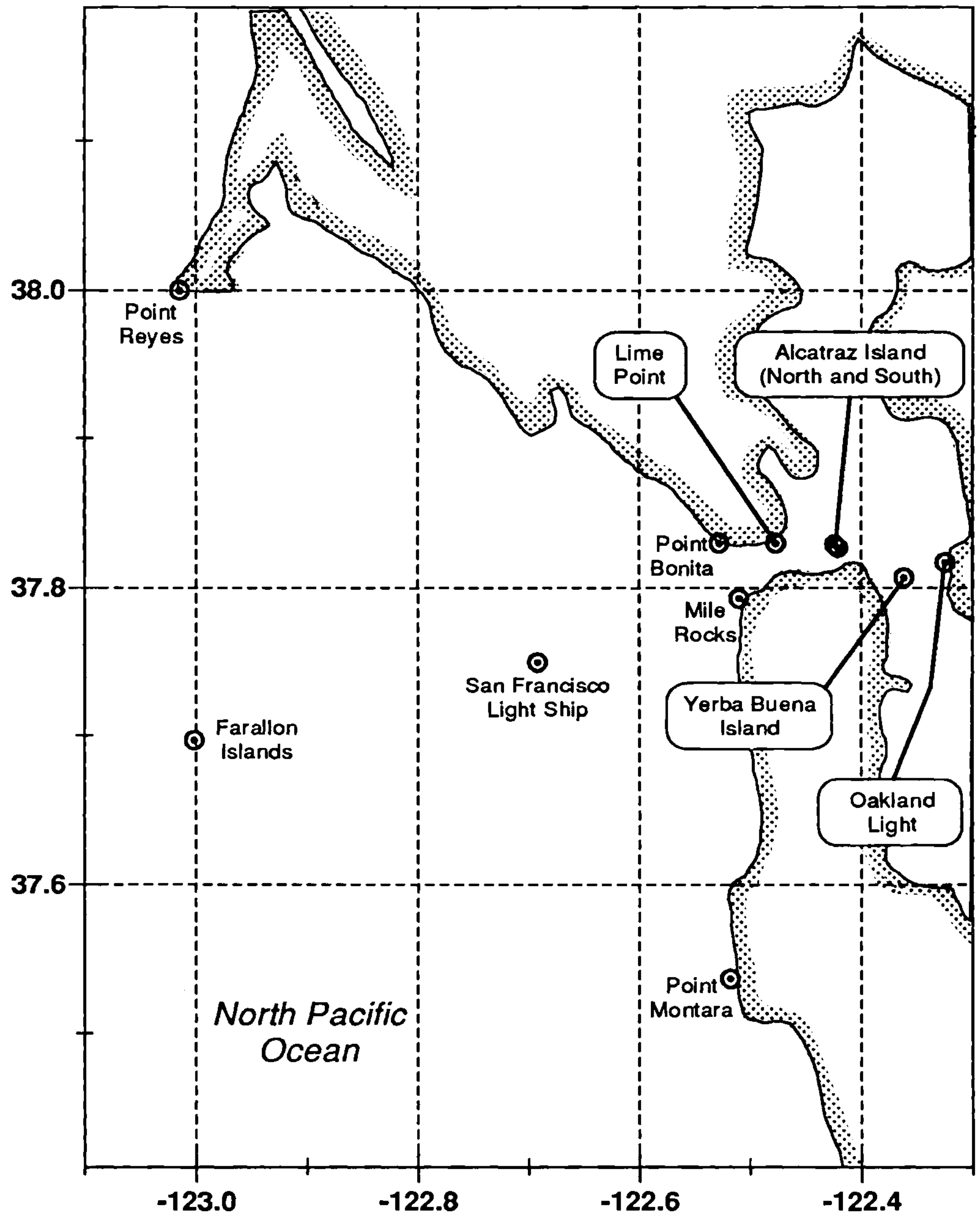


Figure D.7

Figure D.8 Foghorns in the San Francisco Bay Area



Mist Over La Jolla Cove, San Diego, California

This photograph illustrates normal visibility conditions when mist is present in the Southern California Bight region. Visibility, although greater than 1 *km*, is restricted operationally and such conditions fall into our "fog" category. Notice how it is difficult to distinguish details of the small fishing boats in the center of the photograph.

A brief episode of heavy fog (visibility < 200 *meters*) was observed in the cove and on shore about one hour prior to the time of the photograph (approximately 10:00 AM). Photograph by L.G. Riddle, September 19, 1992.