②

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

CLIMATOLOGY AND ANALYSIS OF THE MONTEREY BAY SEA BREEZE

by

Lt. Robert D. Round
September 1993

Thesis Advisor Prof. Carlyle H. Wash

Approved for public release; distribution is unlimited.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
September 93

3. REPORT TYPE AND DATES COVERED
Master's Thesis

4. TITLE AND SUBTITLE
CLIMATOLOGY AND ANALYSIS OF THE MONTEREY BAY SEA BREEZE

5. FUNDING NUMBERS

6. AUTHOR(S)
Robert D. Round, Lieutenant, USN

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93940

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for unlimited distribution

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Sea breeze events on the Monterey Bay are examined from a single station at the mouth of the Salinas Valley. Data analyzed are continuous, two-minute meteorological samples of windspeed, wind direction, temperature, dew point, incoming shortwave irradiance, and incoming longwave irradiance. A speed index is defined using the average hourly maximum and minimum windspeeds oriented in the cross-shore direction thereby reflecting the thermally induced diurnal windspeed enhancement. Large-scale effects on this mesoscale circulation are presented through evaluation of changes in boundary layer depth with changes in speed index. Changes in boundary layer depth as reflected in trends of inland stratus penetration and offshore flow provide insight for anticipating sea breeze intensity.

14. SUBJECT TERMS
Sea breeze, Marine Atmospheric Boundary Layer, Speed index, Stratus penetration, Mesoscale circulations

15. NUMBER OF PAGES 120

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
UL

Approved for public release; distribution is unlimited.

CLIMATOLOGY AND ANALYSIS OF THE MONTEREY BAY SEA BREEZE

by

Robert D. Round

Lieutenant, United States Navy
B.S., United States Naval Academy, 1986

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PHYSICAL OCEANOGRAPHY AND METEOROLOGY

from the

NAVAL POSTGRADUATE SCHOOL
September 1993

Author: ______________________________
Robert D. Round

Approved by: ______________________________
Carlyle H. Wash, Thesis Advisor

____
Wendell A. Nuss, Second Reader

____
Robert L. Haney, Chairman,
Department of Meteorology

ABSTRACT

Sea breeze events on the Monterey Bay are examined from a single station at the mouth of the Salinas Valley. Data analyzed are continuous, two-minute meteorological samples of windspeed, wind direction, temperature, dew point, incoming shortwave irradiance, and incoming longwave irradiance. A speed index is defined using the average hourly maximum and minimum windspeeds oriented in the cross-shore direction thereby reflecting the thermally induced diurnal windspeed enhancement. Large-scale effects on this mesoscale circulation are presented through evaluation of changes in boundary layer depth with changes in speed index. Boundary layer depth as reflected in trends of inland stratus penetration and offshore flow provide insight for anticipating changes in sea breeze intensity.

TABLE OF CONTENTS

I. INTRODUCTION

Surface sea breeze events have been widely studied by meteorologists and continue to receive much research attention. The ability to predict the sea breeze is of great interest since a large percentage of the global population is directly affected by its occurrence. As a result, man has learned to use aspects of the sea breeze to his advantage. Aviation and sailing have used the sea breeze to assist operations since their outset. The local weather influenced by and associated with the sea breeze may be responsible for sudden thunderstorm development, temperature and humidity changes and rapid changes in wind speed and direction.

Aviation in the coastal region is directly affected by sea breeze circulations. Wind strength and direction determines aircraft takeoff and landing configuration and direction. Ultimately, wind strength determines the practicability of all aircraft operations. Turbulence, especially in the vicinity of aircraft takeoff and landing, affects the safety and comfort of flight and is normally invisible to the crew unless detectable visually by cloud or haze signature. A variety of local weather conditions (temperature, humidity, wind strength, etc.) contribute positively or negatively to the amount of power and lift necessary to achieve flight. Obviously, there is a need to understand and predict the onset and strength of the sea breeze and the likely strength should it occur.

This thesis examines sea breeze events along the California central coast and the Monterey Bay. Rapidly changing, small-scale events such as the sea breeze require a high sampling rate to determine the changes occurring over the span of a few minutes within the local environment. The higher temporal resolution offered from a single continuous sampling site allows a complete analysis and description of the local sea breeze circulation in terms of time of onset, maximum wind speed and direction, and sea breeze intensity, among others. Other quantitative sea breeze attributes which describe the initiation, development and strength of the sea breeze are proposed. Attributes are chosen to provide a general, common framework from which to analyze sea breeze behavior regardless of location and remain adaptable to additional stations.

The number of these continuous surface observation sites is growing rapidly with the implementation of the National Weather Service Automated Surface Observing Systems (ASOS) and similar DOD systems.

Chapter II of this thesis provides an in-depth background covering thermally induced circulations and a lengthy description of the sea breeze phenomenon. Readers already familiar with this subject may want to proceed directly to Chapter III which presents a description of the data and descriptors used throughout the remaining portions of this work. Chapter IV begins the analysis of data and a general description of the sea breeze event as it occurs in the Monterey Bay. Chapter V presents two case studies demonstrating the temporal relationship between changes in boundary layer depth with changes in sea breeze intensity. Chapter VI summarizes conclusions gleaned from the analysis and presents recommendations for further study.

II. BACKGROUND

In studying the sea breeze it is convenient to first examine the general characteristics of the broader study of thermally induced circulations. Weather conditions favorable for the sea breeze and its initiation are then discussed, which is followed by a general list of sea breeze characteristics. Emphasis is placed on the large-scale topographic and meteorological influences on the sea breeze as a local feature of the synoptic weather pattern.

A. THERMALLY INDUCED CIRCULATIONS

Mesoscale atmospheric phenomena are commonly investigated in terms of thermally induced circulations. Three such systems have received extensive coverage in the literature. Moving from the smallest scale to the largest, these are: non-classical mesoscale circulations, land and sea breezes and upslope (up-valley)/ downslope (down-valley) winds. Briefly, non-classical mesoscale circulations (NCMCs) arise from spatial differences in surface sensible heat flux caused by spatial changes in surface heat capacity, absorption/reflection of solar irradiance and surface evapotranspiration. Land and sea breezes are the most observed and investigated mesoscale circulation. A differential heat flux between the sea and adjacent coast induce surface winds which flow from sea to land by day (sea breeze) and from land to sea at night (land breeze). Slope induced winds depend on local topography for the scale of circulation which arises from air flowing upslope during the day in response to surface heating and dense air travelling downslope at night.

B. FEATURES OF THERMALLY INDUCED CIRCULATIONS

Thermally induced circulations demonstrate a great dependence on both small-scale (local) environmental conditions as well as large-scale (synoptic) features. Segal & Arrit (1992) present some of the features that contribute to the formation and intensity of these circulations. **Insolation** is the single greatest factor which determines the forcing of thermally induced circulations. The absorption or reflection of incoming solar radiation (insolation) directly determines the amount of energy the surface receives which may then be radiated back to the overlying atmosphere. Both reflection and absorption depend on the surface reflectivity (albedo). Aside from surface characteristics, Skupniewicz, et al. (1991) and Segal, et al. (1986) discuss the effects of cloud cover on thermally induced circulations. Clouds reflect insolation reducing the amount of shortwave radiation available for surface heating. The loss of shortwave radiation is greater than the gain of longwave radiation causing a net loss of energy at the surface so that the cloud-covered surface is cooler than it would be otherwise.

The dependence of thermally induced circulations on surface thermal characteristics (Segal and Arrit, 1992) indicates that the **heat capacity** of the surface has an effect on the extent and intensity of circulation (Fig. 1). The figure illustrates the increase in sensible heat flux and air temperature with increasingly clear skies. Of considerable importance is that maximum heat flux occurs at midday while air temperature response is delayed four to five hours. Surface characteristics also include properties of the surface which regulate surface sensible heat flux such as soil moisture, snow cover, ice and sand.

Large-scale winds over the domain of a thermally induced mesoscale circulation often govern circulation development even more than direct forcing terms. Studies (Estoque, 1962 & Arrit, 1993) have shown that the direction of the ambient wind and its magnitude directly affect whether such a circulation will form and its ultimate intensity. Generally, two considerations concerning the ambient wind and the thermally induced circulation must be addressed: 1) does the ambient wind flow in the same sense as the thermally induced circulation or 2) do the flows oppose each other? Perhaps counter-intuitively, the most favorable synoptic conditions for thermally induced circulations occur when the ambient wind is light in magnitude and opposite in direction to the induced circulation. The opposing flow aids in the concentration of the temperature (and pressure) gradient while flow in the same sense as the circulation tends to disperse or weaken the temperature gradient reducing the thermally induced flow.

Surface friction plays a large role in these circulations as shown by Pielke (1974), Banta et al. (1992) and Haurwitz (1947). Friction affects the direction of flow in turning the flow toward lower pressure and the initiation of flow by imposing a minimum threshold temperature gradient needed to start the circulation.

Provided the time a parcel remains in the circulation is long enough, the **Coriolis** effect acts to turn the flow to the right, or veer, in the Northern Hemisphere. Time is the key factor since the Coriolis effect is not instantaneous as is the pressure gradient force. A closed cell circulation increases the ability of the Coriolis force to act on a parcel by increasing the time it has to take effect.

Surface evapotranspiration describes moisture evaporation from the surface or transpiration from vegetation stomata which contributes to the release of latent and sensible heat from the surface. Obviously then, the **moisture content of the soil** and the **type, maturity and coverage of vegetation** play a significant role in thermally induced circulations. Observations (Segal, et al., 1988) demonstrate that vegetative thermally induced circulations may approach the intensity of sea breeze circulations.

Formation of all thermally induced circulations follows a similar pattern with minor differences applicable to the specific mechanisms producing the differential surface sensible heat flux. The process begins with insolation heating the surface of the earth to varying degrees according to the albedo and heat capacity of the irradiated surfaces. Differential heating induces a differential surface heat flux which heats the overlying atmosphere accordingly. The air over the region with the greatest surface heat flux becomes warmer and lighter than its surroundings producing a temperature gradient between the surrounding relatively dense air. Temperature and density gradients induce pressure gradients through the equation of state. Two flows are thus started, upward motion over the region of greatest surface heat flux and horizontal motion from high pressure to low pressure.

C. SEA BREEZE CIRCULATION

The sea breeze circulation results from differential surface heat flux between land and water and is thus restricted to coastal areas where the spatial scale of each surface is large enough to produce a significant circulation. This requirement limits sea breeze circulations to large lakes, large islands and continental coastlines. The considerable difference in heat absorption between land and water governs the amount of surface heating which occurs and thereby the difference in surface heat flux. Solar heating of a land surface is limited to the top layer or skin of the earth's land surface (Wexler, 1946). The topmost layer of the sea is termed the "mixed layer" which maintains a roughly constant temperature throughout the day due to the large amount of mixing which occurs here. Segal and Arrit (1992) give typical values for the surface heat flux, H_s, for land ≈ 450 W/m^2, and for water, $H_s \leq 50$ W/m^2.

A typical sea breeze/land breeze circulation cycle is depicted in Fig. 2. The land breeze normally persists into mid-morning when radiative heating has increased temperatures over land enough to reverse the circulation induced by nocturnal radiative cooling. The sea breeze gains intensity with increased heating throughout the day reaching peak surface windspeeds by mid-afternoon corresponding to the peak in air temperature (Fig. 1). Decreased air temperatures then permit the circulation to decay to calm conditions during the evening prior to initiation of the land breeze.

D. WEATHER CONDITIONS DURING SEA BREEZE PRODUCTION

Various studies [Wexler, (1946), Fisher, (1960), Simpson, (1964)] point out local weather conditions favorable for the production of a sea breeze circulation. The two most obvious conditions are clear skies and light winds which allow sufficient surface heating and prevent the sea breeze from being overwhelmed by the ambient flow. Still, Wexler (1946) notes that sea breeze circulations form under various cloud conditions according to the following percentages:

Scattered clouds (0 - 5 tenths coverage) = 90 %
Broken clouds (6 - 8 tenths) = 39 %
Overcast (9 - 10 tenths) = 27 %

Observational studies [Simpson, et al., (1977), Wexler, (1946)] indicate that sea breeze circulations occur most commonly during summer months with the greatest frequency during June.

E. THERMALLY DIRECT CIRCULATION (BJERKNES' THEOREM)

Standard treatment of the sea breeze uses Bjerknes' circulation theorem which describes a closed loop circulation centered about the coast. Haurwitz (1947) and Pielke (1974) describe the convergence zone created by atmospheric heating over land. Low pressure forms over land in response to inland heating resulting in horizontally convergent surface flow from sea to land. Horizontal surface convergence assists the upward motion started by surface heating of the atmosphere creating vertical convergence aloft. Again by continuity, upward mass transport is released aloft through upper level divergence (upper level high).

Relatively high pressure at the surface over the sea means there is a mass transport (surface flow) toward land leaving an area of horizontal divergence. Invoking continuity for the surface flow, this horizontal divergence is balanced by downward motion and vertical convergence. Loss of mass at the surface of the column of air over the water is compensated by vertical divergence and horizontal convergence aloft (upper level low).

The circulation "loop" is closed as required by Bjerknes theorem through upper return flow from the upper level high over land to the upper level low over water. Consequently, mass is conserved in the sea breeze circulation. A closed loop system implies that air parcels are trapped in the "loop" and recirculated through the system (Anthes, 1978). In reality, the system is not closed. Wexler (1946) points out that new air is continually introduced into the circulation.

F. CHARACTERISTICS OF THE SEA BREEZE CIRCULATION

Average values and ranges for various features considered characteristic of the sea breeze circulation are presented next to provide a sense of the intensity and scale of the phenomenon. North Pacific ocean west coast values are given in italics.

- Temperature gradient (∇T): Inland heating produces a thermal low pressure system. Johnson and O'Brien (1973) indicate that a mean temperature difference of 1 °C between land and sea is sufficient to produce a sea breeze circulation. The magnitude of ∇T drives the intensity of sea breeze surface flow (Simpson, et al., 1977). Again, Johnson and O'Brien find the maximum magnitude of the temperature gradient as *5°C/20 km*.

- Surface wind velocity: Various observations of surface wind velocity yield the following mean and maximum values;

  max: 3.8 m/s (Simpson, 1977) to ≈ 14 m/s (Fisher, 1960)
  mean: 2.2 m/s (Wexler, 1946 & Hsu, 1970)

- Depth of onshore flow:

max: 200 m (Wexler, 1946) to 2 km (Johnson & O'Brien, 1973)
mean: 330 m (Simpson, et al., 1977) to 1 km (Anthes, 1978)

Note that according to Wexler (1946) an increase in depth results in an increase in surface wind velocity and relative humidity and accompanying decrease in temperature.

- Penetration inland: Observations of sea breeze penetration inland are greatly dependant on local topography. As a consequence, observations of sea breeze penetration reveal extreme values; 5 km (Neumann & Mahrer, 1974) to 200 km (Simpson, et al., 1977) which are generally due to latitudinal variation.

- Seaward extent: Limited observations are available for this figure due to the lack of observation platforms at sea. Wexler (1946) quotes seaward extent of the sea breeze circulation along the California coast as approximately 60 mi. Fett and Tag (1984) examined the balance between large-scale offshore synoptic winds in balance with the pressure gradient produced by the sea breeze. The effect here is to create a surface calm due to zero wind stress caused by opposing winds between the coast to distances greater than 150 km offshore. This effect is detectable by satellite imagery in the form of sun glint and reflects the location and extent in the cross-coastal direction. Note that such a situation is an example of offshore ambient winds preventing the sea breeze circulation from reaching the coast.

- Return flow:

  max speed: < 1.4 m/s (Pearce, 1955) to ≈ 5 m/s (Hsu, 1970)
  mean speed: ≈ 2.7 m/s (Hsu, 1970)
  depth: ≈ 2 km (Hsu, 1970) to 4 km (Anthes, 1978)

- Time of onset: Hsu (1970) notes that the sea breeze starts earlier near the coast than farther inland or seaward. Wexler (1946) provides a range for sea breeze onset from 0700 (local) to 1900 (local) depending on ambient conditions. Sea breeze onset is later for stronger offshore gradient winds.

- Duration of circulation: The duration of the sea breeze is limited by the time at which the temperature difference produces a pressure gradient strong enough to overcome friction and the prevailing winds until the time at which the temperature gradient falls below this threshold value [Haurwitz, (1947), Biggs & Graves, (1962)].

- Sea breeze passage: A review of assorted studies [Banta, et al., (1992), Estoque, (1955), Hsu, (1970), Simpson, (1964 & 1967) Wallington, (1965), Wexler, (1946) and Yetter, (1990)] reveals the common characteristics of sea breeze passage: sharp temperature drop, wind shift, wind speed increase and a rise in relative humidity. Additional features that may mark the passage are a sudden pressure rise or discontinuity in pressure fall (Wexler, 1946), the presence of a line of haze marking the boundary between land and sea air (Simpson, 1964 & 1967) or a rise in dewpoint temperature (Simpson, 1964).

- Rate of advance: The speed of advance is related to the density difference across the sea breeze front (Simpson, et al., 1977)

max: 2.2 m/s (Wexler, 1946) to 7 m/s (Simpson, et al., 1977)
mean: 2 m/s to 4 m/s (Simpson, et al., 1977)

G. GRADUAL DEVELOPMENT VERSUS FRONTAL SEA BREEZE

Two types of sea breeze circulations form in response to different gradient wind conditions. Wexler (1946) distinguishes between two distinct types of sea breeze, gradual development and frontal, regardless of the temperature gradient. This is a direct assessment of the significance of the prevailing winds on sea breeze formation. The gradual development type forms with either the pressure gradient oriented parallel to the coast with resultant alongshore winds or with ∇p perpendicular to the coast and light, onshore winds. In either case, the sea breeze forms as a small circulation in the immediate vicinity of the coast (Hsu, 1970). The frontal type circulation develops when the pressure gradient is oriented perpendicular to the coast with offshore winds and is distinguishable by definite frontal characteristics. The gradual development type displays a more subtle onset of onshore flow while the change is abruptly noted in the wind and temperature difference for the case of the frontal sea breeze. A number of other substantial differences between the two circulations merit note.

The gradual development type sea breeze is a classical thermally driven mesoscale circulation between land and sea. Circulation begins in "the immediate vicinity of the shoreline" (Wexler, 1946) then spreads both landward and seaward, increasing in vertical extent. Upward motion and onshore flow result from heating of the air directly over the land surface. This circulation follows Bjerknes' Theorem for horizontal convergence/divergence compensated through continuity by vertical divergence/convergence.

The frontal type sea breeze circulation is produced by a combination of offshore advection effects and thermal contrast. Offshore advection "piles up" cold air over water producing an offsetting pressure gradient which balances the ambient wind. Instability resulting from continued heating over land allows the pressure gradient over water to overcome the prevailing winds. Once the circulation is established, thermal contrast reinforces the sea breeze. As implied above, the frontal type sea breeze forms over water. Once equilibrium between the ambient flow and high pressure over water is destroyed, the frontal sea breeze advances inland. The frontal circulation "loop" differs from the gradual development type in its production of upward motion and return flow. In this case, both are the result of frictional drag from advected warm, land air overriding the piled up cold, marine airmass. Flow is initiated in the cold airmass from the induced vertical motion between offshore advection overriding the cold marine airmass and sustained by the thermally induced pressure gradient and associated rising motion toward the inland convergence zone. Downward motion over the water is a consequence of continuity resulting from horizontal divergence caused by the evacuation of cold air toward land.

H. LOCAL EFFECTS ON THE SEA BREEZE CIRCULATION

Two distinctly different regions influence the sea breeze circulation unlike other thermally induced circulations. These are the local sea surface and the adjacent local land surface. Each of these environments imposes its own particular traits upon the circulation which affect sea breeze formation and development. The emphasis on the local environment is important since the sea breeze may change drastically along different portions of the same coastline.

Land terrain features bordering the shoreline affect the sea breeze in the same manner as any other thermally induced circulation. As discussed above, the "engine" of any thermally induced circulation is differential surface heat flux. Obviously, then, any environmental feature which produces a change in surface heat flux affects the thermally induced circulation (Segal & Arrit, 1992). These features include differences in albedo and surface heat capacity due to differences in soil type, moisture content and vegetative cover which govern the absorption and reflection of insolation and ultimately determine the amounts of latent and sensible heat released to the atmosphere. Of particular interest is the variable effect vegetation has on surface heat flux throughout the stages of the growing season since the release of heat is a function of the maturity of plant life.

The peculiarities of coastal topography vary in its effects on the sea breeze circulation. Four topographical features readily alter the circulation; friction, coastal irregularities in shape, slope and barrier effects. Friction resulting from the flow of surface wind over land imposes a temperature gradient threshold on the initiation of sea breeze flow. Friction affects the wind vector by turning the wind across isobars from high pressure to low pressure and the magnitude by requiring the wind speed profile to increase with height (Wexler, 1946). The affect of friction may cause the sea breeze to appear aloft before it becomes evident at the surface (Wexler, 1946). Finally, Wallington's (1965) observation that sea breeze fronts tend to meander with gaps in their line structure implies a response of sea breeze front movement to surface friction.

Surface vegetation also contributes to the frictional effect. Wexler (1946) recognized that forests hinder the movement of the sea breeze inland. Pielke (1974) addresses the impact of differential roughness on the circulation in his three-dimensional model. The conclusion is that differential roughness has a negligible effect on the formation of the sea breeze convergence zone compared to the effect of differential heating. Differential roughness has an indirect impact on the magnitude of the convergence zone by augmenting the turbulent transfer of heat.

Coastal irregularities (the shape of the coastline relative to its water boundary) may either enhance or diminish the sea breeze circulation according to the concavity of the coast (Pielke, 1974). A coastline which is convex toward the sea augments sea breeze convergence and reduces land breeze convergence to sea. A coastline concave to sea reduces sea breeze convergence inland but augments land breeze convergence to sea.

Slope effects normally act to enhance the local land and sea breeze circulations since the shore naturally slopes upward from the sea to land. Daytime heating of slopes heats the atmosphere directly above causing air to rise. Temperature and pressure gradients between the warm air over the slope and the cooler air over the crest are thus established. The land breeze is aided by nocturnal cooling of the atmosphere over slopes which then sinks downslope having greater density than the surrounding warm air.

The final topographical effect of note has to do with the fact that topographic features limit the growth of mesoscale circulations simply by their presence. Elliot and O'Brien (1977) record the limiting effect of a coastal mountain range on inland penetration of the sea breeze. Gaps or valleys in coastal mountain ranges also tend to funnel sea breeze flow. This is especially important for the Monterey Bay area.

Sea water has an extremely high value of specific heat, $C_p \approx 1$ cal/gm*°C, which indicates its ability to absorb tremendous amounts of heat. So the ocean surface mixed layer maintains a roughly uniform temperature at the sea surface, regardless of time of day, due to turbulent mixing. The uniformity of SST is essential to the formation of the temperature differential which propels the sea breeze circulation. The sea surface has the additional property of providing very little resistance to the overriding flow of air. This aids in the establishment of surface convergence inland during the sea breeze and surface divergence over water during the land breeze.

I. LARGE-SCALE EFFECTS ON THE SEA BREEZE

The synoptic pressure pattern determines the orientation of the ambient flow at any given time which impacts the development of the local sea breeze circulation. According to Wexler (1946), the orientation of the synoptic pressure gradient parallel to the coast makes sea breeze initiation unlikely since the pressure gradient induced by differential heating only enhances or diminishes the existing pressure gradient. This claim is refuted by studies such as Johnson & O'Brien's (1973) study of the U.S. Pacific west coast sea breeze which includes synoptic pressure gradients parallel to the coast and sea breeze formation. The unanimous attribute of all sea breeze studies is that the pressure gradient, regardless of orientation, must only produce light surface winds to permit sea breeze formation. Wexler (1946) provides insight into the effect of surface heating on a pressure gradient oriented perpendicular to the coast; surface heating inland causes isobars to bend creating a "thermal low" which creates strong local pressure gradients.

The prevailing surface wind vector (magnitude and direction) is equally as important as the direction alone in its effect on sea breeze intensity and time of onset. The sea breeze develops as a small circulation in the vicinity of the coast once the land produces a surface heat flux greater than the water under calm gradient conditions. Simpson (1967), examining sea breeze events along the shore of southern England, found that with offshore gradient winds ≥ 10 kts (≈ 5 m/s) no sea breeze circulation is expected. Penetration of the sea breeze front inland is limited to ambient offshore conditions < 2 - 3 m/s (Simpson, et al., 1977). The front itself (Simpson, et al., 1977) is associated with an offshore pressure gradient of 1.5 mb/50 km (0.03 mb/km).

Recently, Arrit (1993) performed a controlled experiment using a two-dimensional sea breeze model investigating the effects of ambient winds ranging from 15 m/s onshore to 15 m/s offshore. Arrit asserts that even slight onshore flow is sufficient to suppress the thermally induced sea breeze and that offshore flow up to 11 m/s permits sea breeze formation. Again, the strongest sea breeze circulation forms with light offshore winds owing to the location of the sea breeze surface convergence zone below an area of neutrally stable or unstable air. As a result, limitations on vertical and horizontal motion are minimized. The strong stability associated with a subsidence inversion over water causes a weaker sea breeze when offshore winds keep the sea breeze convergence zone from reaching the shore. This is especially significant in demonstrating that a sea breeze circulation may exist offshore and remain undetectable at surface stations inland. Finally, very strong offshore prevailing winds prevent the necessary establishment of the temperature and pressure gradients which induce the sea breeze circulation.

The subsidence inversion associated with a high pressure system over the coastal region also restricts upward motion which lowers boundary layer depth (Skupniewicz, et al., 1991) and may effectively "cap" the depth of onshore flow of the sea breeze circulation (Johnson & O'Brien, 1973). Such a stable stratification may decrease the intensity of the circulation and depth of landward flow (Estoque, 1962). Observations (Johnson & O'Brien, 1973) indicate that the depth of the marine layer increases with the onset of the sea breeze.

The synoptic weather situation over the area of interest directly affects sea breeze formation and development by determining the amount of cloud coverage present. Cloud presence and advection, onshore and offshore, dramatically affect sea breeze circulation. Clouds over the coastal region prevent sufficient heating of the land surface to build a strong thermal gradient thereby preventing sea breeze flow. The work of Skupniewicz, et al.

(1991) and Segal, et al. (1986) demonstrate the effect cloud shading has on thermally induced circulations. In particular, with cloud advection > 6 km/hr (≈ 1.7 m/s), the advection of clouds onshore causes the sea breeze circulation to decay as cloud shading "overruns" the surface baroclinic zone (Segal, et al., 1986).

The length of time an air parcel remains in the sea breeze circulation determines the effect Coriolis force has on the parcel. The recirculation of closed loop circulations increases the time Coriolis force has to act upon a parcel causing the parcel to veer. Hsu (1970) documents a continuous veering of surface winds throughout day and night which implies a land and sea breeze circulation which turns through 360 degrees during the diurnal variation of surface sensible heat flux. The effect is not always this extreme as noted by Anthes (1978) who claims Coriolis causes an alongshore displacement of the sea breeze or Fisher (1960) who notes that the Coriolis force may not impose actual veering of the wind but may reduce the amount of backing which occurs. It merits note that gradient wind and local influences may cause veering or backing which is not a result of Coriolis.

J. LARGE-SCALE "CONTINENT-OCEAN WIND"

The local sea breeze circulation across a continental coastline is embedded within a larger scale continent-ocean circulation which arises from the formation of a large-scale temperature gradient between the inland surface unaffected by coastal circulations and the general offshore sea surface temperature. This is a thermally induced circulation on a much larger scale than the mesoscale circulation discussed above.

- Johnson and O'Brien (1973) attach values to the temperature difference and gradient between the continental surface temperatures and SST;

range: 2 - 11 °C
mean: 7 °C
∇T: 7 °C/100 km

- Wexler (1946) assigns magnitudes for the speed of flow from the continent to the ocean (continent wind) and the flow from the ocean to the continent (ocean wind);

continent wind: 1 m/s
ocean wind: $\geq$ 1 m/s

- Wexler continues by noting the depth of flow not including the return aloft;

continent wind: 1300 m
ocean wind: ≥ 3 km

A return flow aloft closes the continent-ocean wind circulation, though values for the strength and depth of flow are unavailable.

K. PACIFIC WEST COAST FEATURES

Large-scale features affecting the development of the sea breeze along the west coast of the United States merits further discussion. The dominant synoptic feature characteristic of this area during the summer months is the North Pacific Ocean high pressure system which dominates over the ocean and adjacent coastal areas. This semi-permanent feature is responsible for almost daily coastal fog and low level stratus associated with large-scale subsidence inversions over relatively cold ocean surface water. This same feature determines the direction of the large-scale ambient wind which is generally either onshore or parallel to the coast, which produces "northerlies" owing to the anti-cyclonic (clockwise) flow associated with a high pressure center located offshore.

The consequences of this typical synoptic weather pattern indicate that the gradual development type sea breeze circulation is expected throughout the summer months along the Pacific West coast. As presented above, the sea breeze may be hard to distinguish from onshore ambient winds. Also, the low level stratus of the subsidence inversion will certainly play a significant role in sea breeze development. The exact impact of the low level stratus on the sea breeze will depend on the direction and speed of motion (if any) of the stratus deck.

Topographical effects of California cause a significant large-scale diurnal temperature difference between the central valley bounded by the coastal and Sierra Nevada mountain ranges and the cold ocean surface waters produced by coastal upwelling form a large-scale continent-ocean wind system. This effect is accentuated by the fact that relatively few gaps in the coastal range prevent cool, marine air from penetrating into the valley. Narrowing the scope to the Monterey Bay area, the concavity of the bay to the ocean should diminish the inland convergence of the sea breeze circulation if the circulation is oriented perpendicular to the central coastline of the bay. This effect may be reduced if the circulation follows a line which reduces this affect. A southerly orientation down the Salinas valley is such an example. The Salinas valley may also contribute to the circulation by the "funneling" effect discussed above.

Results from the CODE (Coastal Ocean Dynamics Experiment) data concerning the summer surface wind and current data along the U.S. Pacific west coast of 1981 and 1982 demonstrate the intense effect of the subsidence due to the Pacific anticyclone. The Pacific high is responsible for predominantly alongshore surface winds during the summer months. The local heating of the land surface creating the sea breeze effect is also responsible for a lowering of the marine inversion along the coast which creates an intense lower atmospheric, alongshore jet which varies diurnally (Beardsley, et al., 1987). The variation of the surface wind field in the alongshore direction is not rightly termed part of the sea breeze circulation due to its basic orientation. The clockwise turning of the wind, is also documented in the Beardsley study which is less separable from the sea breeze circulation than the predominant alongshore flow. Beardsley notes that the comparatively weak cross-coastal sea breeze circulation (compared to the alongshore flow) resulting from diurnal heating lowers the alongshore jet and moves it toward land. Lastly, Beardsley notes the strong coupling between the surface wind flow and the ocean surface. Rosenfeld (1988), in another CODE study examines the connection between the surface wind field and surface currents. The results compare favorably with those of Neal (1992) and demonstrate the diurnal variation and clockwise turning of both the wind and wind stress forced surface current field. The findings of the CODE study indicate one of the best descriptors of the sea breeze flow is the clockwise turning of an initially cross-coastal surface flow.

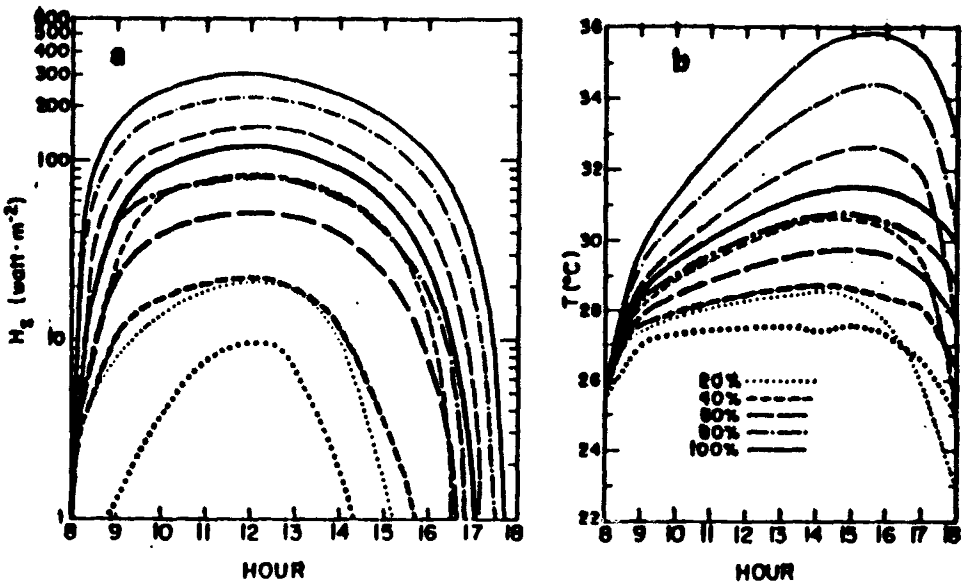
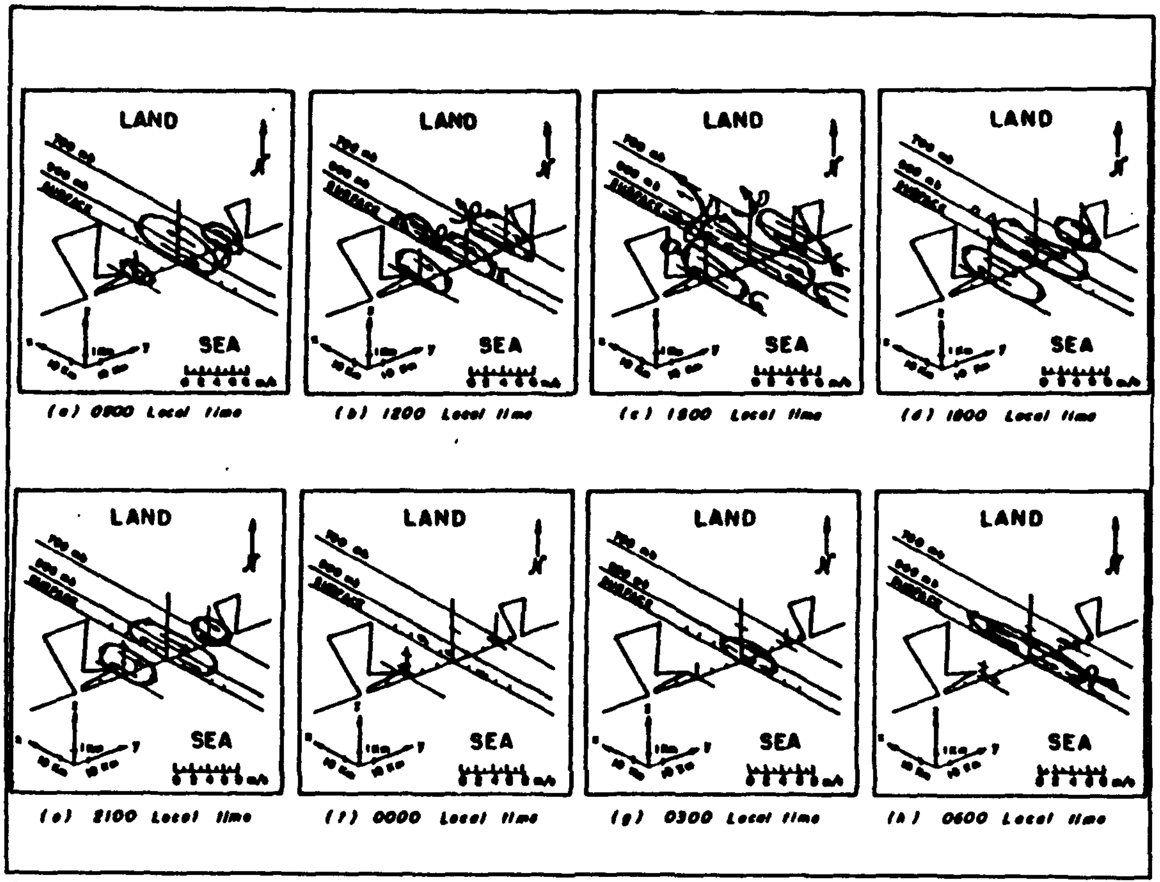


Figure 1. Temporal variation of (a) sensible heat flux and (b) air temperature at 2 m for fractions of clear sky solar radiation incoming to the surface. Thin curves indicate dry soil values, thick curves reflect wet soil values. (From Segal, et al., 1986).



(a) 0900 Local time (b) 1200 Local time (c) 1500 Local time (d) 1800 Local time

(e) 2100 Local time (f) 0000 Local time (g) 0300 Local time (h) 0600 Local time

Figure 2. Sea breeze circulation cycle. (From Hsu, 1970).

III. SEA BREEZE DATA AND DEFINITIONS

Continuous meteorological data for this study is obtained from a single station located at the airfield of the Fort Ord Army base (Fritsche Field) at the mouth of the Salinas valley near the Monterey Bay (Fig. 3), providing continuous two-minute meteorological surface data. Hourly windspeed running averages are calculated and evaluated for the maximum and minimum values during a local 24 hour period. The significant heating which occurs within the valley and the orographic funneling effect of the topography causes a preferred direction of the sea breeze up the Salinas Valley, at the location of the data sensor (Fig. 3). Directionality is incorporated into the running averages by computing the cross-shore component using the Salinas Valley orientation as the predominant sea breeze direction. Onshore directions are assigned positive values, offshore negative.

Data used in sea breeze analysis consisted of continuous records of daily two-minute averages of windspeed, wind direction, temperature, dew point temperature, incoming shortwave irradiance and incoming longwave irradiance (Fig. 4), for a 24 hour period. Daily records permit continuous analysis of changes in these parameters at a sampling rate consistent with mesoscale analysis. Thus, rapid, small-scale changes can be interpreted and analyzed as a response to changes in the local atmospheric environment.

A sea breeze speed index was developed to monitor daily sea breeze intensity and behavior. The sea breeze index is calculated from the maximum and minimum hourly averaged onshore windspeeds and is a measure of diurnal windspeed enhancement. The index is defined as the difference between the maximum daytime and minimum nighttime/early morning hourly averaged winds. Thus, the index resolves the diurnal change in the cross-shore wind component. As sea breeze activity is a major factor in diurnal wind changes, the index provides an estimate of daily sea breeze intensity. Fig. 4. illustrates the computation of the speed index. The index is derived from a 4.1 m/s average offshore early morning wind at 0652 PST changing to a 7.8 m/s average onshore wind centered about 1238 PST. The result is a speed index value of 11.9 m/s. Byproducts of the computation of this index are the daily maximum wind speed and the time this occurs.

Time of sea breeze onset is determined from daily station records of wind speed and direction, temperature, dew point, pressure, incoming shortwave radiation and incident longwave radiation. Quantitative onset criteria used in the manual determination of sea breeze onset followed the following prioritization: 1) Wind shift to the onshore direction, 2) wind speed increase ≥ 3 m/s in 30 min, 3) temperature drop > 1° C in 30 min and 4) a decrease in temperature - dew-point depression > 1° C. Fig. 4 provides an example of sea breeze onset at 1035 PST identifiable by the shift in surface winds in the onshore direction, increase in windspeed, drop in temperature and rise in dew point. Though not subjective, the determination of sea breeze onset using the above criteria does not lend itself to easy automation.

Each day was evaluated manually for the type of sea breeze day. All days were placed into one of the following six categories: 1) no sea breeze, 2) gradual development sea breeze, 3) clear onset sea breeze, 4) frontal sea breeze 5) double surge sea breeze and 6) unclassifiable days. Sea breeze day determination closely followed the quantitative criteria for time of onset accompanied by manual judgement of conditions dominating prior to sea breeze onset.

Gradual development type sea breeze days includes all days in which a definite sea breeze occurred without a clear and definite time of onset. Clear onset type sea breeze days, as depicted in Fig. 4, are days in which either a definite wind shift without a significant speed increase occurred or onshore conditions prevailed prior to sea breeze onset which is revealed by a distinct increase in onshore wind speed. The frontal sea breeze is the case of wind shift accompanied by a definite increase in wind speed. The final sea breeze categorization termed a "double surge" type sea breeze includes all days in which two separate and distinct onshore events occurred. Days determined to have no sea breeze either fell below the sea breeze index threshold of 5 m/s or were subjectively analyzed to show no sea breeze through visual inspection of the station data. That is, these days lacked a definite wind shift, windspeed increase, drop in temperature or increase in dew point. Days for which no clear determination could be made for the existence and onset of the sea breeze are declared unclassifiable. In this case, the absence or existence of clear sea breeze characteristics could not be verified from the data. Unclassifiable days often include days for which subsequent manual reviews of daily data produced conflicting results with the previous analysis.

A "stratus index" quantifies the number of hours of stratus coverage at the sensor site. A minimum threshold denoting stratus coverage is determined from plots of downward infrared irradiance. The threshold is set at 380 W/m^2 which adequately eliminates insignificant or "thin" stratus. This threshold corresponds to a cloud base temperature of 13 °C. Stratus is obviously significant in controlling the amount of heating which occurs and also in the cloud edge contribution to the sea breeze effect as previously mentioned. The index assists in the analysis of the sea breeze index and time of onset.

The results of this data analysis are presented primarily in histograms to reveal frequency types of sea breeze behavior. Six categories are presented which characterize the type of sea breeze activity. The categories: time of maximum wind, time of sea breeze onset, speed index, sea breeze category, average maximum wind speed and stratus coverage, provide the daily description. Average maximum wind and the time associated with it incorporate the directionality of the wind. As a consequence, the strongest winds are the highest positive values for the day which indicates the strongest onshore averaged wind. The data are summarized both monthly and for a six month total of daily behavior, then sorted according to the above characteristics. The result is a series of plots covering 183 days revealing sea breeze behavior between April and September of 1992 which describes the sea breeze of the Monterey Bay at this station.

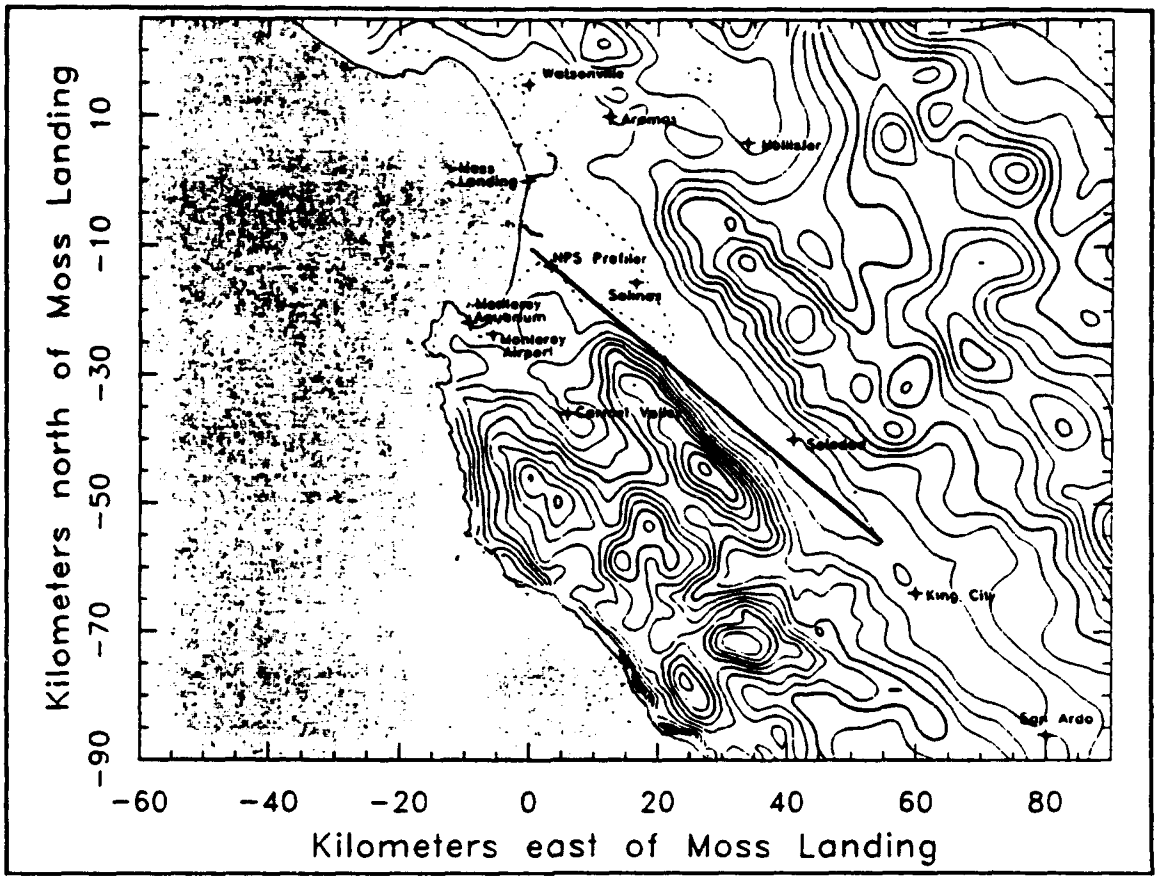


Figure 3. Topographical map of the Monterey Bay coastline and Salinas Valley. Heavy line indicates onshore orientation.

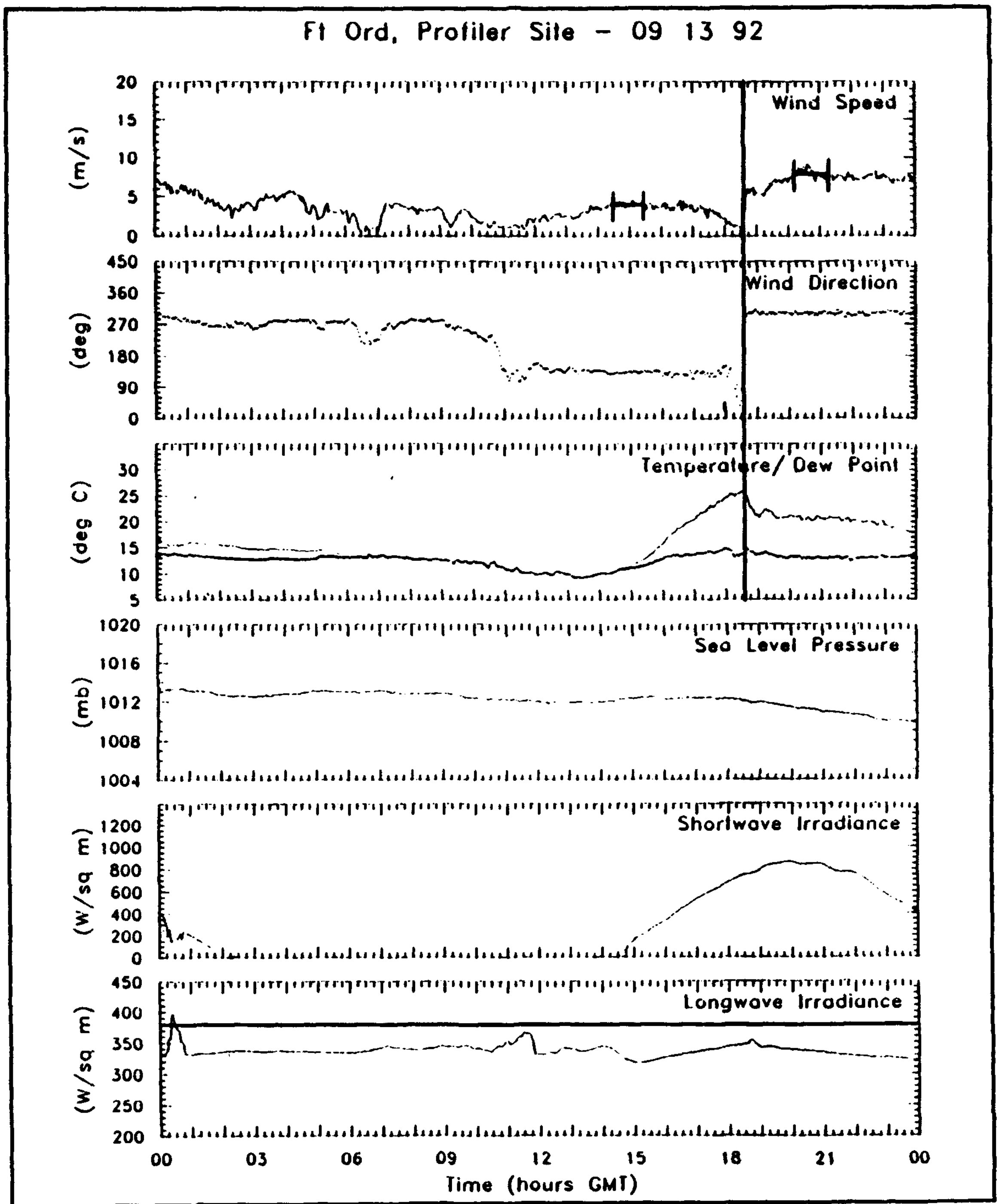


Figure 4. Surface meteorological data from the NPS profiler site. Heavy line in first panel indicates hourly averages derived for speed index calculation. Heavy line in final panel indicates stratus threshold. Heavy vertical line indicates sea breeze onset.

IV. DIURNAL WIND ENHANCEMENT CHARACTERISTICS

A. SIX-MONTH SUMMARY

Sea breeze behavior and characteristics during the six-month period ending September 30, 1992 are defined by the characteristics described in Chapter III. Results concerning time of maximum wind, time of onset, sea breeze category, average maximum windspeed, speed index and stratus coverage are presented.

The most common time of maximum wind (Fig. 5) occurs at 1330 PST. Average time of maximum wind occurrence, Table 1, for the entire period is 1400 PST. The dominant range of occurrence for this phenomenon covers the hours 1300 to 1600 PST. This range is skewed to the right indicating the dominance of later rather than earlier times. Maximum winds earlier than 1230 and later than 1630 PST are uncommon.

TABLE 1. MONTHLY SEA BREEZE AVERAGES FOR THE FORT ORD PROFILER SITE

1992 Month	MAX (PST)	ONSET (PST)	AVE (m/s)	SI (m/s)	Stratus (hours)
April	14.5	10.5	7	9	3.1
May	14.2	9.7	8	8	11.4
June	14.5	9.0	8	8	12.7
July	13.8	9.0	7	8	12.3
August	13.1	9.7	8	8	12.7
Sept.	13.7	9.9	7	9	9.3
Ave.	14.0	9.7	8	8	10.3

(MAX: Time of Maximum Wind, ONSET: Time of Onset, AVE: Average Maximum Windspeed, SI: Speed Index, Stratus: Stratus coverage)

The most likely time of sea breeze onset (Fig. 6) is between 0830 and 1100 PST with the most frequent time being 1000. The six-month average time, Table 1, is slightly earlier than the most frequent time at 0940 PST. This distribution is skewed earlier than 1000 PST. Onsets later than 1100 are uncommon.

Histograms of sea breeze category (Fig. 7) reveal that two categories dominate. The gradual development type sea breeze occurs 36 percent of the time while the frontal type breeze is the next most common at 29 percent. Together, they describe nearly 2/3 of the days studied. The clear onset is the third most frequent category at 16 percent and the double surge accounted for approximately 7 percent of the days. Thus, 88 percent of the days experienced sea breeze activity. No sea breeze and unclassifiable days account for the remaining days examined.

The most common average maximum windspeed is 8 m/s. The most likely range (Fig. 8) is 7-9 m/s, a narrow subset of the total range of 5 m/s to14 m/s. The six-month mean, Table 1, average maximum windspeed is also 8 m/s with the greatest value occurring in June. The distribution of maximum windspeed shows a roughly Gaussian distribution. The value of 8 m/s is in the middle of the 4 m/s to 14 m/s range described earlier.

Speed index is even more normally distributed (Fig. 9). The most frequent value of 8 m/s is the same as the six-month average, Table 1. The most likely range covers 7-10 m/s. Comparison of speed index with average maximum windspeed reveals that higher indices occur with offshore flow and therefore a greater windspeed enhancement.

Stratus coverage over the period (Fig. 10) shows that clear days have the greatest frequency of occurrence, 34 of 183 days, or

19 percent. Thus, clear days occur roughly every 1 in 5 days. The distribution of hours of stratus coverage from 1 to 24 hours are spread reasonably evenly over the entire period.

B. MONTHLY DATA

Monthly distributions are now presented to discuss seasonal changes in sea breeze behavior. Some month-to-month variability is present in the time of maximum wind histograms, Figs. 11-16. During spring and early summer, April through June, the average time occurs later than 1400 PST, Table 1, and the distribution is skewed toward earlier times of occurrence. The time of occurrence covers a broad range of hours during the period. Later in the summer through early fall, average time occurs earlier than 1400, Table 1. The distribution is skewed toward later times. These months, July to September, also illustrate a more distinct peak period of occurrence, between 1300 and 1400, than earlier months.

Time of sea breeze onset, Figs. 17-22, also show some monthly variation. Earliest onsets occur in June and July following earlier sunrises, while the onset occurs later in the spring and fall months.

The distributions are broad indicating considerable day-to-day variability within a given month.

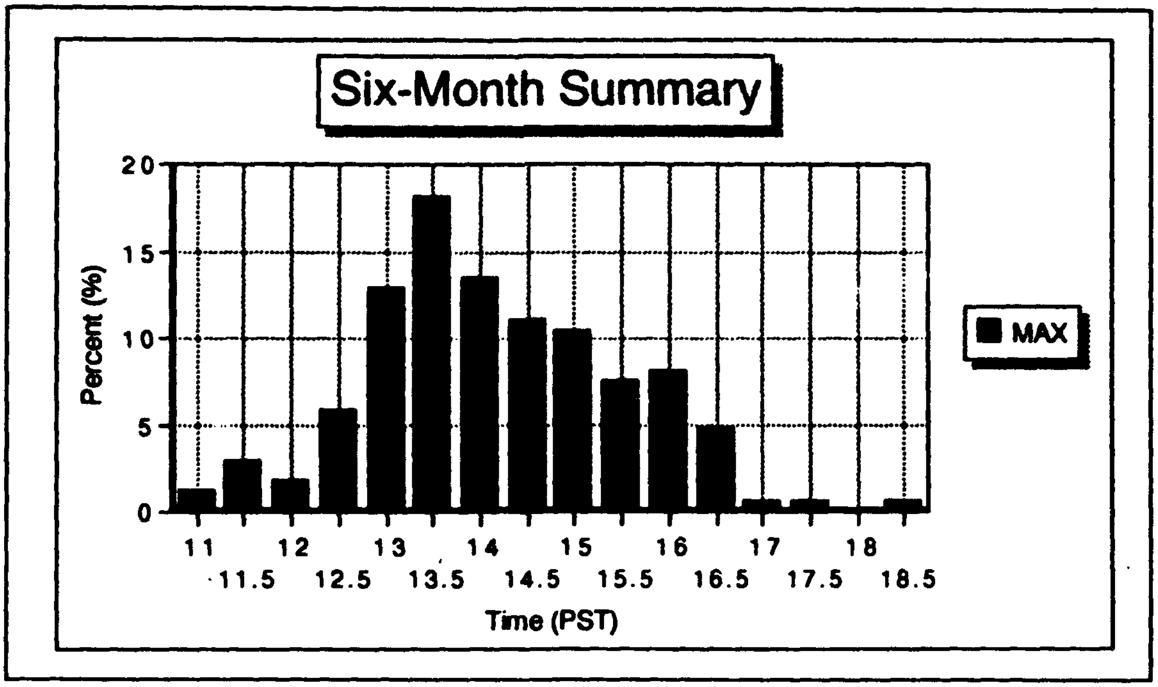


Figure 5. Six-month distribution of time of maximum wind (PST).

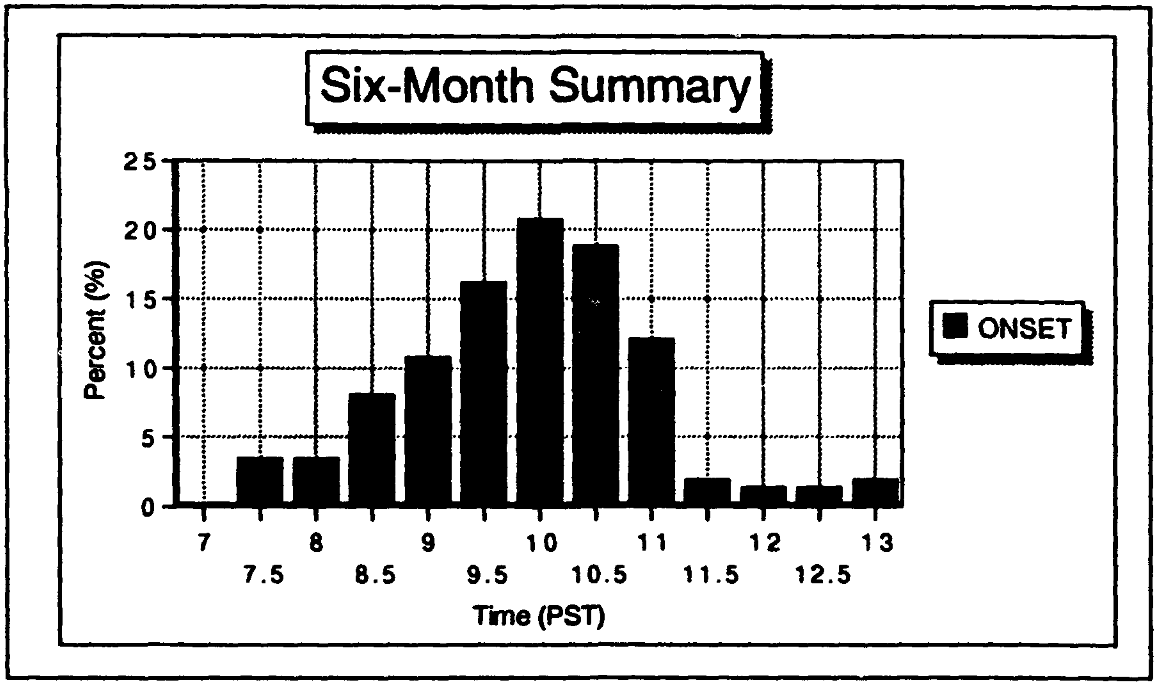


Figure 6. Six-month distribution of time of onset (PST).

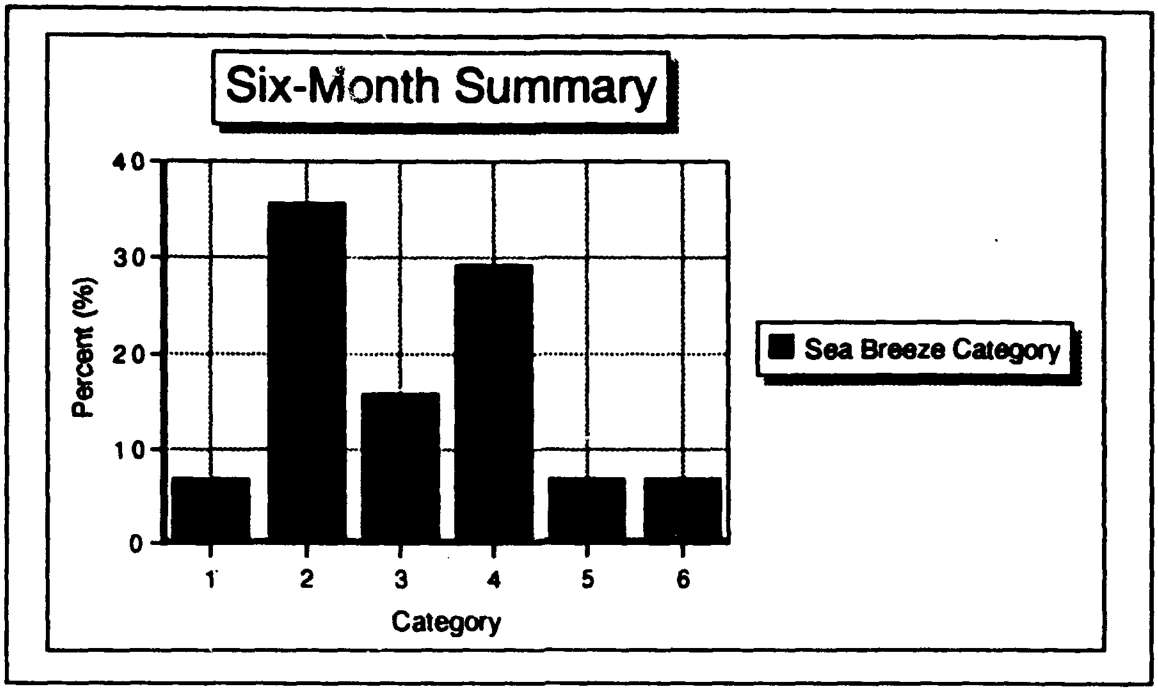


Figure 7. Six-month sea breeze category distribution. 1) No sea breeze, 2) gradual development, 3) clear onset, 4) frontal, 5) double surge sea breezes, 6) unclassified days.

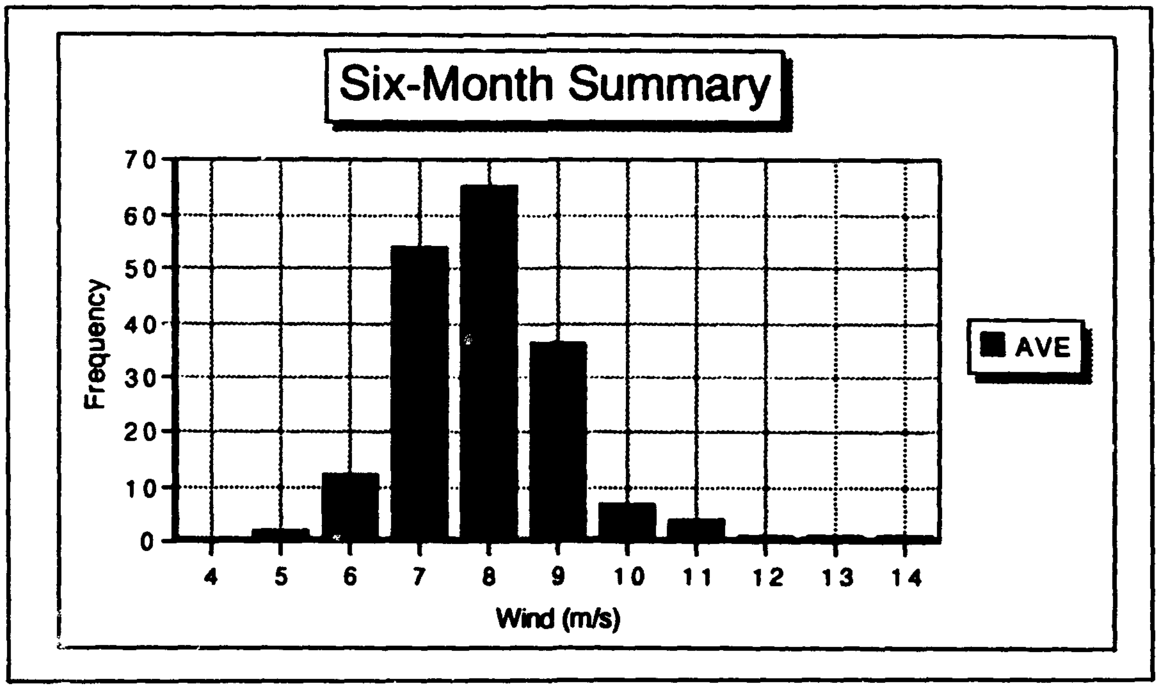


Figure 8. Six-month distribution of ave. max. windspeed.

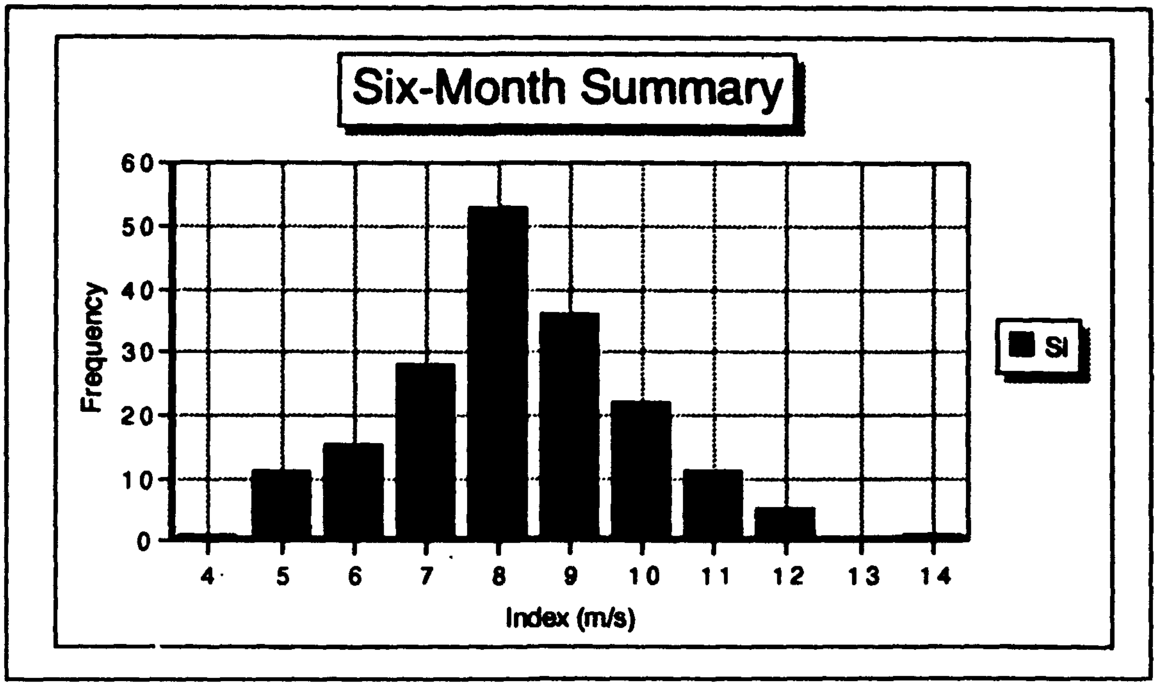


Figure 9. Six-month distribution of speed index.

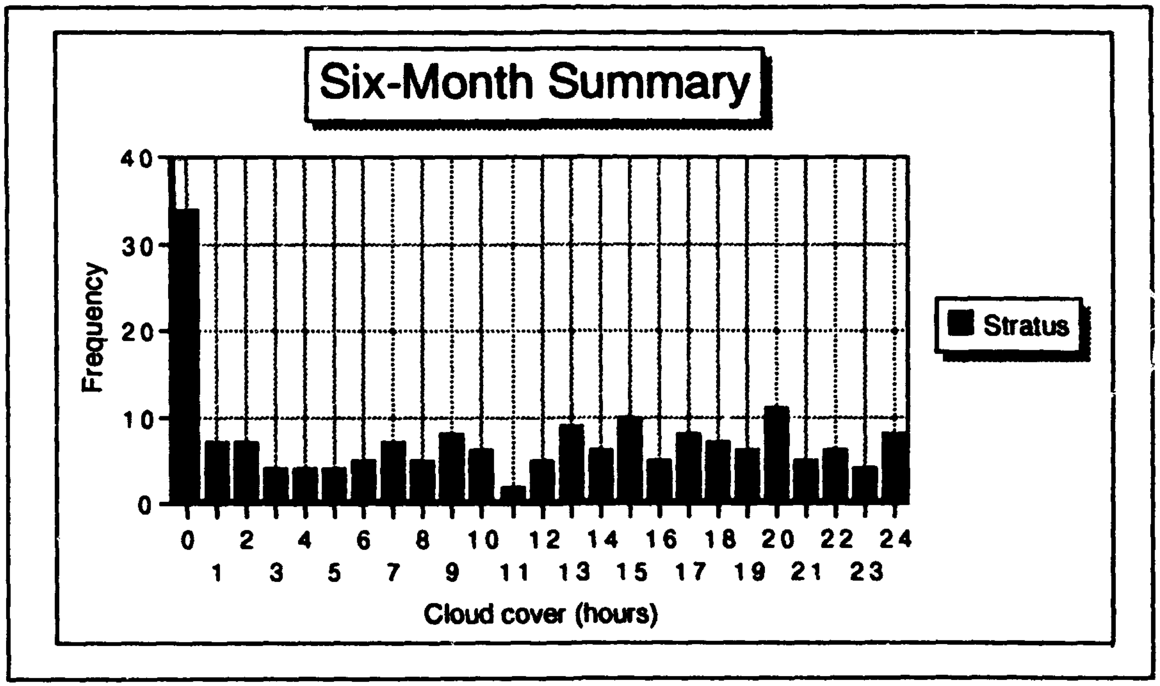


Figure 10. Six-month distribution of stratus coverage.

Monthly sea breeze categories, Figs. 23-28, demonstrate a seasonal preference in sea breeze type. The gradual development sea breeze (type 2) is most common in spring and early summer, April through July. The frontal sea breeze (type 4), which displays a wind shift and wind speed increase, is most common in April, August and September. This spring and fall maximum is likely due to a higher frequency of transiting weather systems giving periods of easterly, offshore winds.

Monthly histograms of average maximum windspeed show a peak value of 7 or 8 m/s, Figs. 29-34. Summer months exhibit a normal type distribution with the peak at 8 m/s. Cooler months, April and September, show a peak of 7 m/s. The range of maximum windspeed is quite narrow with most maxima falling between 7 and 9 m/s. High windspeed days (> 10 m/s) are confined to the spring months of April, May and June.

Speed index monthly plots also show considerable month-to-month variation, Figs. 35-40. Recall that speed index measures the diurnal windspeed enhancement in the cross-coast wind component so it incorporates the presence of night and early morning offshore winds. Speed index in most months shows a broader range of values compared to the maximum winds. The most frequent value is still either 7, 8 or 9 m/s. Minimum values are typically 4-5 m/s.

Monthly stratus coverage at the profiler site during the period indicates greater stratus coverage during the summer, Figs. 41-46, as expected. August, in particular, has a large number of days with greater than 12 hours of stratus. The average number of hours of coverage between May and August is greater than 11 hours, Table 1. Less cloud cover occurs during the spring with few days of more than a few hours of stratus. Both these results are consistent with the climatology of the region.

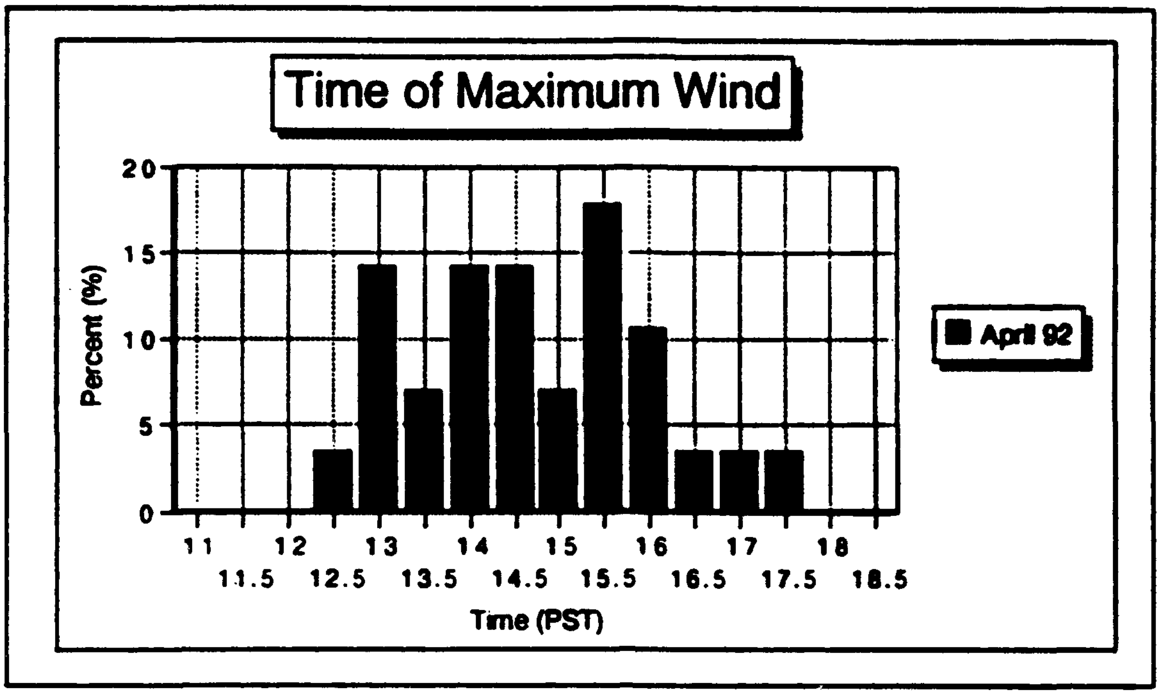


Figure 11. April 1992 distribution of time of maximum wind.

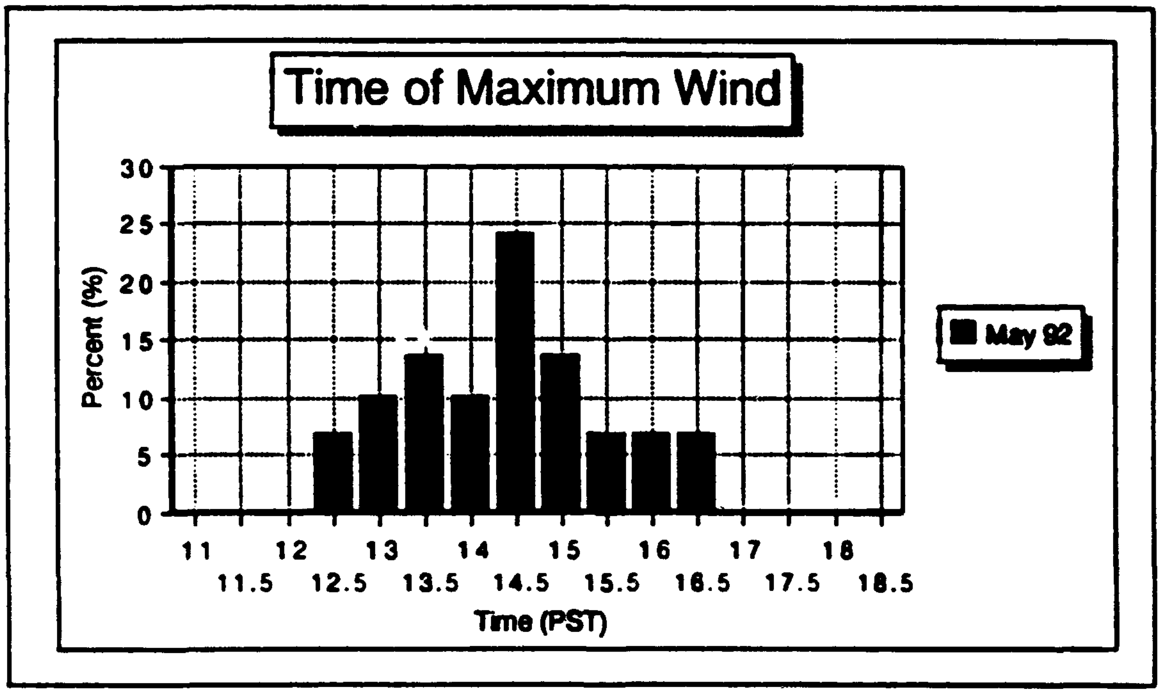


Figure 12. Same as 11 for May 1992.

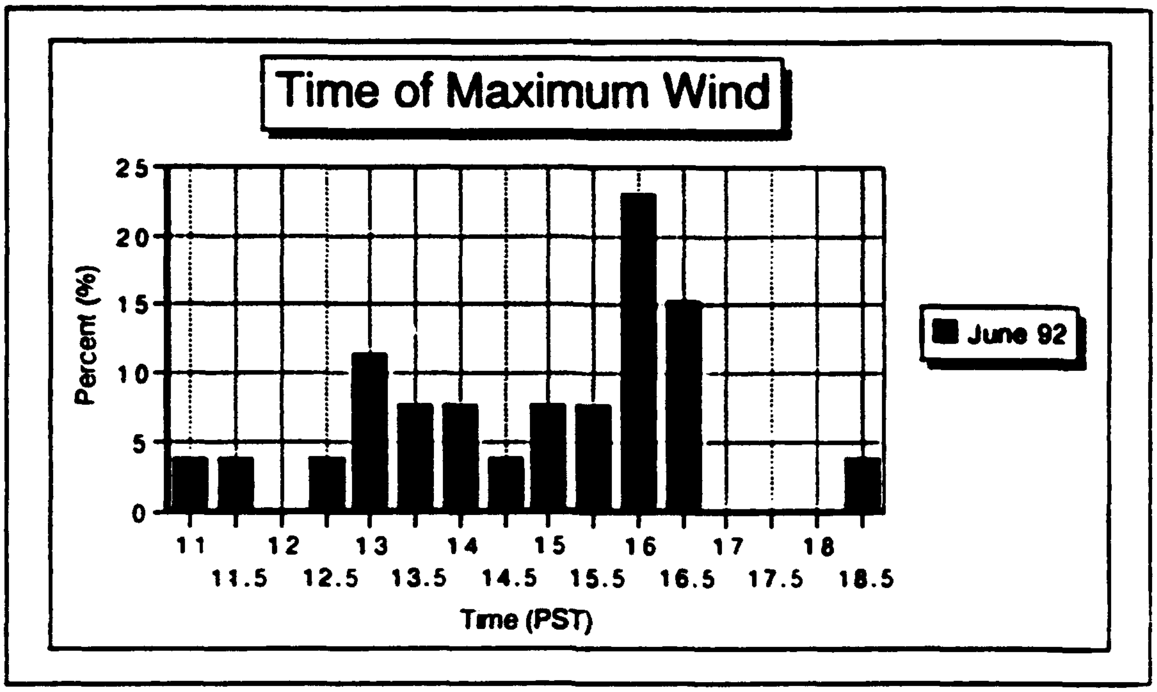


Figure 13. Same as 11 for June 1992.

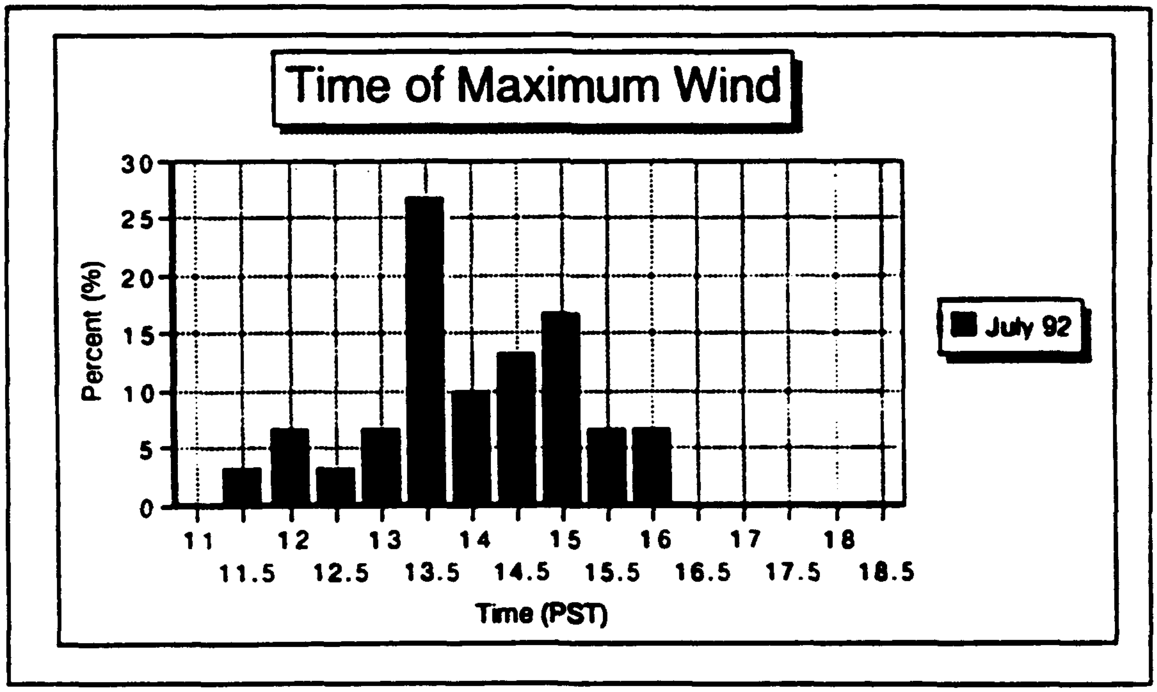


Figure 14. Same as 11 for July 1992.

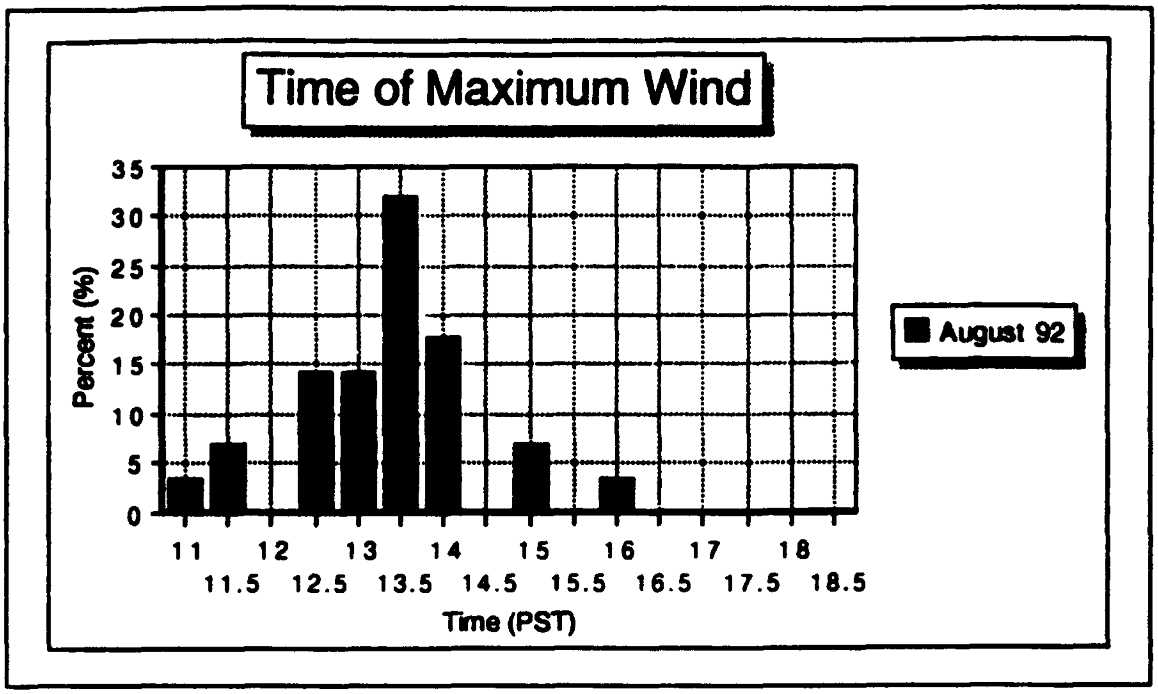


Figure 15. Same as 11 for August 1992.

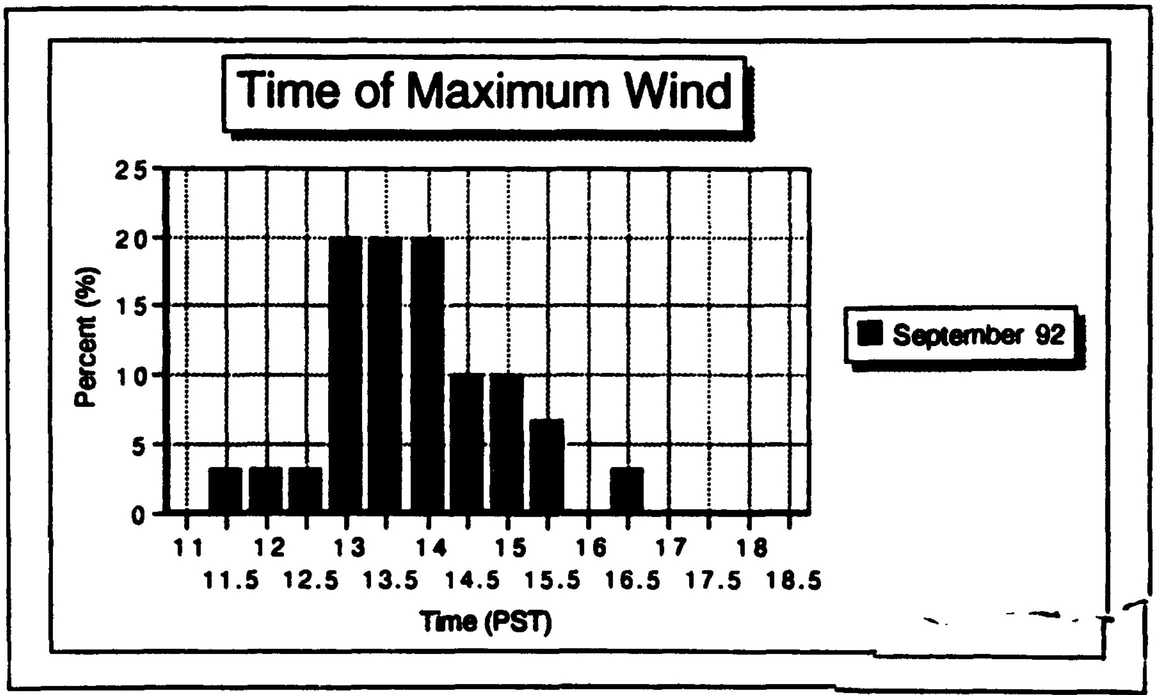


Figure 16. Same as 11 for September 1992.

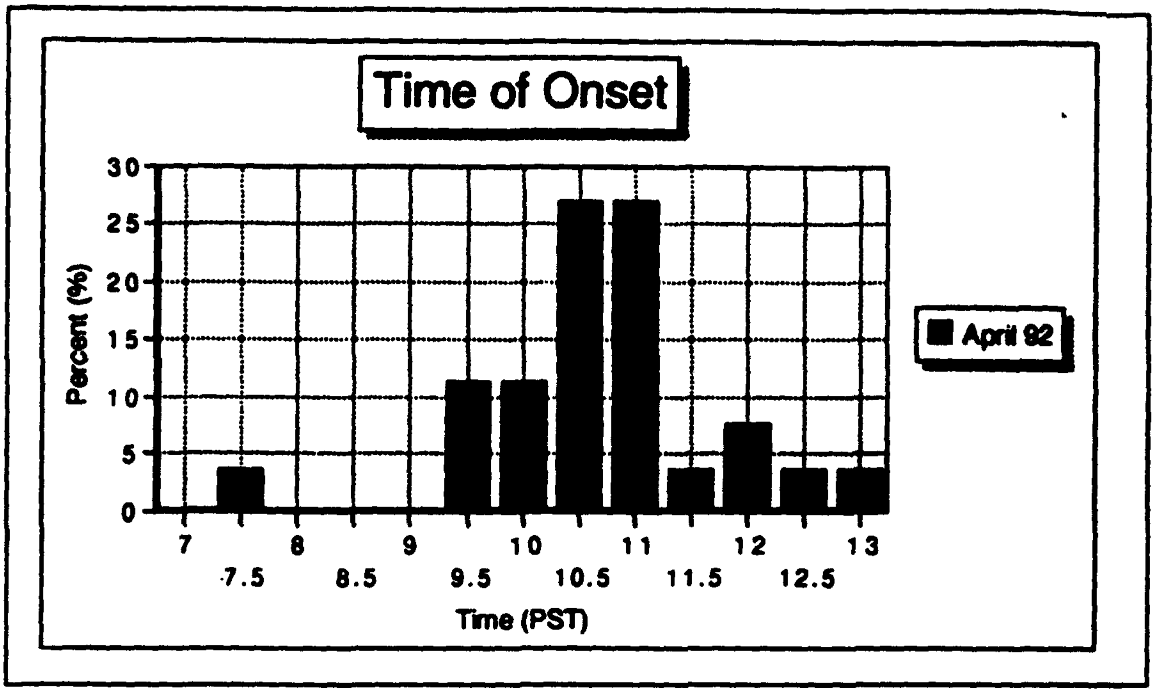


Figure 17. Monthly distribution of time of sea breeze onset for April 1992.

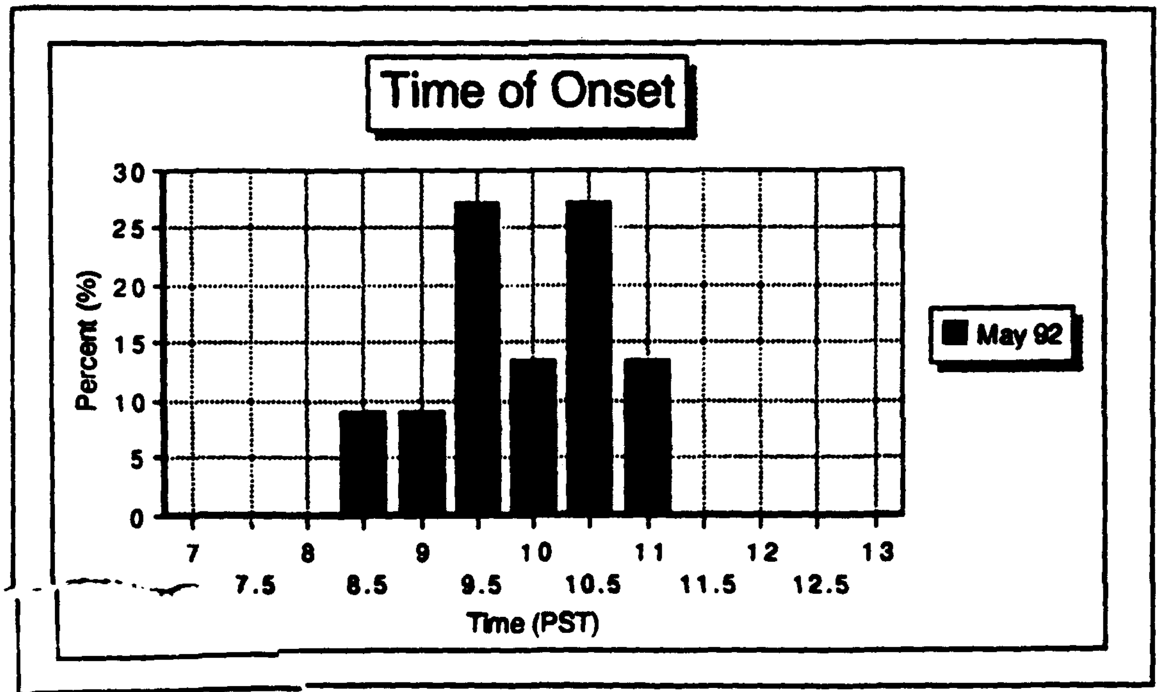


Figure 18. Same as 17 for May 1992.

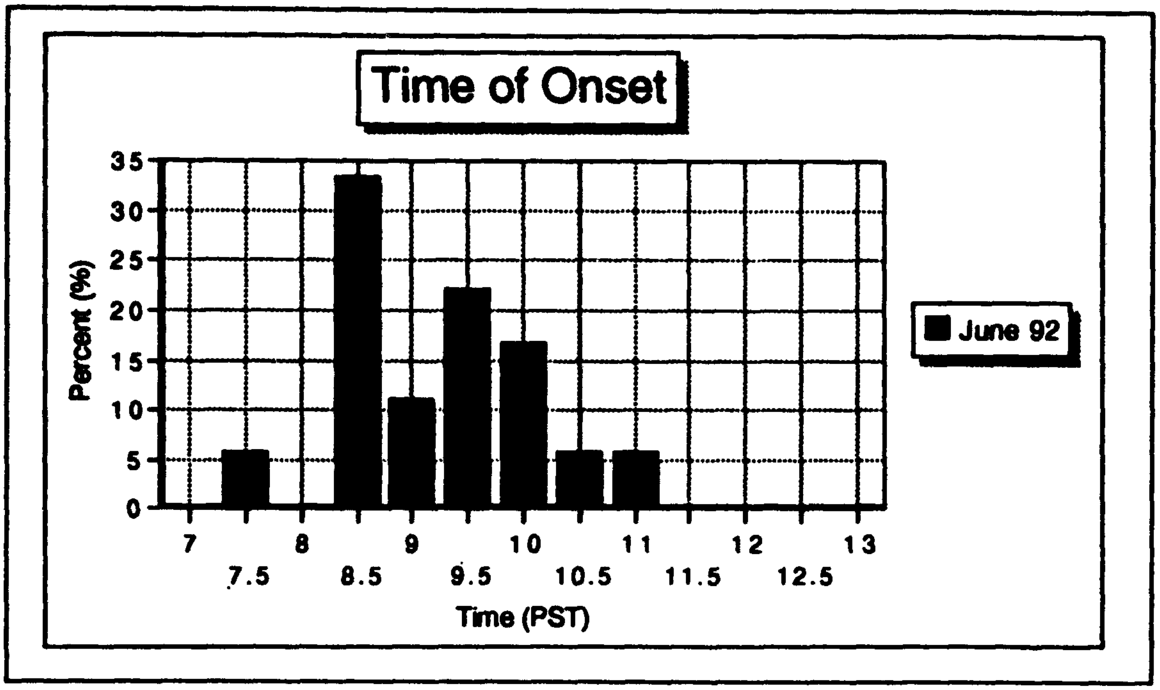


Figure 19. Same as 17 for June 1992.

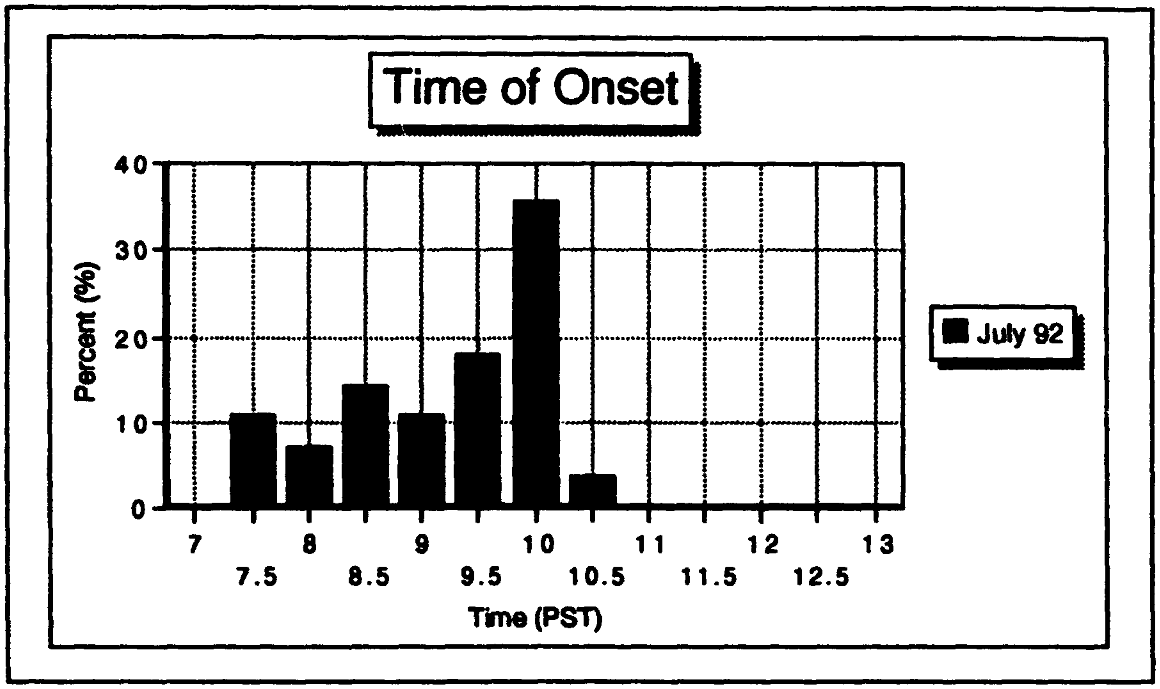


Figure 20. Same as 17 for July 1992.

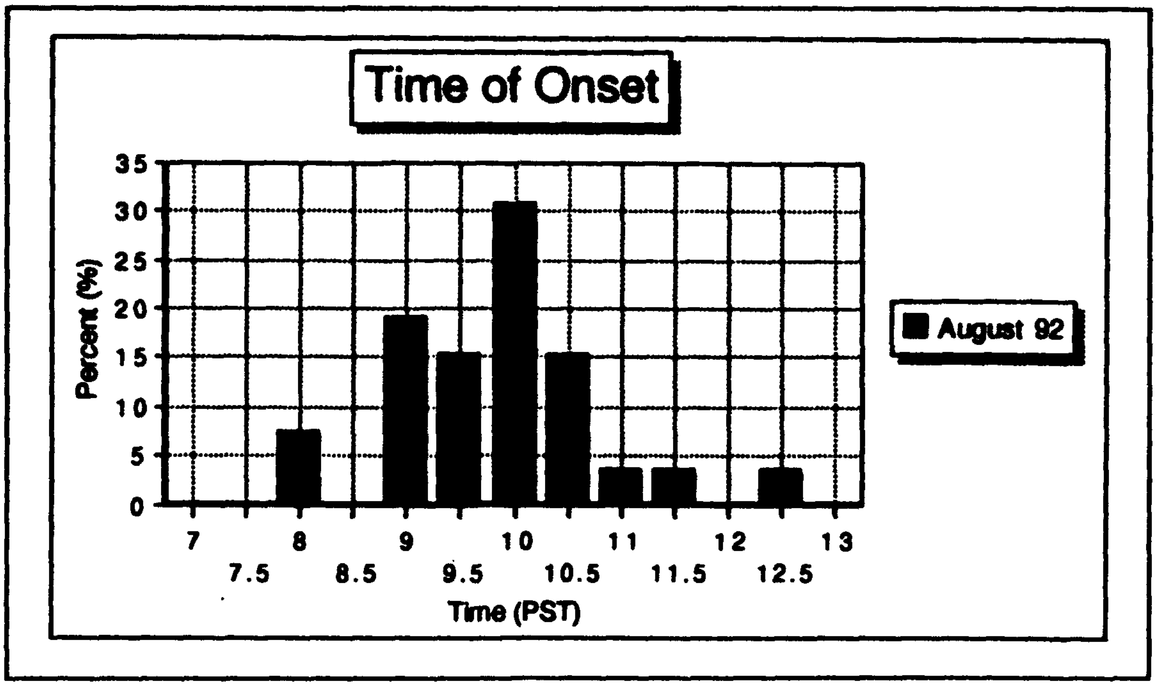


Figure 21. Same as 17 for August 1992.

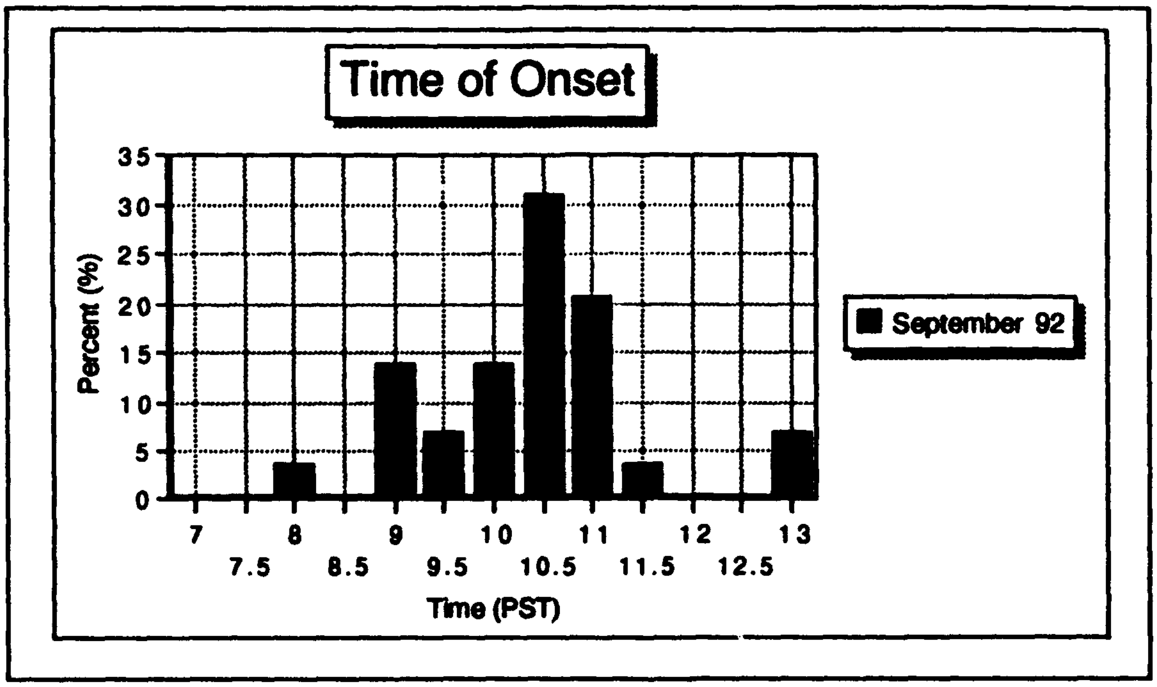


Figure 22. Same as 17 for September 1992.

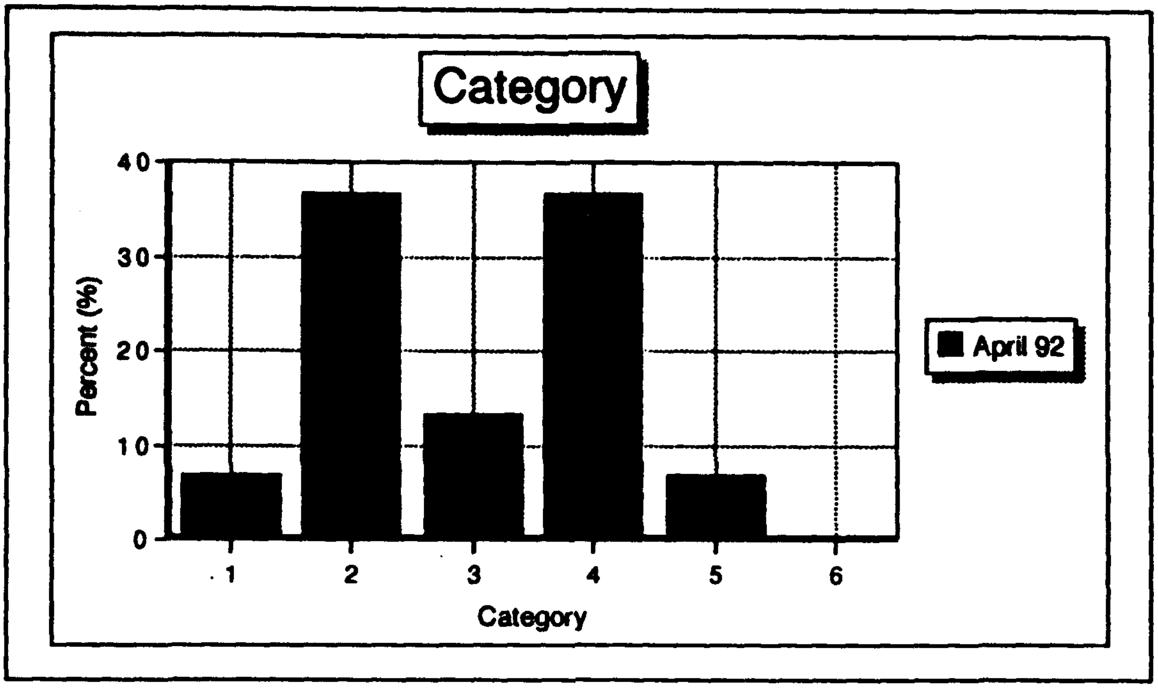


Figure 23. April 1992 distribution of sea breeze category. 1) No sea breeze, 2) gradual development, 3) clear onset, 4) frontal, 5) double surge sea breezes, 6) unclassified days.

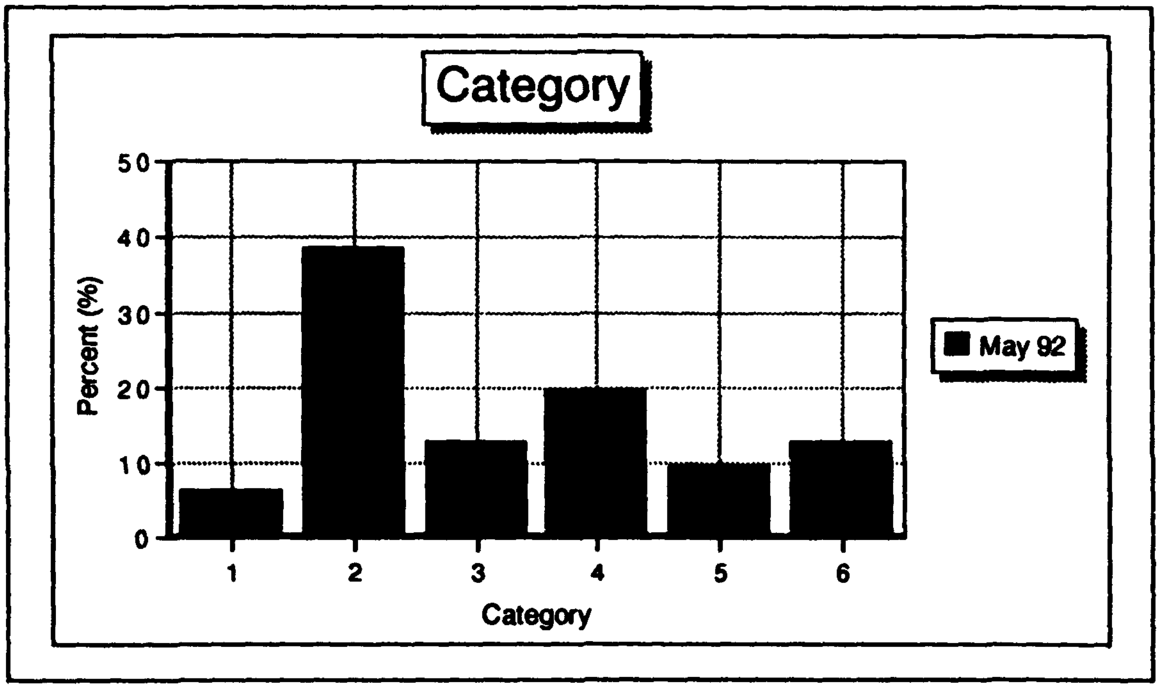


Figure 24. Same as 23 for May 1992.

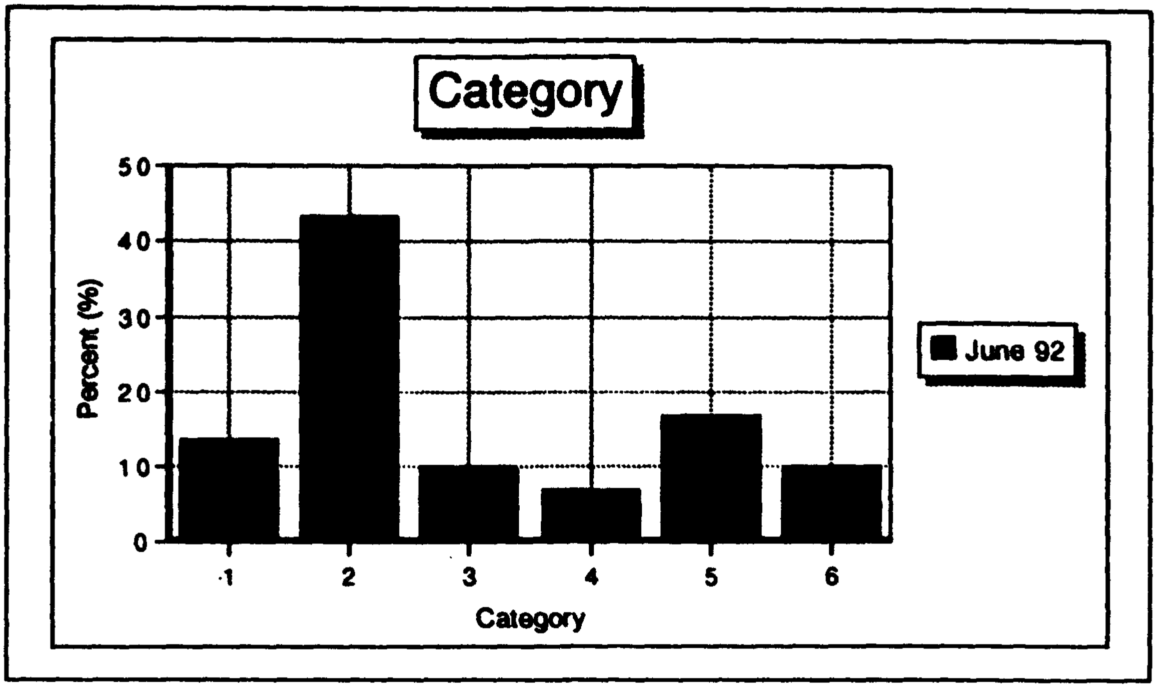


Figure 25. Same as 24 for June 1992.

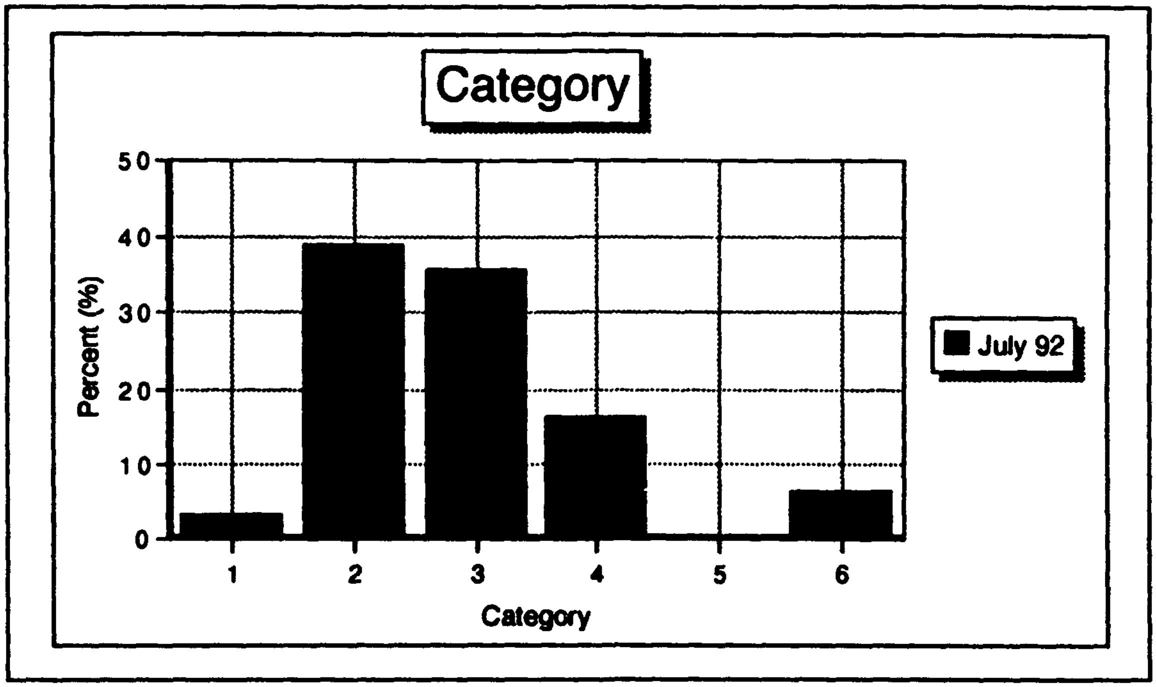


Figure 26. Same as 24 for July 1992.

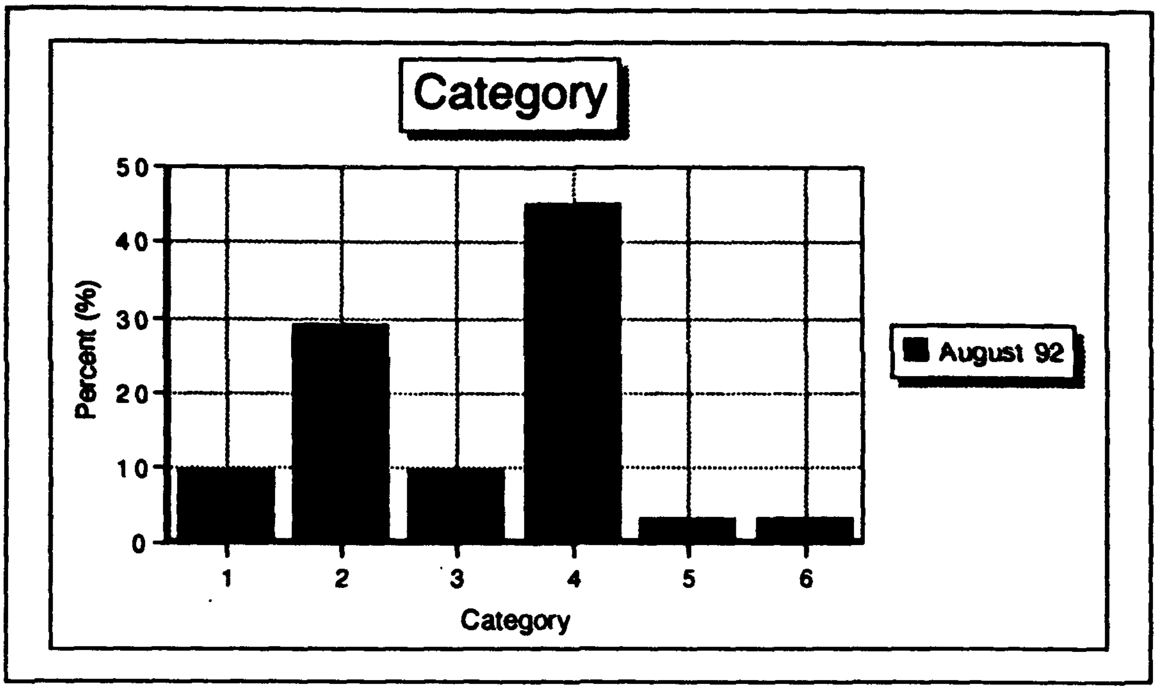


Figure 27. Same as 23 for August 1992.

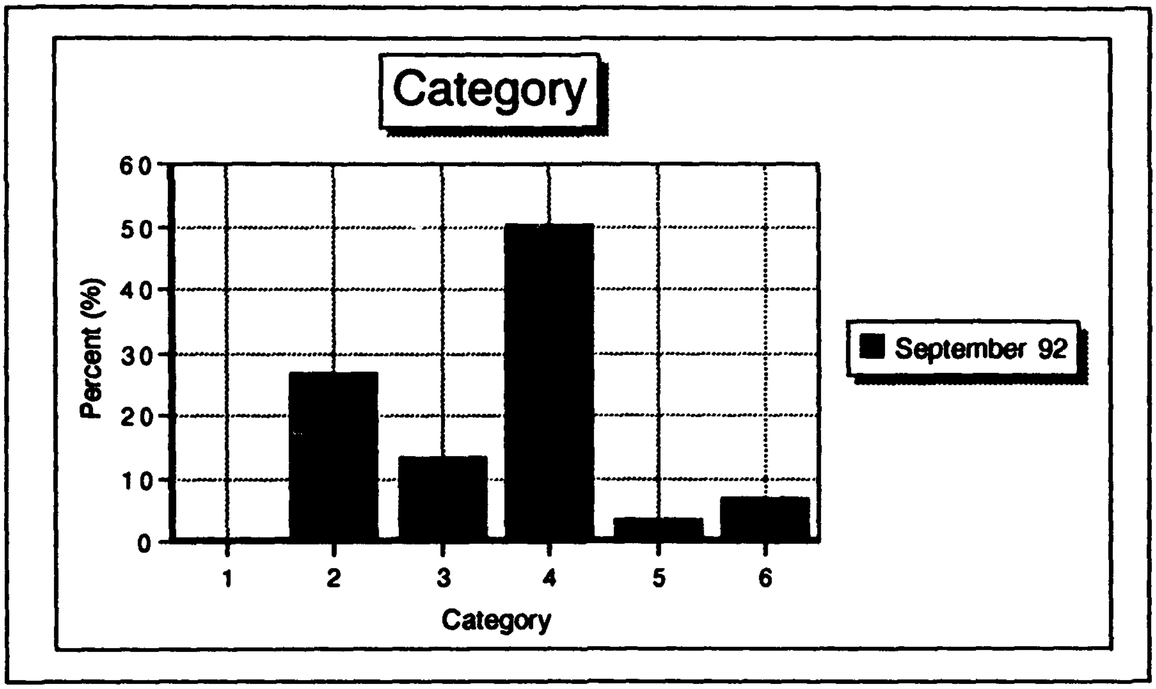


Figure 28. Same as 23 for September 1992.

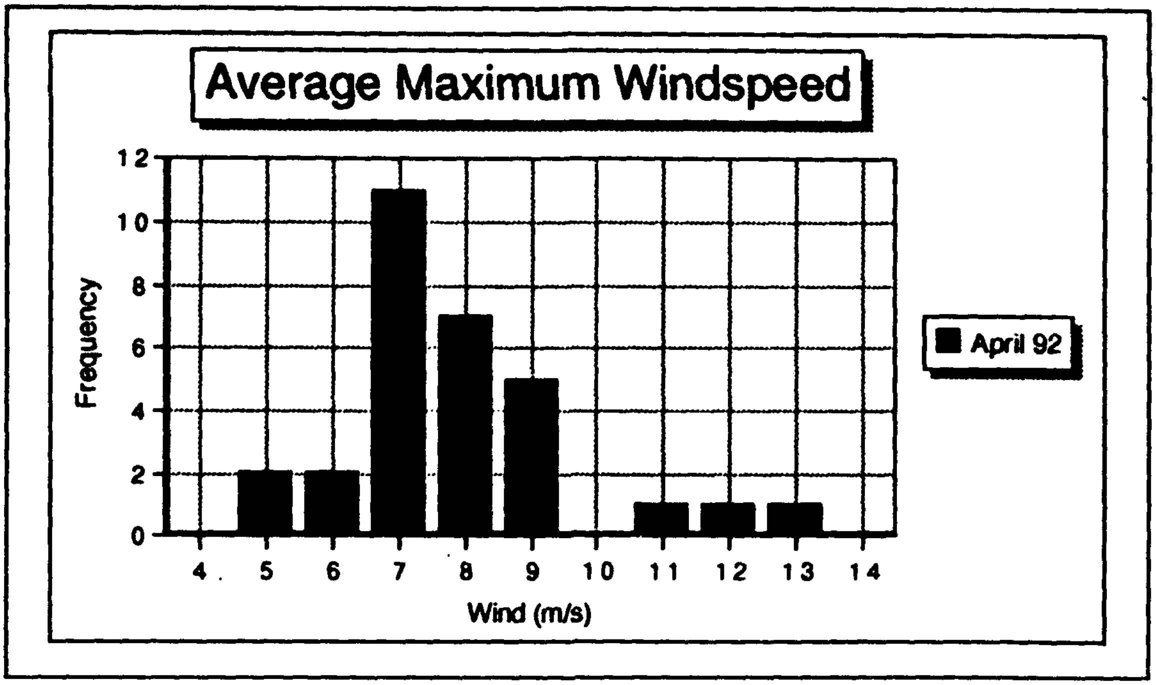


Figure 29. Monthly distribution of average maximum windspeed for April 1992.

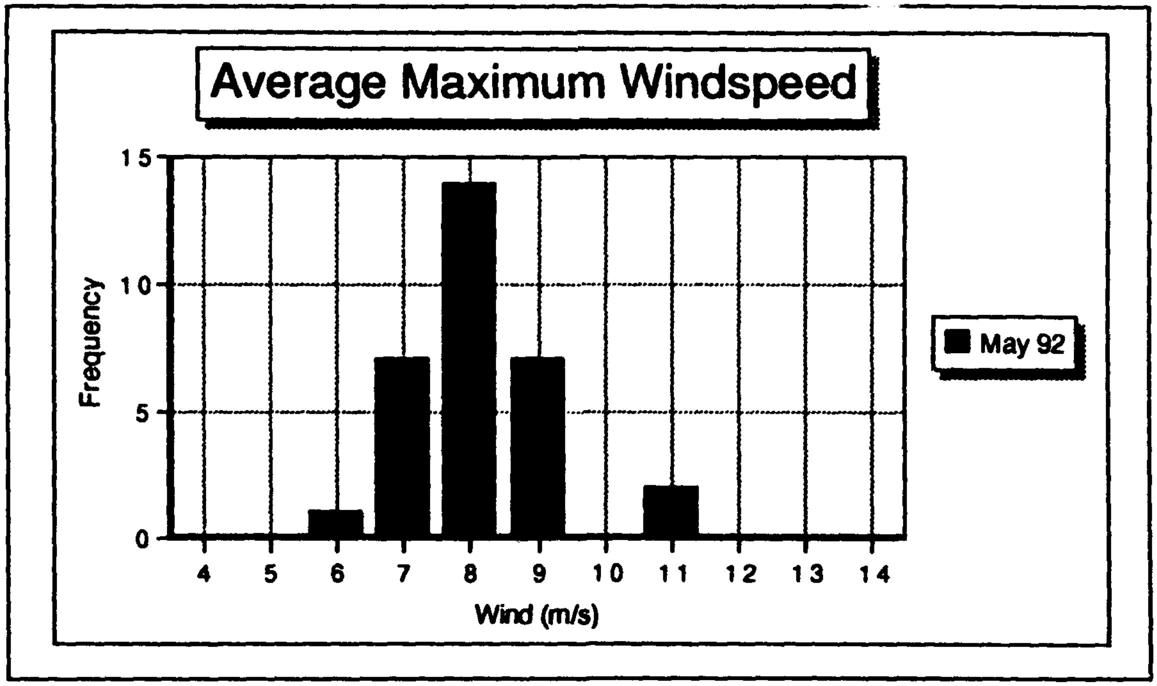


Figure 30. Same as 29 for May 1992.

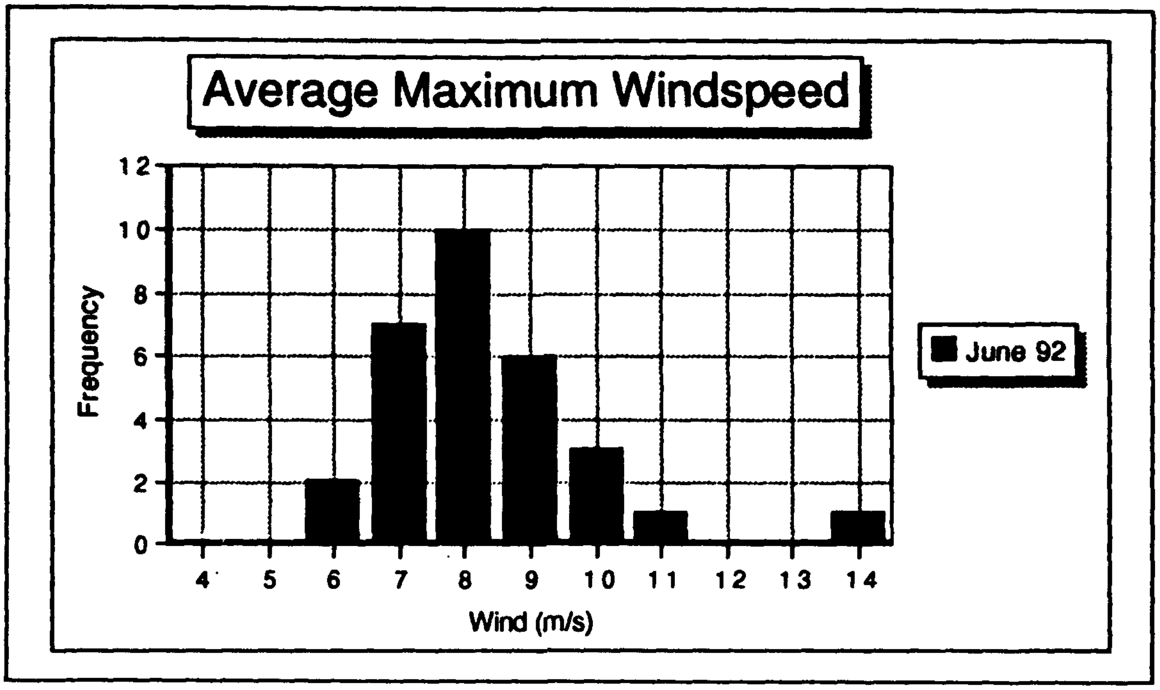


Figure 31. Same as 29 for June 1992.

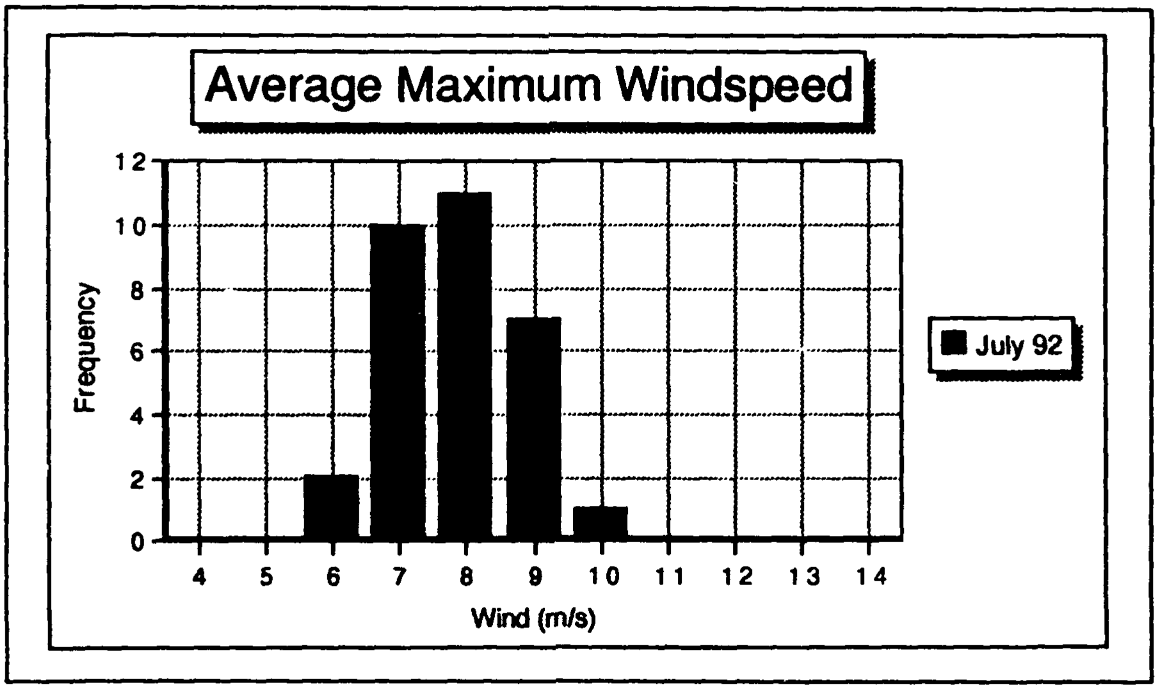


Figure 32. Same as 29 for July 1992.

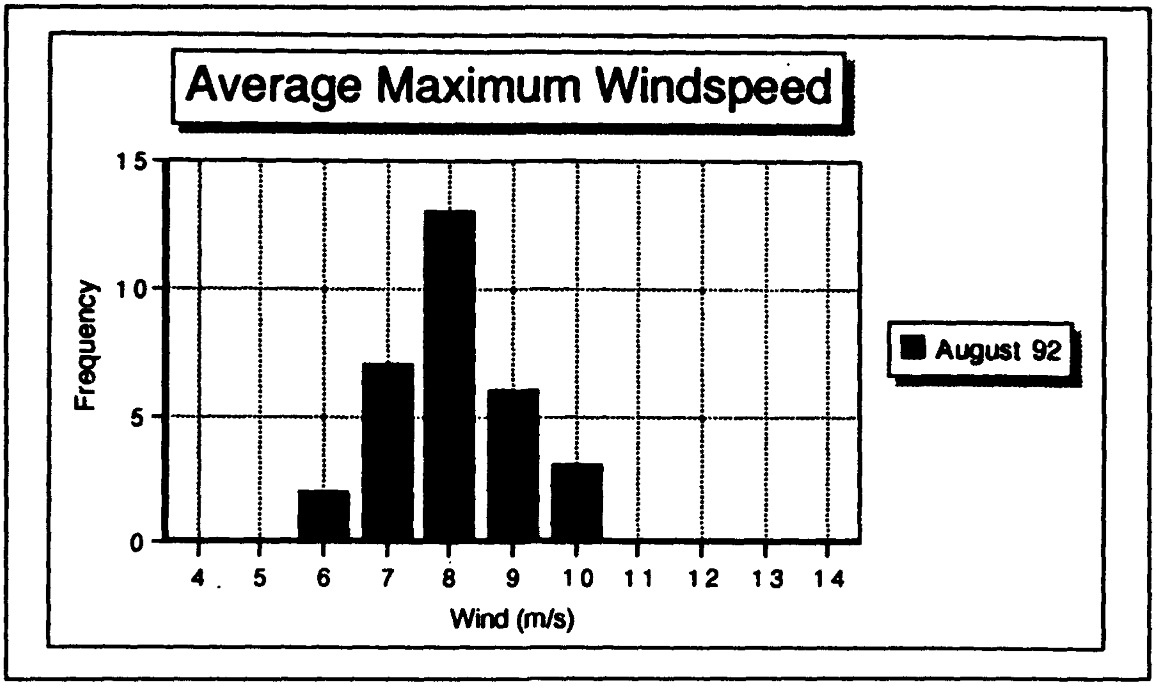


Figure 33. Same as 29 for August 1992.

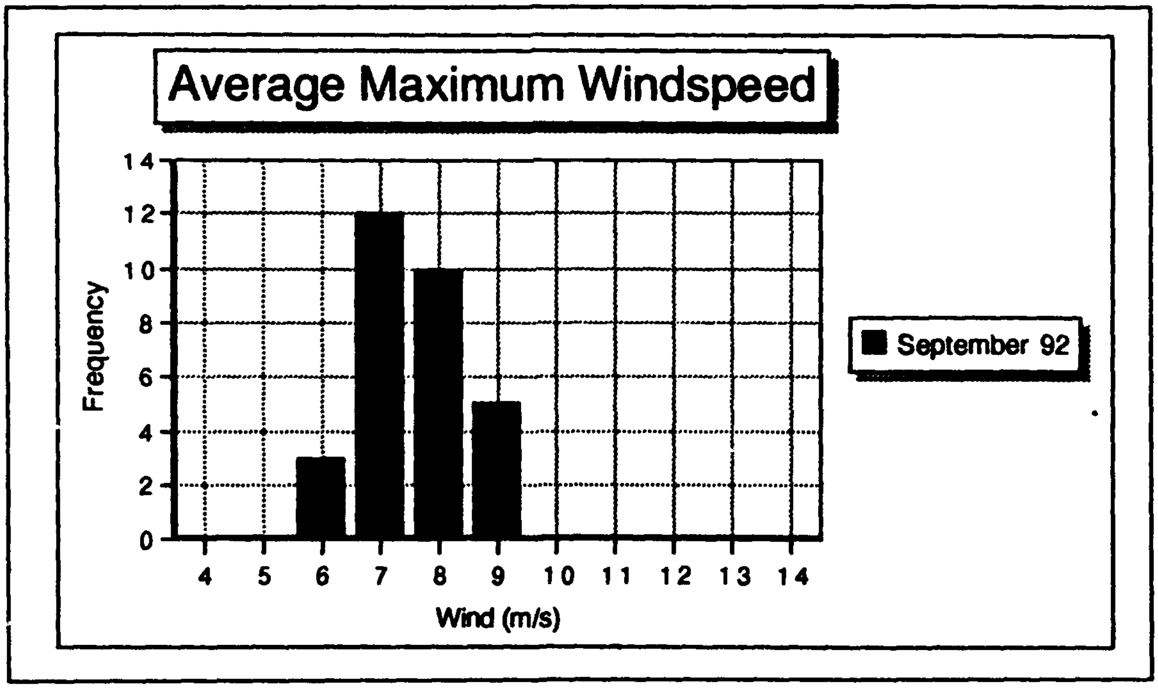


Figure 34. Same as 29 for September 1992.

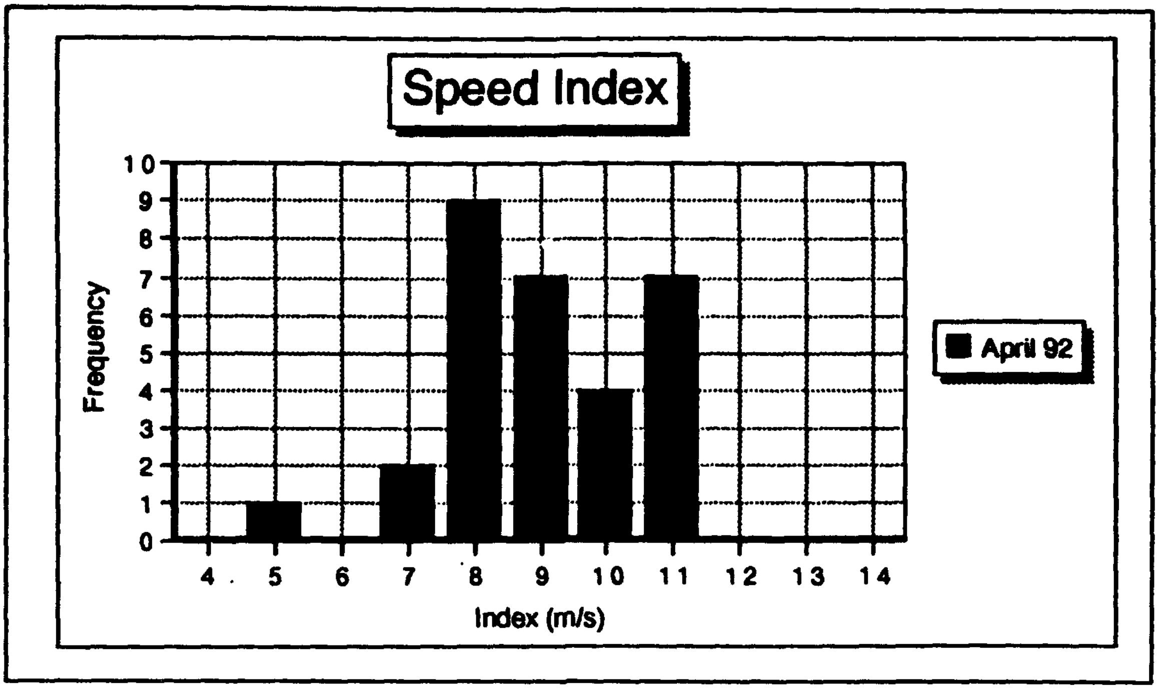


Figure 35. Monthly distribution of speed index revealing diurnal windspeed enhancement for April 1992.

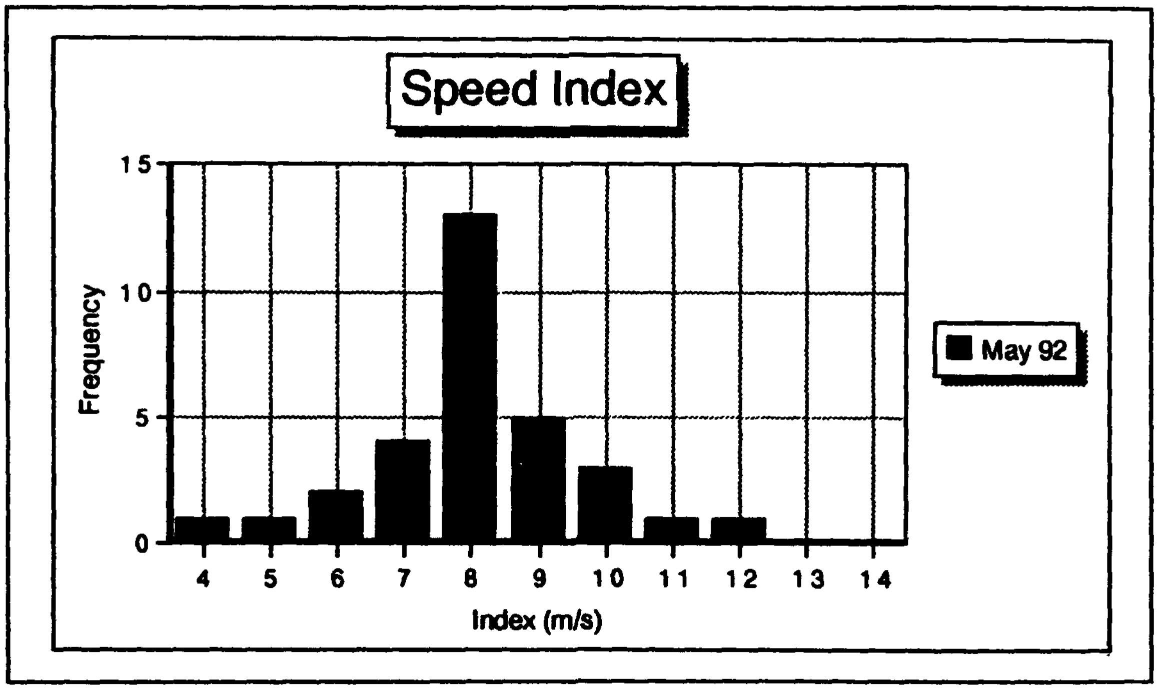


Figure 36. Same as 35 for May 1992.

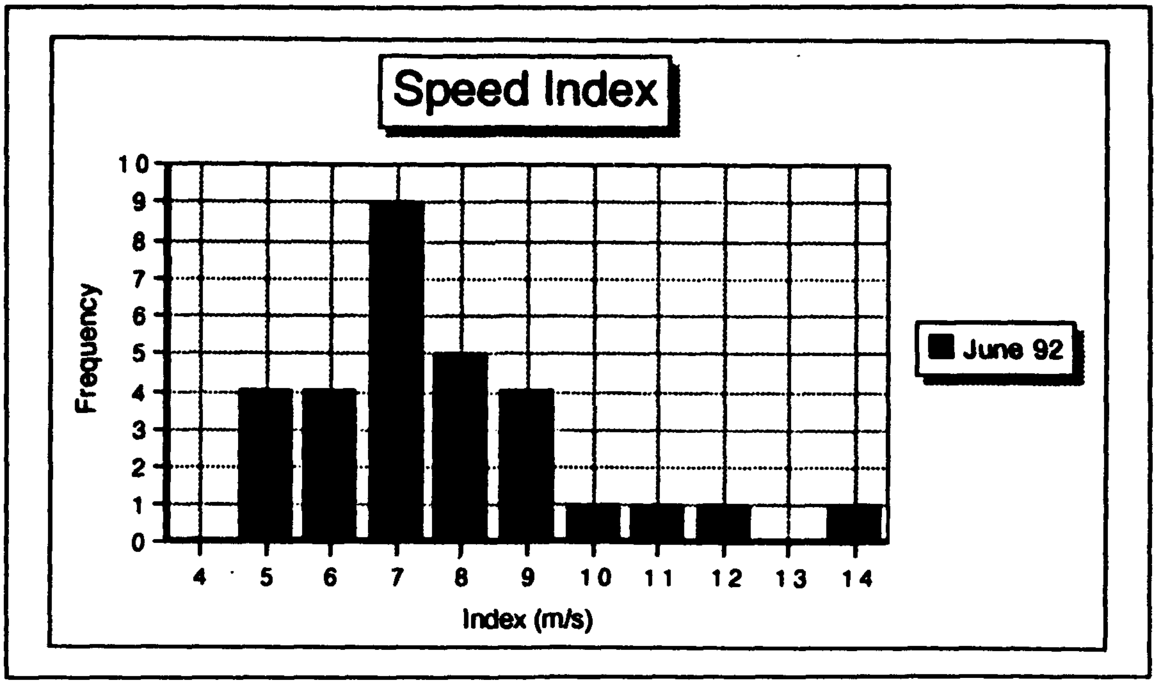


Figure 37. Same as 35 for June 1992.

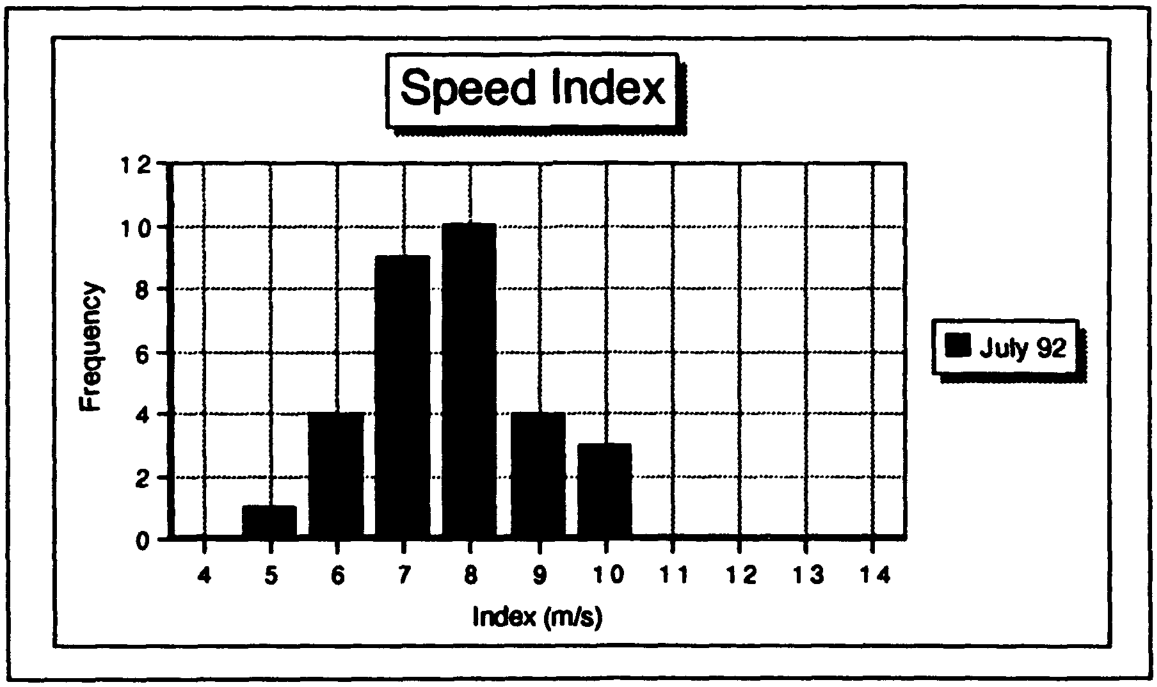


Figure 38. Same as 35 for July 1992.

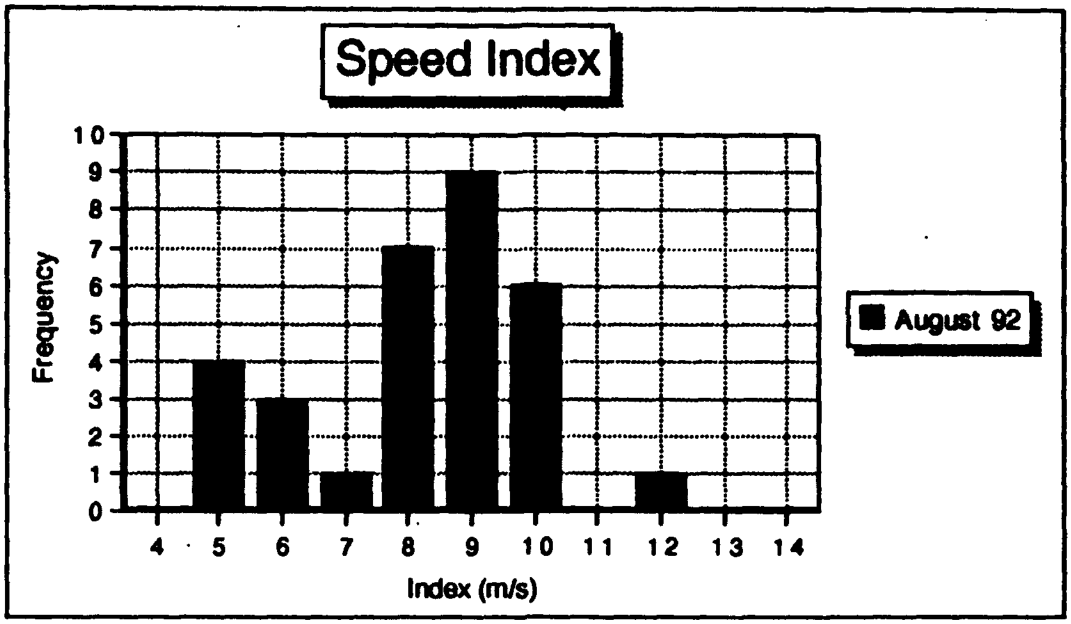


Figure 39. Same as 35 for August 1992.

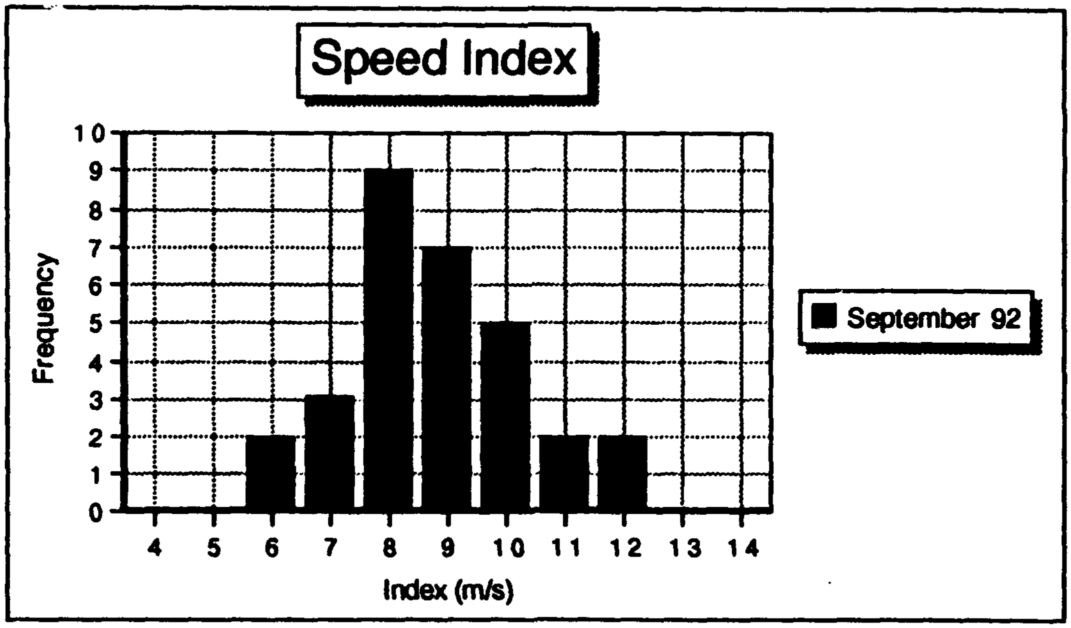


Figure 40. Same as 35 for September 1992.

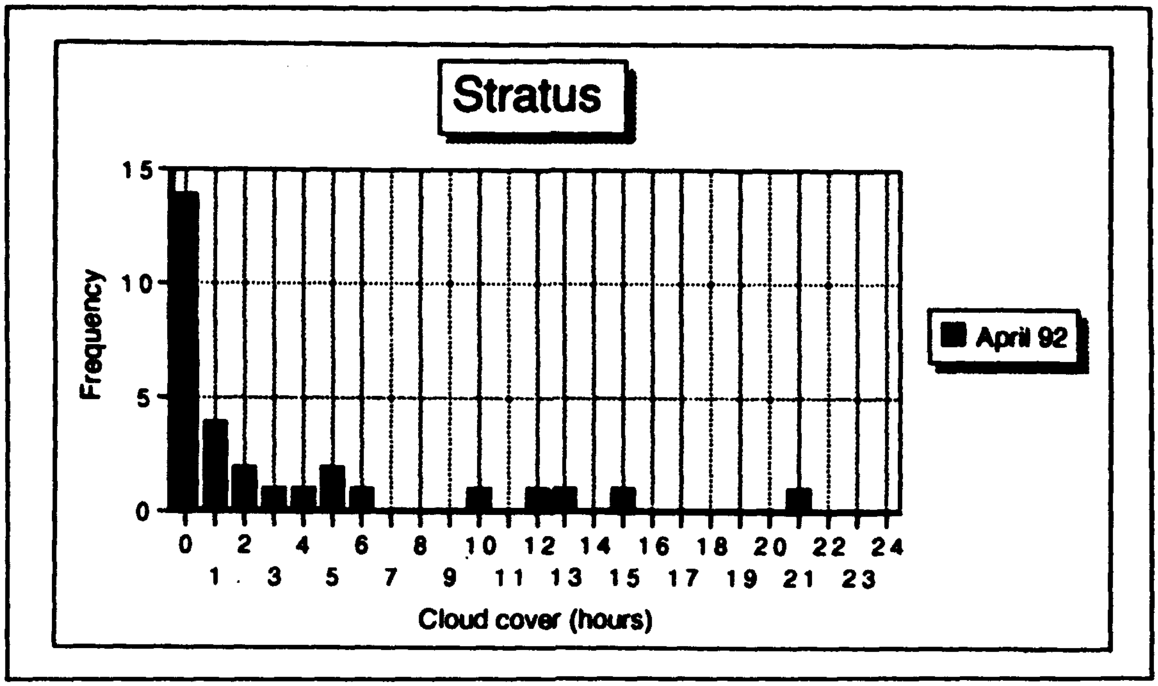


Figure 41. Monthly stratus coverage distribution showing frequency of hours of stratus cover for April 1992.

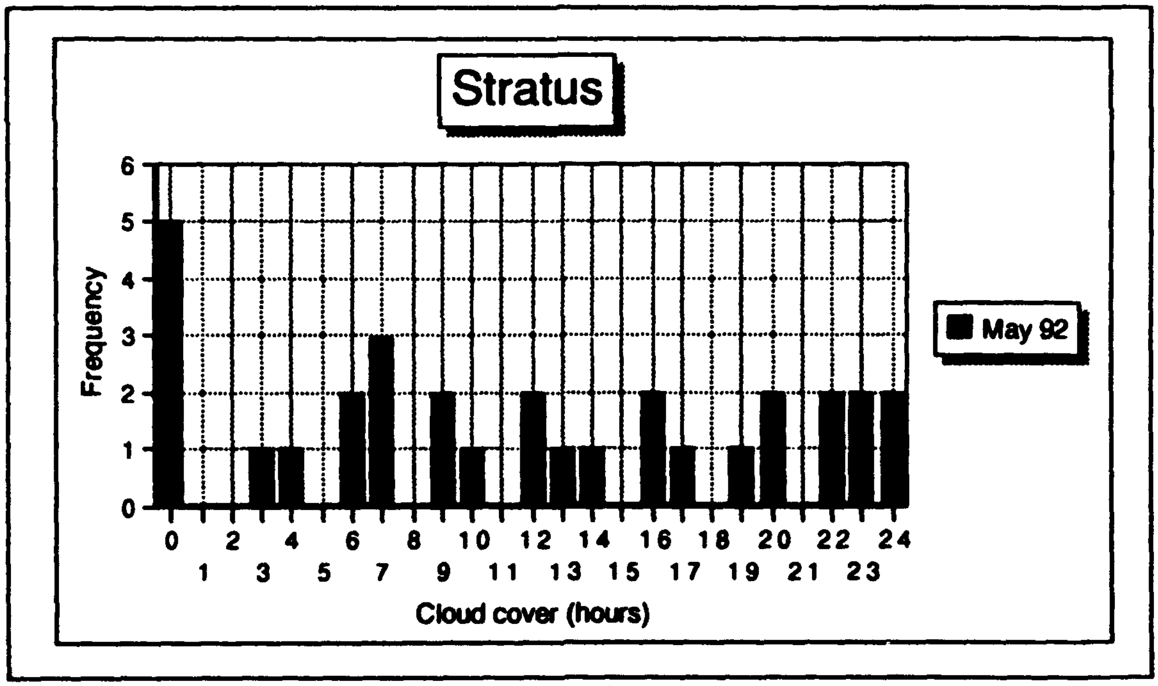


Figure 42. Same as 41 for May 1992.

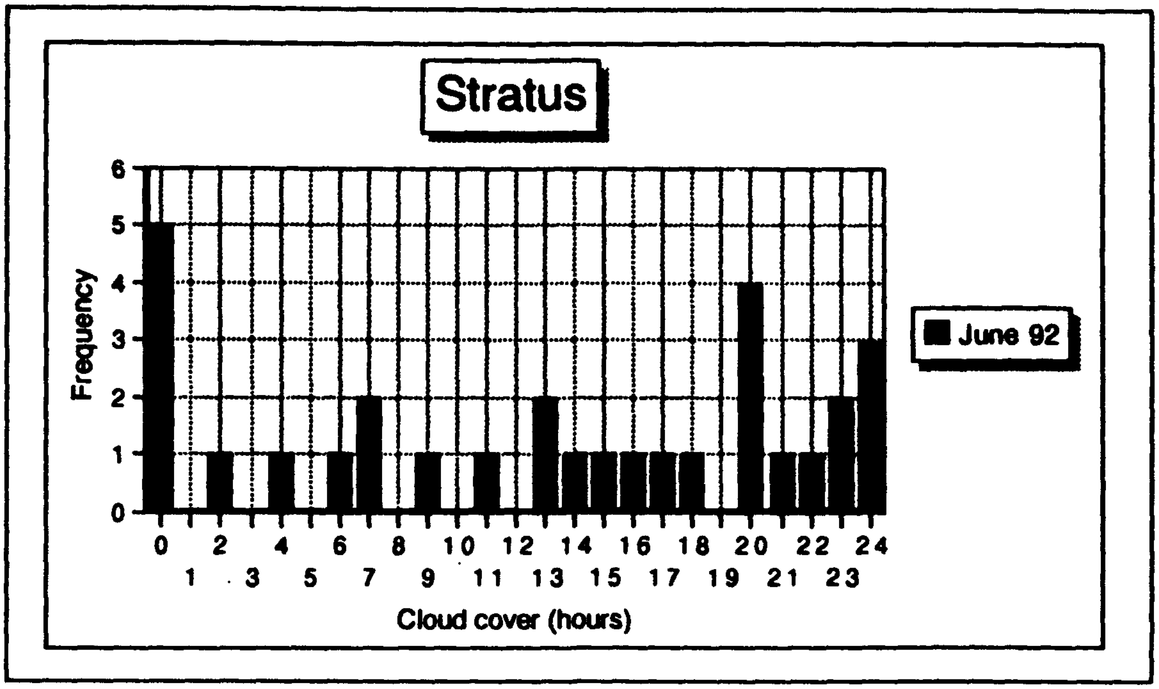


Figure 43. Same as 41 for June 1992.

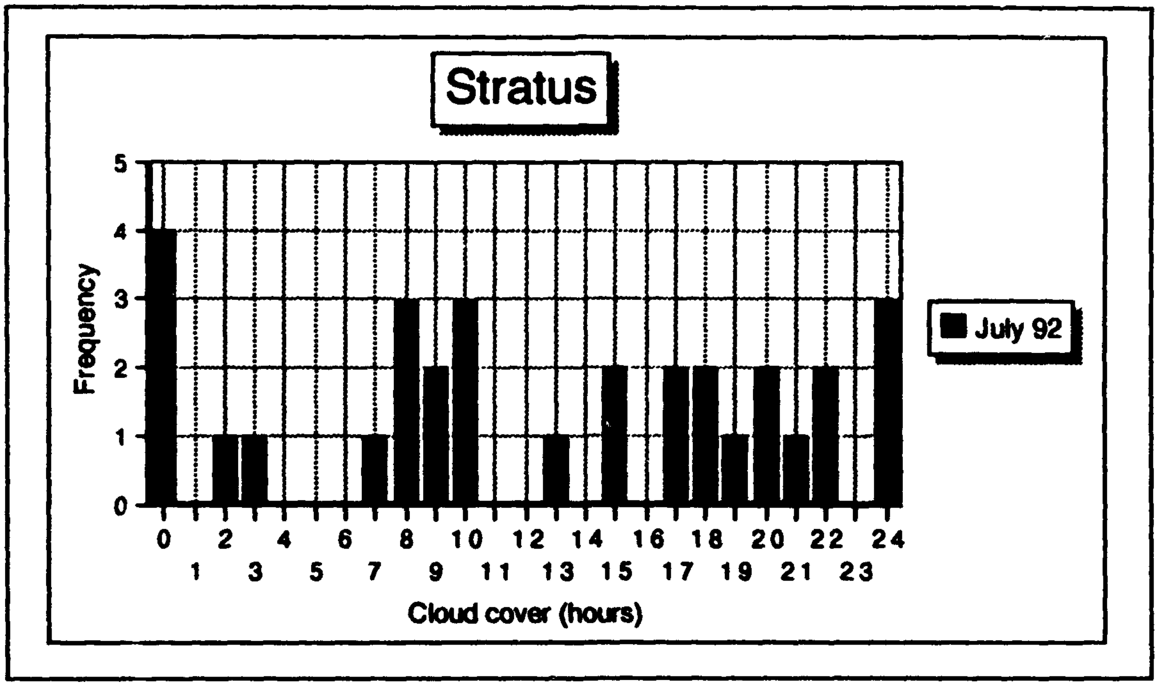


Figure 44. Same as 41 for July 1992.

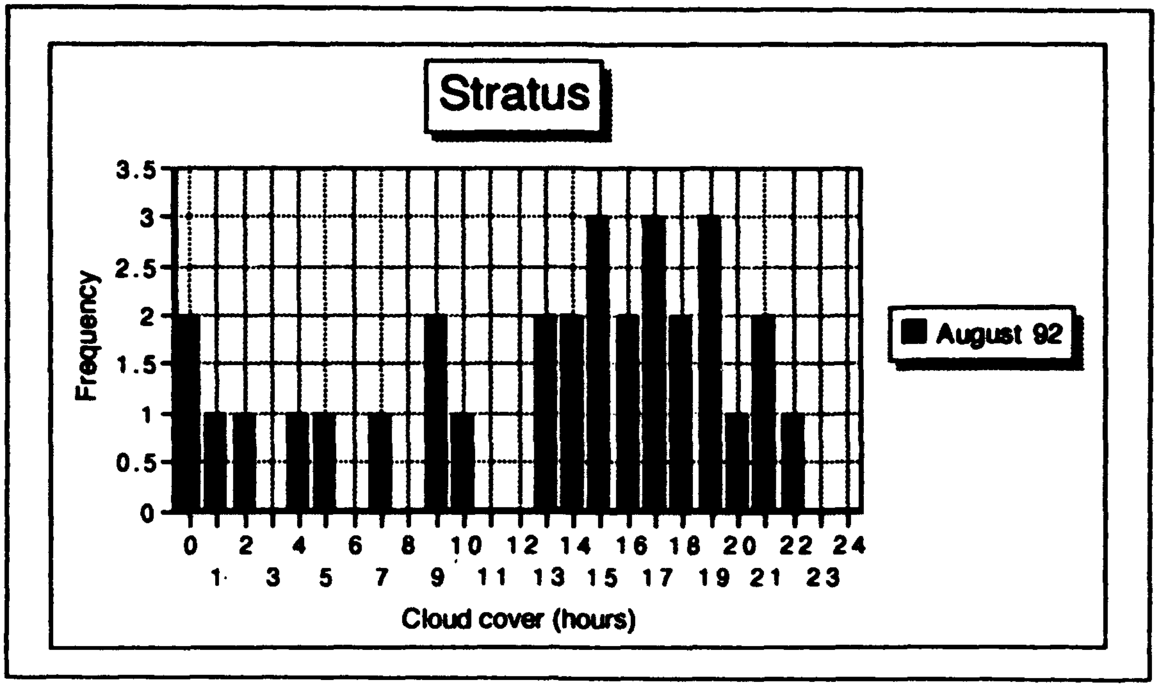


Figure 45. Same as 41 for August 1992.

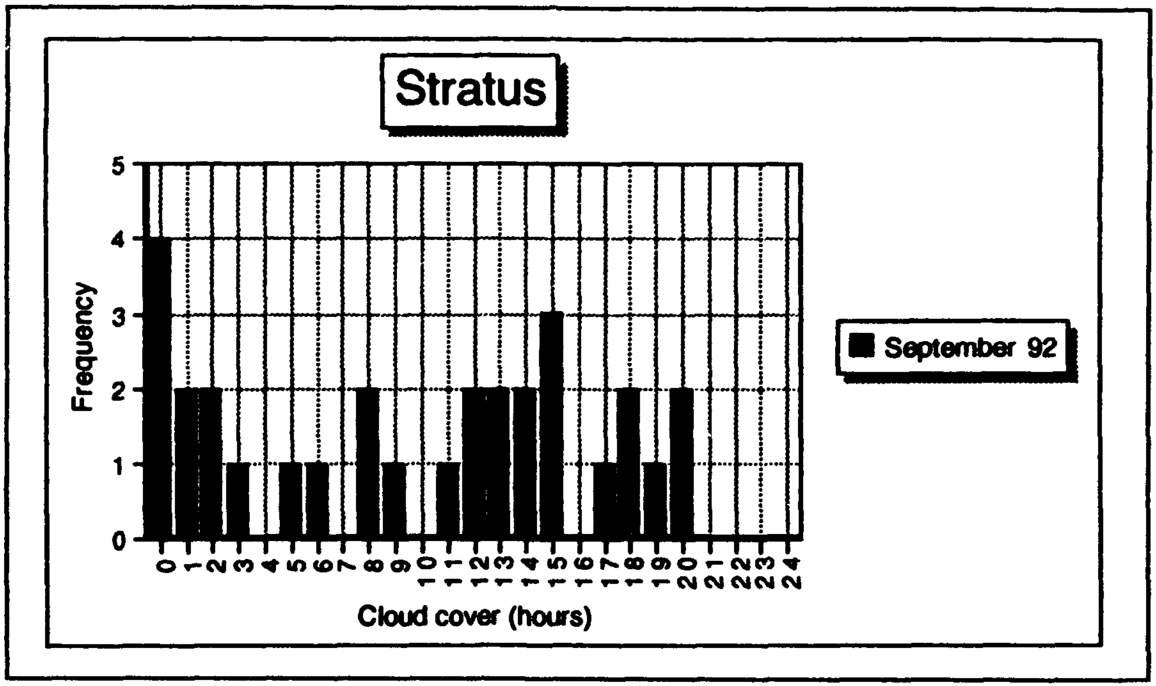


Figure 46. Same as 41 for September 1992.

C. SEA BREEZE CHARACTERISTICS

Additional analysis permits a better understanding of Monterey Bay sea breeze characteristics. As strong wind events are of most concern and interest, the attributes of strong and weak sea breeze days, as described by the sea breeze index, were analyzed from the six-month data set. Days with speed index greater than and less than 8 m/s were examined. Figs. 47 and 48 present the distribution of sea breeze category according to speed index, for indices greater than and less than 8 m/s respectively. Speed index values greater than 8 m/s, are representative of Frontal (category 4, 46 %) and clear onset (category 3, 20 %) sea breezes dominating the occurrence of strong sea breeze events as shown in Fig. 47. Weak sea breeze events (Fig. 48) are almost exclusively restricted to the gradual development (category 2, 48 %) category. All other cases each amount to less than 15 %. These results may alternatively be illustrated in the distribution of speed index for the two dominant sea breeze categories, frontal and gradual development. Fig. 49 shows that the frontal sea breeze is typically a strong diurnal windspeed enhancement event with the most common speed index of 10 m/s. By contrast, Fig. 50 reveals that the gradual development sea breeze is a weak to moderate intensity circulation. The most frequent speed index being 8 m/s. These distributions strongly suggest that the frontal type sea breeze is typically a stronger intensity circulation than the gradual development sea breeze.

The occurrence of stratus coverage is also highly related to sea breeze intensity. The speed index for primarily clear days, (0-1 hours stratus), (Fig. 51) and primarily cloudy days, (20-24 hours stratus), (Fig. 52) demonstrate this relation. Clear days (Fig. 51) show that the absence of stratus is conducive to strong diurnal windspeed enhancement and therefore a large speed index. The greatest frequency is a speed index of 9 m/s and the distribution is skewed to the right. Relatively cloudy days (20-24 hours stratus), (Fig. 52) demonstrate that increased stratus coverage reduces windspeed enhancement producing weak speed index values with a distribution centered about 7 m/s. These speed index distributions for varying degrees of stratus coverage exhibit an inverse relationship between hours of stratus coverage and diurnal windspeed enhancement.

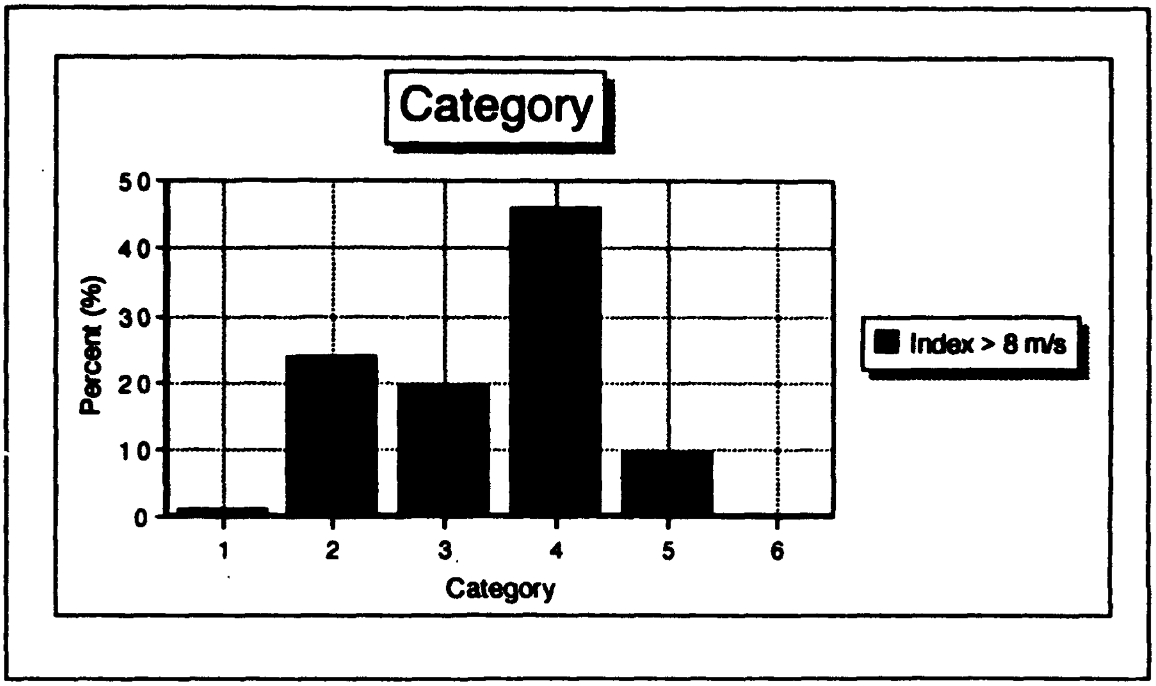


Figure 47. Category distribution for strong diurnal windspeed enhancement (index > 8 m/s).

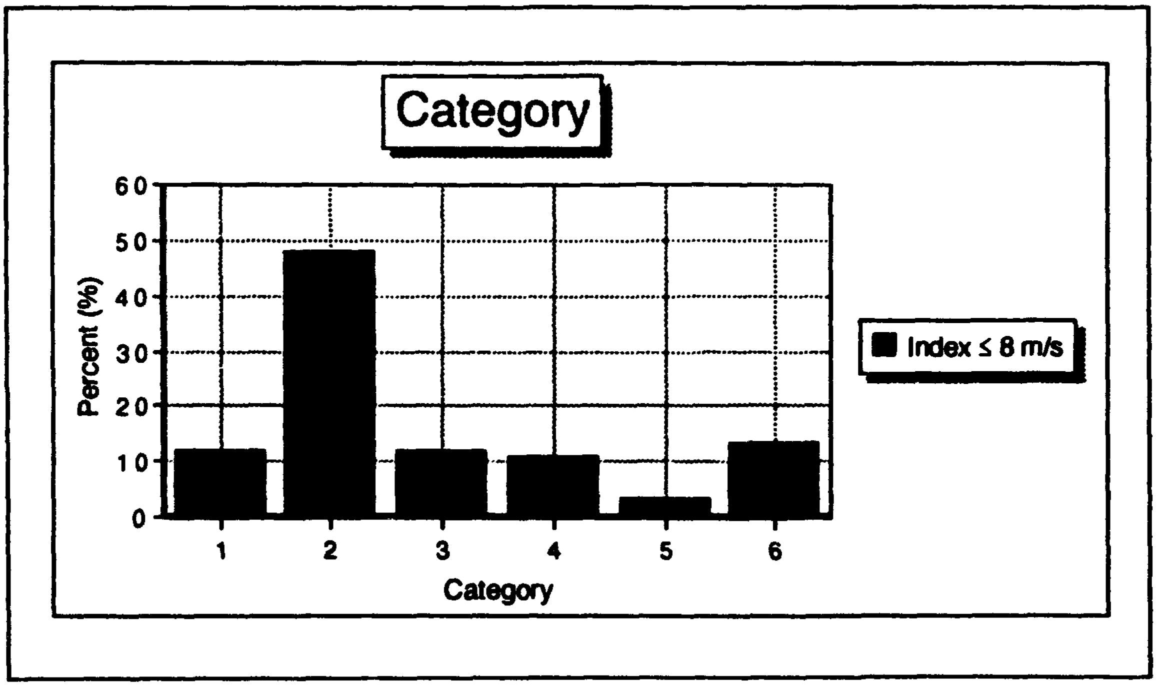


Figure 48. Category distribution for weak to moderate diurnal windspeed enhancement (index ≤ 8 m/s).

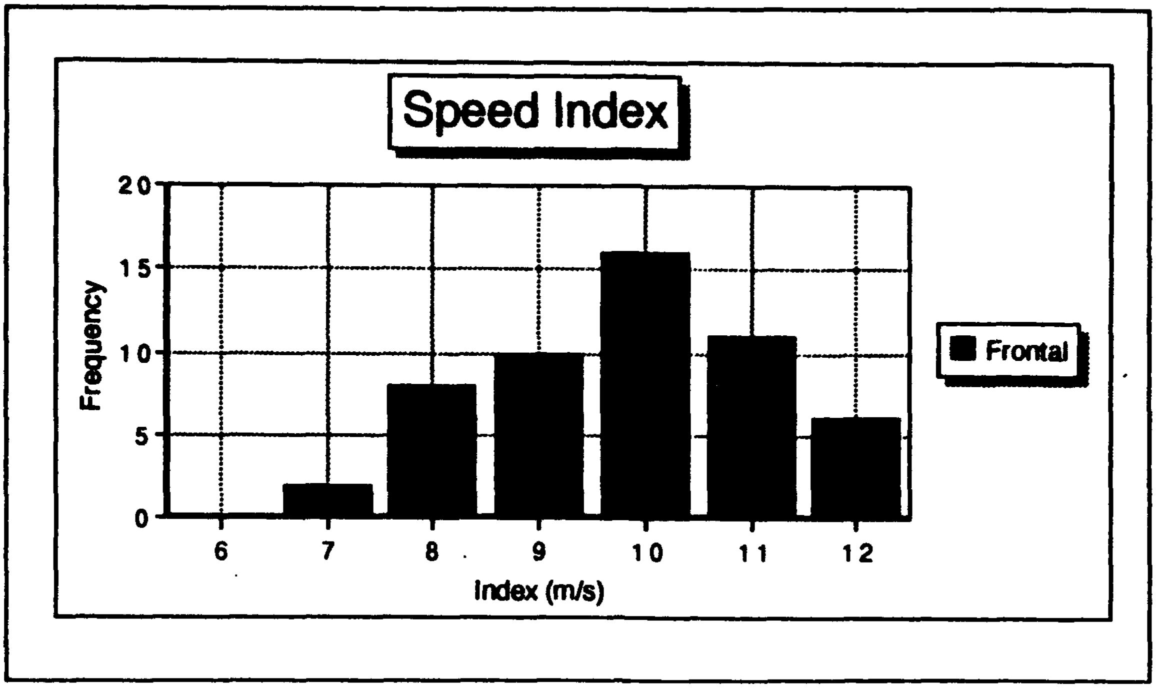


Figure 49. Speed index distribution for frontal sea breeze.

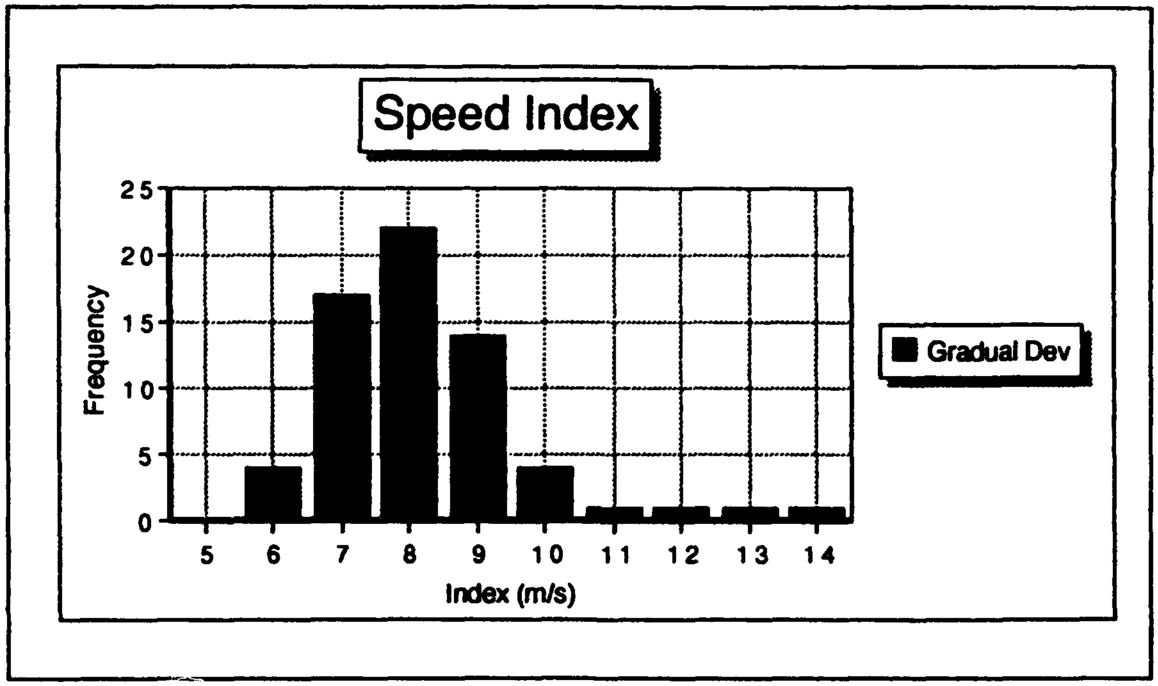


Figure 50. Speed index distribution for gradual development sea breeze.

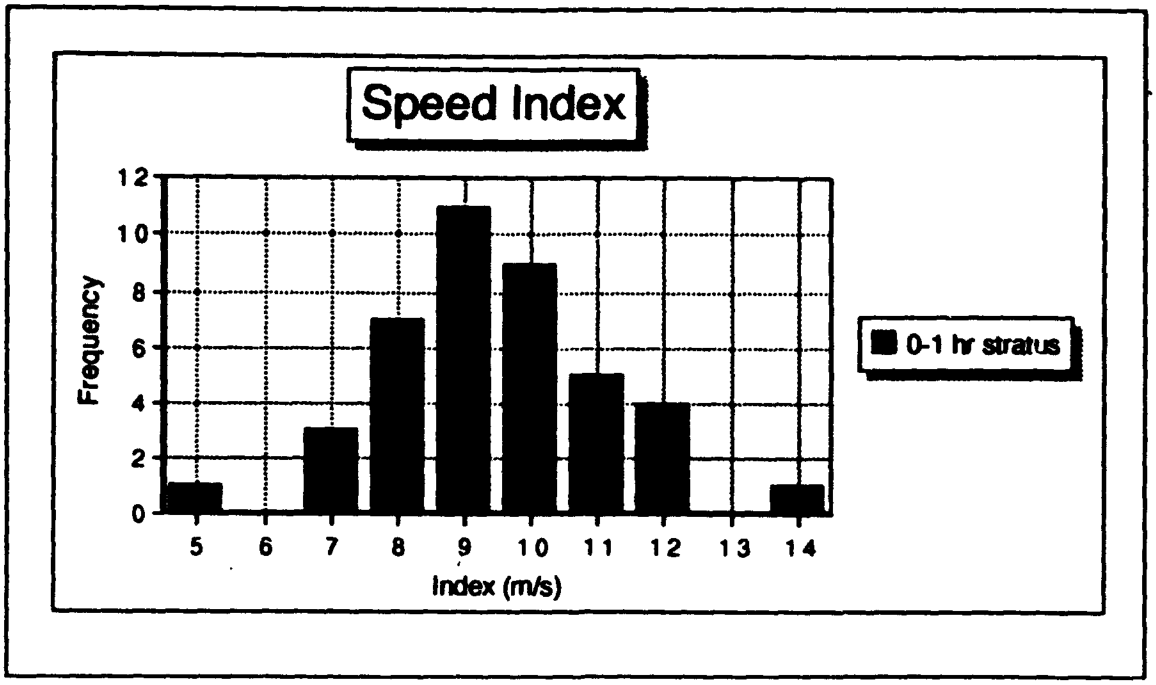


Figure 51. Speed index distribution for periods of stratus cover less than one hour.

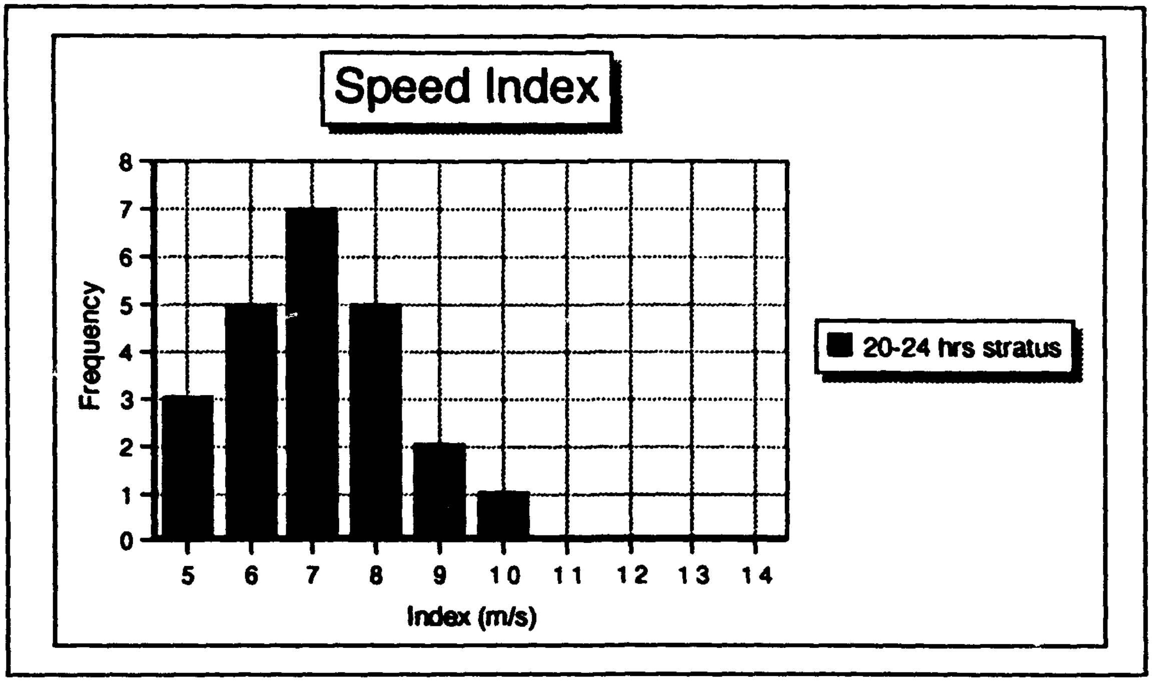


Figure 52. Same as 51 for stratus cover greater than 20 hours.

V. TEMPORAL FLUCTUATIONS IN SEA BREEZE INTENSITY

A. SPEED INDEX VARIATIONS

The speed index is a measure of diurnal windspeed enhancement. Variations in enhancement indicate changes in sea breeze intensity and should be influenced by variations in synoptic conditions present as well. In the effort to study how the large-scale synoptic conditions affect the sea breeze, the index is plotted in a monthly time series. Significant periods of speed index deviation were identified by sequences of days where the index deviates from the mean, which were accompanied by large changes in the index values as compared to the existing trend. Once a period is identified, appropriate weather charts, satellite imagery and vertical sounding data were examined to understand the causes of index variation.

As mentioned earlier, the speed index averages approximately 8 m/s over the entire six-month period. Examples of two monthly time series of the index are given in Figs. 53 and 54. These months show wide variations from this central value indicating strong swings in sea breeze intensity. The period from the 10th to the 14th in June of 1992 demonstrates a wide swing in speed index over a relatively short period (Fig. 53). Similarly, the period from the 4th to the 9th during August of 1992 stands out (Fig. 54). While smaller deviations from the mean are expected, these larger variations merit further investigation.

Of the variables available from the profiler site, stratus coverage data is most closely related to the sea breeze index. Recall that relatively high values of speed index accompanied all clear days, 0-1 hours stratus, shown in Fig. 51, and low values occurred for mostly cloudy days (Fig. 52). This relationship is further evident when a time series of stratus coverage is compared to speed index. Stratus coverage for June and August of 1992 are presented in Figs. 55 and 56 for comparison with the speed index for the same months. Reviewing the stratus coverage for the same periods of large variation in speed index during June and August, an inverse relation immediately becomes evident. The speed index event in June leading to a maximum in windspeed enhancement is characterized by relatively clear skies. The same trend is found during the August period with opposite variation in both speed index and stratus coverage. That is, a minimum in speed index is accompanied by significant stratus coverage. However, other days exhibit opposite behavior which indicate that other factors also influence the relationship.

B. CASE STUDIES

1. Typical Diurnal Wind Enhancement Scenario

In order to further understand the changes in sea breeze index, 10 periods were examined in greater detail of which two are presented in this section. Fig. 57 shows the evolution of the sea breeze index and stratus coverage for the period 28 July to 3 August 1993. Although this period is in 1993 rather than the 1992 data set, it illustrates some of the basic changes in sea breeze intensity and more supporting data was available at this time for analysis. The speed index on 28 July is weak, 6.2 m/s, and is representative of a period of low index values. During this period, stratus coverage was quite high, with a value of 23.6 hours on the 28th. Over the next seven days, the index increases markedly to a value of nearly 12 m/s on 31 July, then decreases the remainder of the period. Meanwhile, stratus coverage decreases from 23 hours on the 28th to 1-2 hours coverage on 31 July and 1 August. The hours of stratus coverage increase during the succeeding days. Note there is a bias in determining stratus coverage based on the 380 W/m^2 threshold for these days. The air was very warm which produced high values of IR irradiance. However, these days were essentially clear based on observational reports.

There is no routine vertical temperature sounding available in the Monterey Bay area. However, the operational sounding at Oakland, CA as well as satellite imagery was studied to infer the vertical structure of the marine boundary for these cases of large index variation. Fig. 58 shows a deep boundary layer at Oakland on the 28th with a strong capping inversion near 850 mb. Fig. 59, GOES visible satellite imagery, reveals the significant stratus coverage covering the coast at 2301 GMT (1501 PST) on the 28th. This pattern of deep boundary layer coupled with intense stratus coverage was typical of the 10 cases of low speed index values. The Oakland sounding for the 31st, Fig. 60, shows the inversion lowering to the surface defining an extremely shallow boundary layer. Satellite imagery for the 31st (Fig. 61) confirms the dominance of clear skies along the majority of the U.S. West Coast. The shallow boundary layer and associated clear skies correlated with high sea breeze values.

The inverse relation between boundary layer height and speed index is evident by comparing the trends of each. With a higher than normal boundary layer height, the speed index demonstrates lower than average diurnal windspeed enhancement as on the 28th. With the lowering of the inversion to the surface, windspeed enhancement is maximized on the 31st and a strong sea breeze results. The trend of offshore flow and inland stratus penetration evident in the satellite imagery parallel the trend in boundary layer height although the relationship is not exact. Below is a summary for each day of the period with a brief synopsis on boundary layer height as revealed by the 1200 GMT Oakland sounding and a review of stratus cover evident in GOES visible satellite imagery.

- 28 July 1993
  Stratus coverage = 23.6 hours
  Boundary layer height = High (Fig. 58)
  Speed index = 6.2 m/s
  Imagery (Fig. 59);
    offshore flow = Non-existent
    inland penetration = Coastal California

- 29 July 1993
  Stratus coverage = 11.4 hours
  Boundary layer height = High
  Speed index = 8.6 m/s
  Imagery;
    offshore flow = North of Monterey Bay
    inland penetration = Salinas and Central valleys

- 30 July 1993
  Stratus coverage = 5.3 hours
  Boundary layer height = Lowering
  Speed index = 8.5 m/s
  Imagery;
    offshore flow = Propagating south to Monterey Bay
    inland penetration = Lesser, Salinas valley

- 31 July 1993
  Stratus coverage = 1.4 hours
  Boundary layer height = surface inversion, (Fig. 60)
  Speed index = 11.9 m/s
  Imagery (Fig. 61);
    offshore flow = Strong, propagating south
    inland penetration = Non-existent

- 1 August 1993
  Stratus coverage = 2.5 hours
  Boundary layer height = surface inversion
  Speed index = 9.6 m/s
  Imagery;
    offshore flow = Strong, recovering northward
    inland penetration = Non-existent

- 2 August 1993
  Stratus coverage = 11.9 hours
  Boundary layer height = surface inversion
  Speed index = 10.1 m/s
  Imagery;
    offshore flow = Weakening, north of Monterey Bay
    inland penetration = Slight in coastal regions

- 3 August 1993
  Stratus coverage = 16.9 hours
  Boundary layer height = Low
  Speed index = 8.9 m/s
  Imagery;
    offshore flow = Well north of Monterey Bay
    inland penetration = Entering Salinas valley

2. Frontal Passage Case

Although sea breeze response to changes in boundary layer height appear to be most common, one sea breeze event during the 1992 six-month period clearly deviates from this pattern. The sea breeze event from 10 to 17 June 1992 indicates that mixing of upper level air into the boundary layer can produce an extremely strong diurnal windspeed enhancement as measured by the sea breeze speed index. This period is characterized by a lack of coastal stratus, frontal passage and the reestablishment of the normal boundary layer inversion.

Fig. 62 presents the variation of speed index and stratus coverage between 10 and 17 June. This period shows a progression from low speed index values, ≤ 7 m/s, on the 10th and 11th rising to a maximum of 14 m/s on the 13th followed by an abrupt decrease to lower values for the remainder of the period. Contrasting the speed index progression is the evolution of stratus coverage for the period. The period begins with less than 5 hours of stratus coverage followed by a complete clearing of stratus through the 15th. The stratus deck begins its return on the 16th and is firmly established by the final day of the period.

Reviewing the Oakland soundings for this event reveals that on the 10th (Fig. 63) the boundary layer was capped by a typical subsidence inversion. The inversion weakened on the 11th in advance of a frontal passage and is non-existent on the 12th permitting upper level air to mix with that at lower levels. The sounding for the 13th (Fig. 64), coinciding with the peak in speed index, is notable in the lack of a lower level inversion with frontal passage. The lack of a boundary layer capping inversion lasts until the 16th when inversion formation begins. The 17th (Fig. 65), shows that the inversion has re-established signaling the return to the normal regime.

An examination of the GOES satellite imagery on the 10th (Fig. 66), shows the stratus deck is limited to south of Monterey Bay. This trend continues through the 13th (Fig. 67) for the peak speed index event and clear skies dominate the bay through the 15th. The 16th opens with initial stratus formation in the bay and the 17th (Fig. 68), demonstrates significant coastal stratus in the local area. Below is a summary of each day.

- 10 June 1992
  Stratus coverage = 2.0 hours
  Boundary layer height = Capping inversion (Fig. 63)
  Speed index = 6.5 m/s
  Imagery (Fig. 66);
    offshore flow = Strengthening, north of Monterey Bay
    inland penetration = Coastal, south of bay to Baja California

- 11 June 1992
  Stratus coverage = 0.0 hours
  Boundary layer height = Rising, weakening inversion
  Speed index = 7.0 m/s
  Imagery;
    offshore flow = Strengthening to south
    inland penetration = Non-existent

- 12 June 1992
  Stratus coverage = 0.0 hours
  Boundary layer height = No inversion
  Speed index = 11.6 m/s
  Imagery;
    offshore flow = Continued strengthening south and west
    inland penetration = Non-existent

- 13 June 1992
  Stratus coverage = 0.0 hours
  Boundary layer height = No inversion (Fig. 64)
  Speed index = 14.0 m/s
  Imagery (Fig. 67);
    offshore flow = Weakening to west, strengthening to south
    inland penetration = Non-existent

- 14 June 1992
  Stratus coverage = 0.0 hours
  Boundary layer height = No inversion
  Speed index = 6.2 m/s
  Imagery;
    offshore flow = Weakening west and south
    inland penetration = Initial inland formation in Central valley

- 15 June 1992
  Stratus coverage = 0.0 hours
  Boundary layer height = No inversion
  Speed index = 7.1 m/s
  Imagery;
    offshore flow = Weakening all directions
    inland penetration = Initial coastal formation to south of Monterey Bay

- 16 June 1992
  Stratus coverage = 6.7 hours
  Boundary layer height = Inversion forming
  Speed index = 6.5 m/s
  Imagery;
    offshore flow = Weak, north of Monterey Bay
    inland penetration = Formation in bay

- 17 June 1992
  Stratus coverage = 22.6 hours
  Boundary layer height = Inversion established (Fig. 65)
  Speed index = 6.6 m/s
  Imagery (Fig. 68);
    offshore flow = Northern California and Oregon
    inland penetration = Coastal thickening

C. Summary of Changes in Speed Index

The study of sea breeze index changes indicates that when the boundary layer height at the coast rises a thicker layer of stratus cover is produced which penetrates further inland than the average. Heating along the coastal region is then reduced. There is an increase in the number of hours of stratus coverage at the coast thereby weakening the thermal gradient between the coast and adjacent water. Consequently, less diurnal wind enhancement occurs at the coast resulting in a lower than average speed index and weaker sea breeze.

Conversely, when conditions support a lower than average boundary layer height at the coast less stratus penetration inland is permitted with less marine air over the coastal region. A thinner cloud deck, or the absence of stratus along the coast decreases the number of hours of stratus coverage at a coastal station resulting in an augmented thermal gradient between the land and water. In this case, a stronger diurnal windspeed enhancement is produced with a higher valued speed index and the arrival of a stronger sea breeze. The speed index and boundary layer variation cycle is well presented in the August 1993 period.

The index can be affected by other processes as well. With the occurrence of frontal passage, typically during the spring, the low level inversion is lifted and weakened. Stronger low and mid level winds associated with a mid-latitude pressure system can then mix with surface winds. This process evidently can also create strong diurnal wind enhancement as illustrated by the June 1992 case.

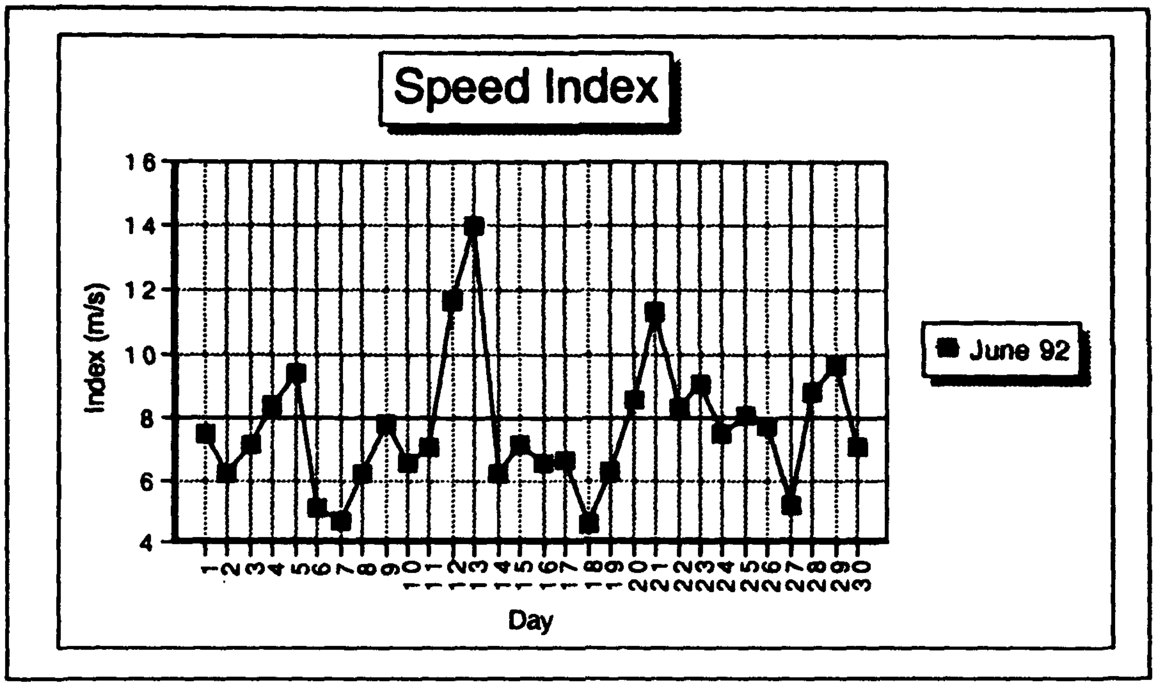


Figure 53. Temporal fluctuations of speed index for June 1992. Heavy line indicates monthly average.

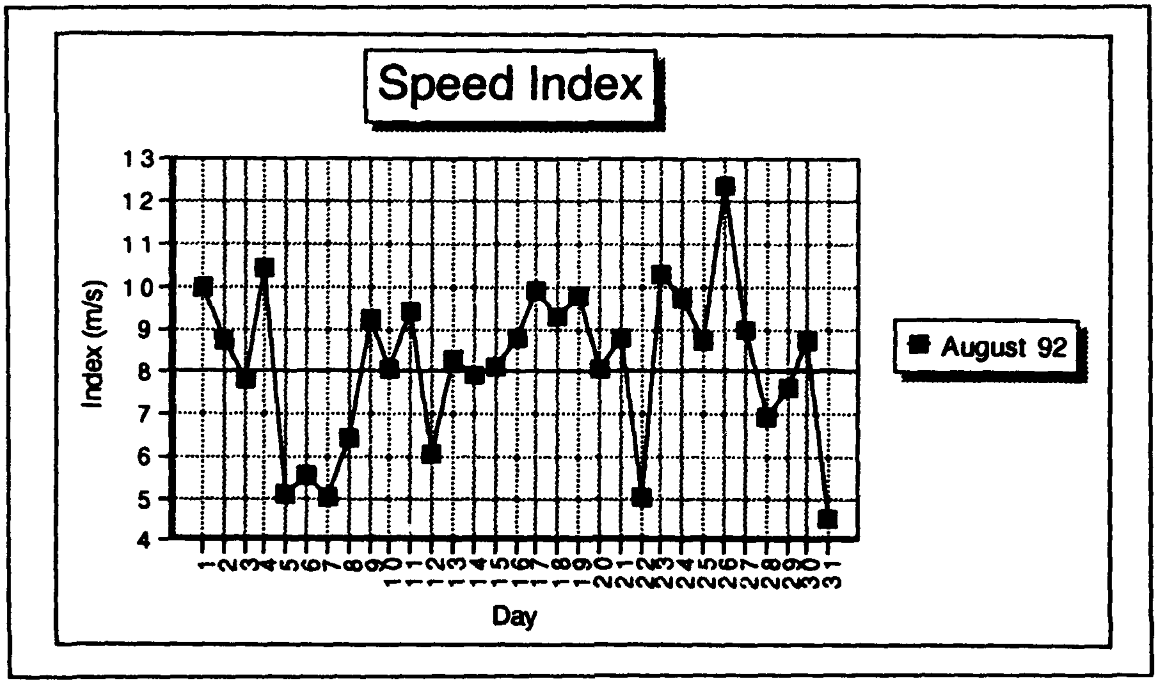


Figure 54. Same as 53 for August 1992.

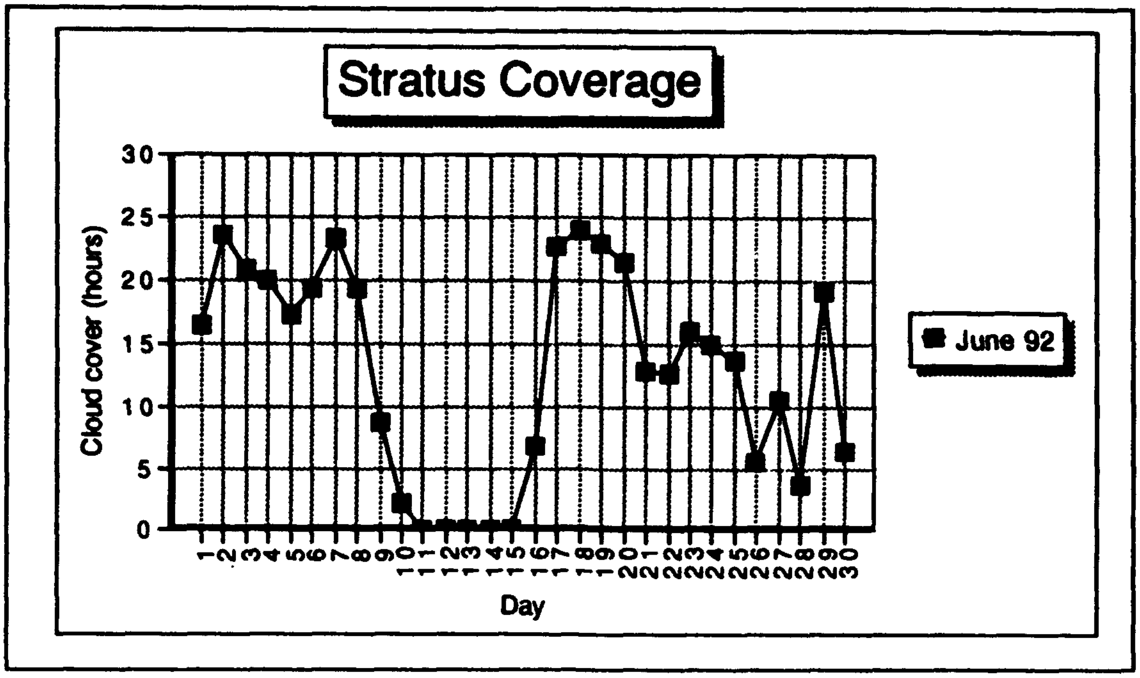


Figure 55. Temporal fluctuations of stratus coverage for June 1992.

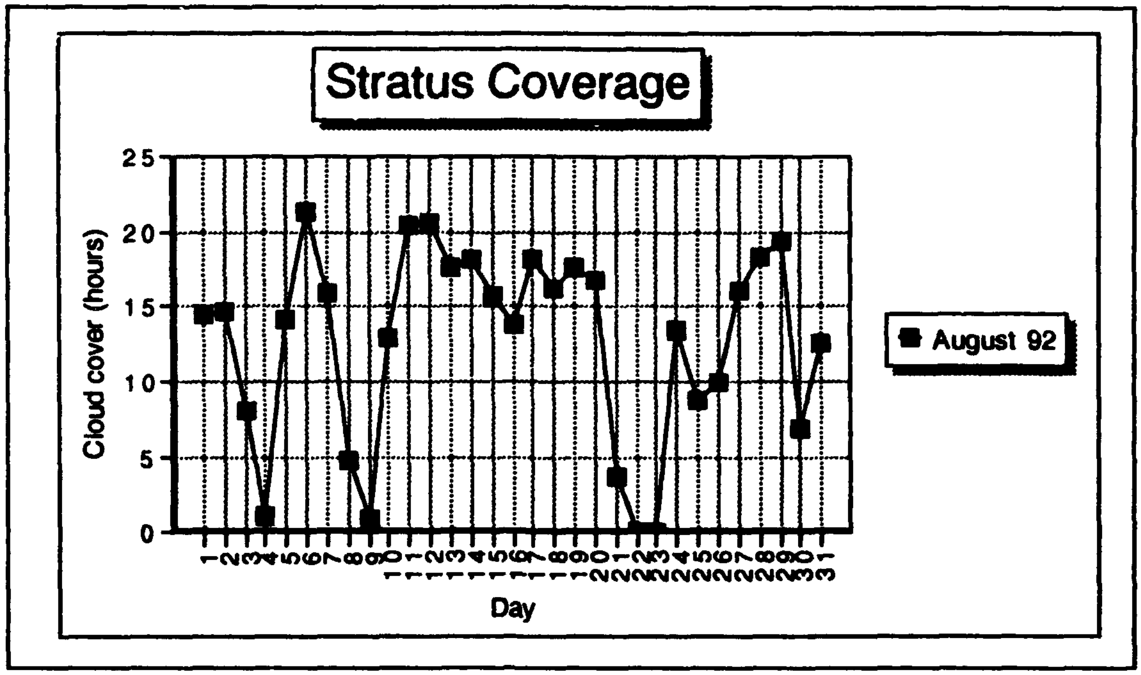


Figure 56. Same as 55 for August 1992.

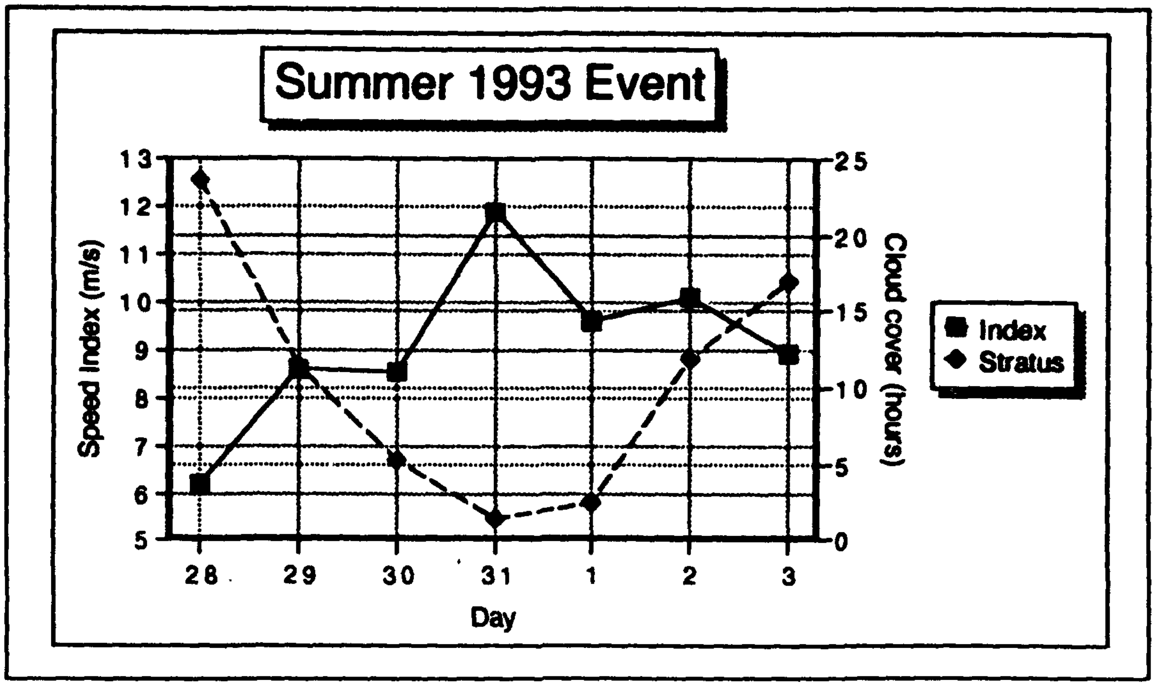


Figure 57. July 28 - August 3, 1993 sea breeze event showing changes in stratus coverage and diurnal windspeed enhancement reflected in speed index.

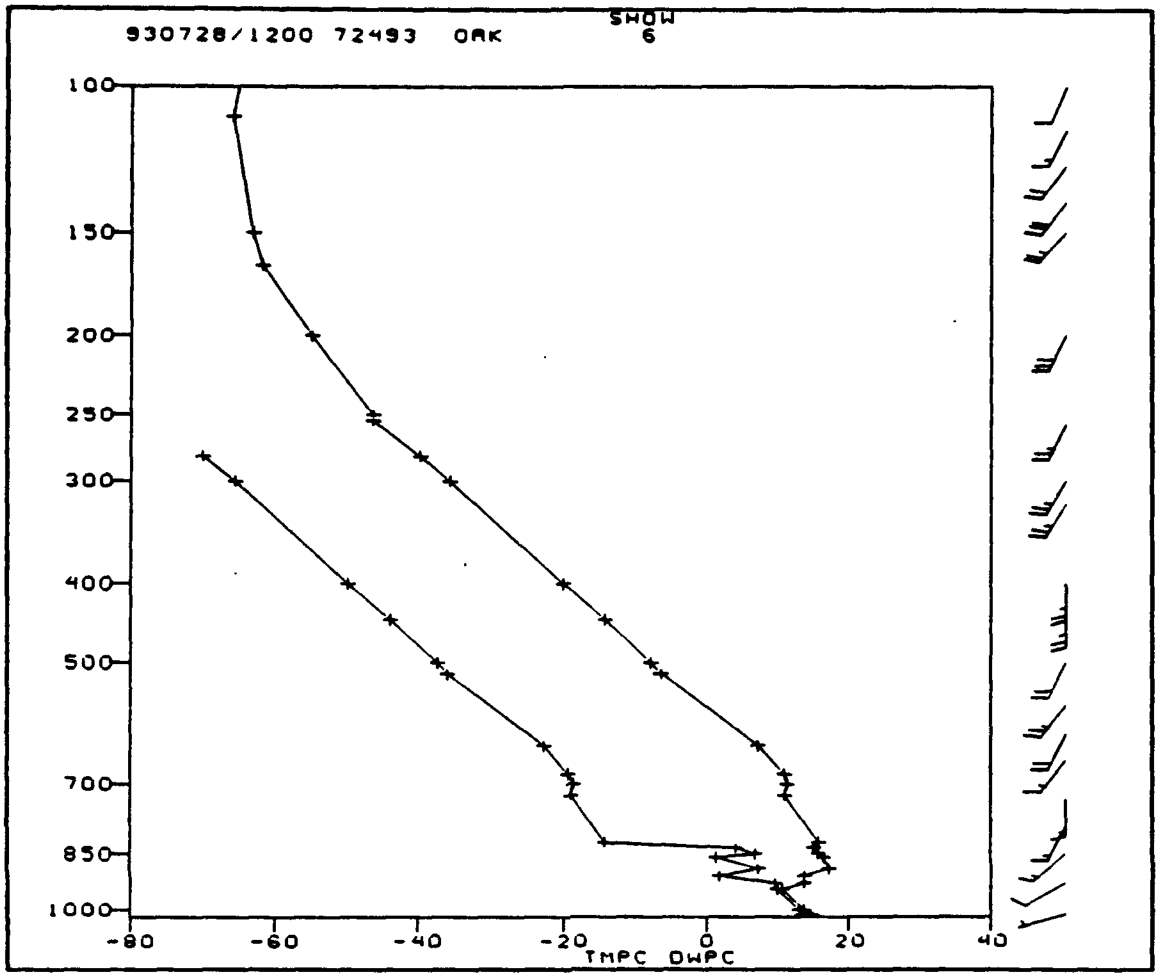


Figure 58. Oakland sounding showing elevated inversion indicating a relatively deep Marine Boundary Layer for 1200 GMT, 28 July 1993.

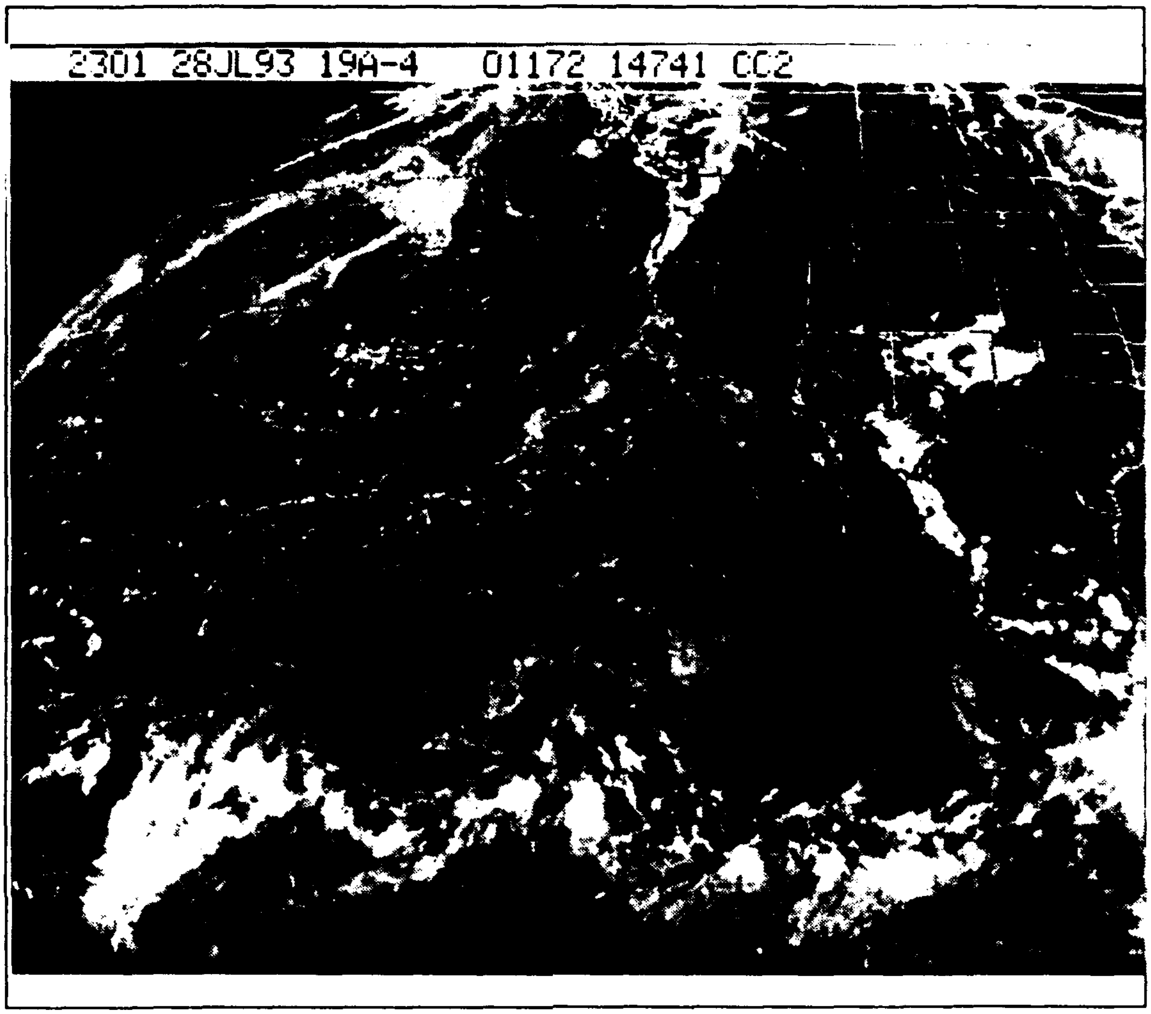


Figure 59. GOES visible satellite image for 2300 GMT, 28 July 1993 showing offshore flow and stratus penetration inland with an elevated coastal boundary layer.

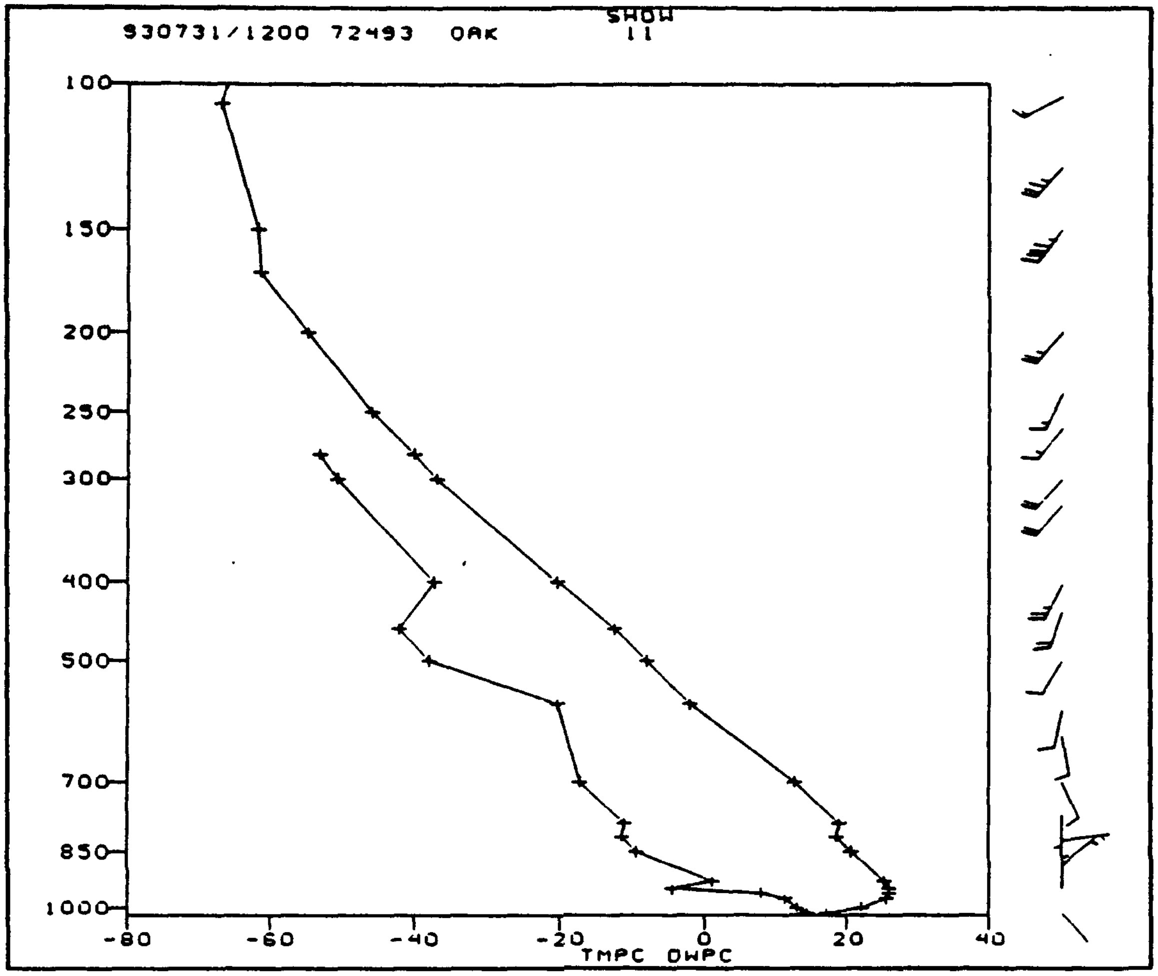


Figure 60. Oakland sounding for 1200 GMT, 31 July 1993.

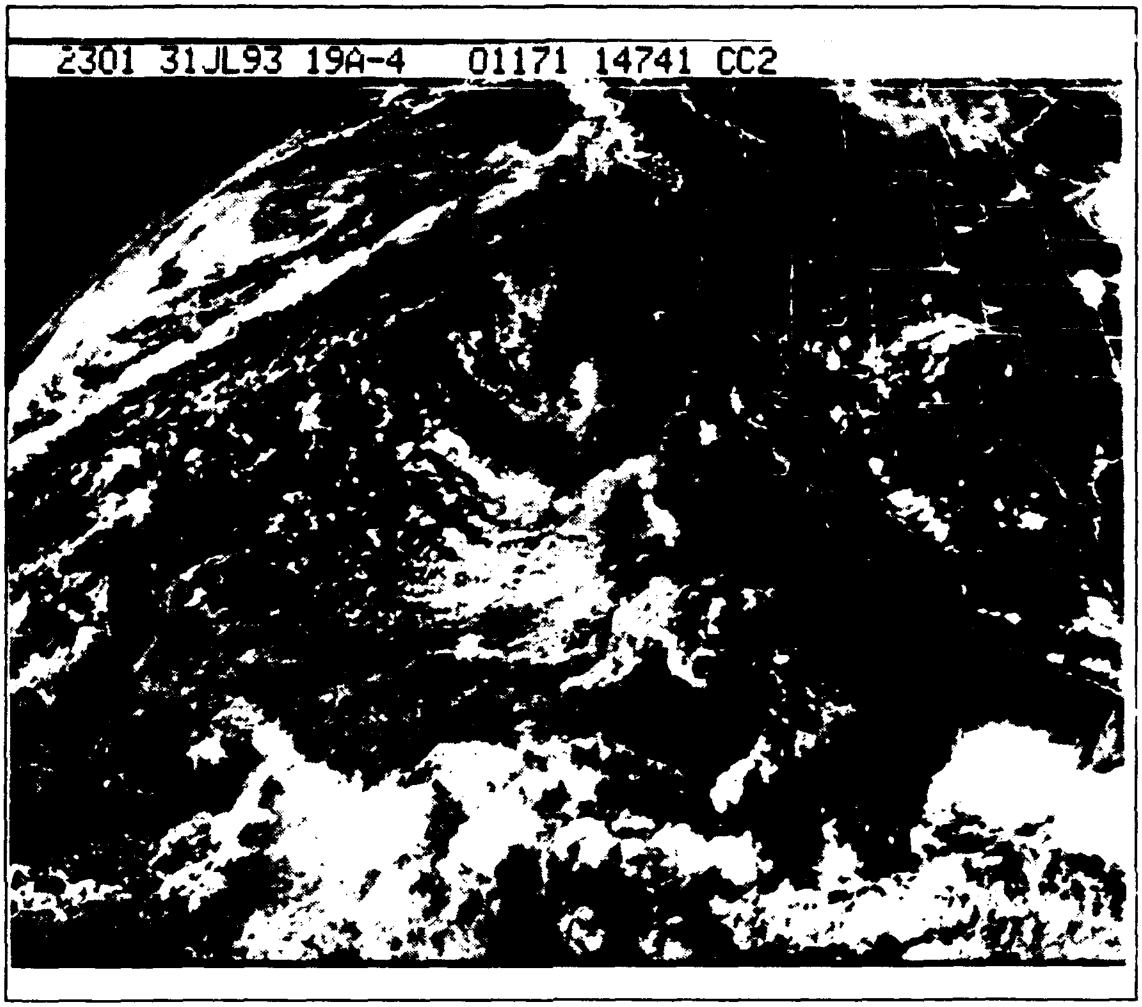


Figure 61. GOES visible satellite image for 2300 GMT, 31 July 1993 showing offshore flow and stratus penetration pattern.

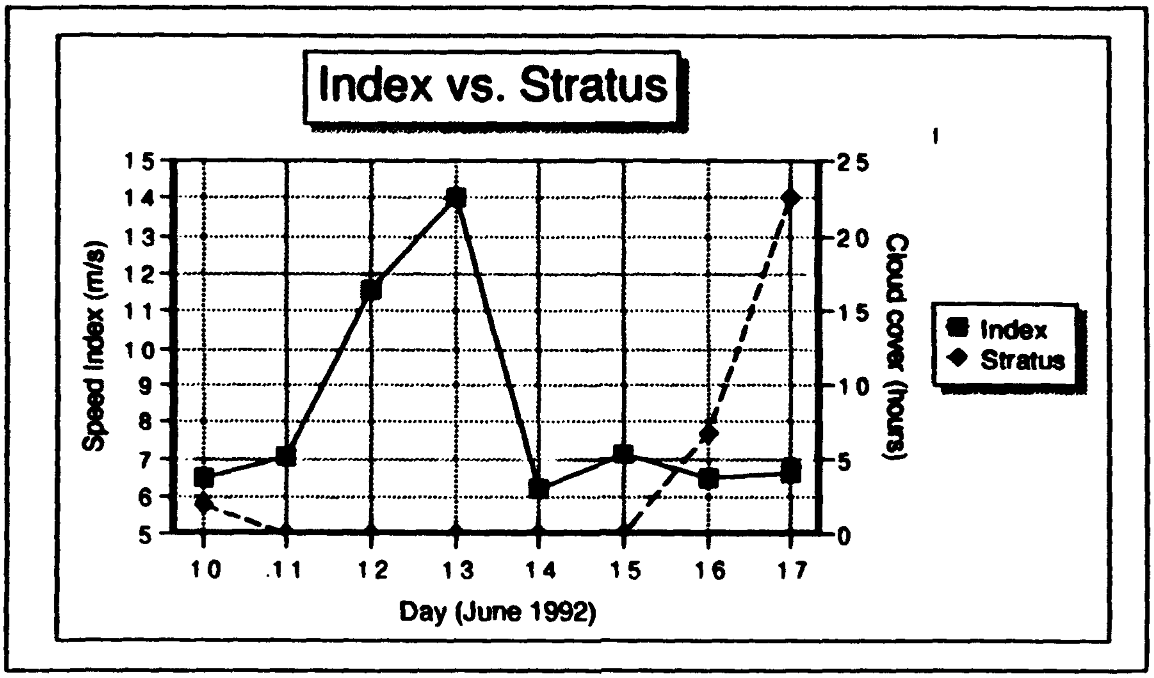


Figure 62. Temporal variation of speed index and stratus coverage for the period 10-17 June, 1992.

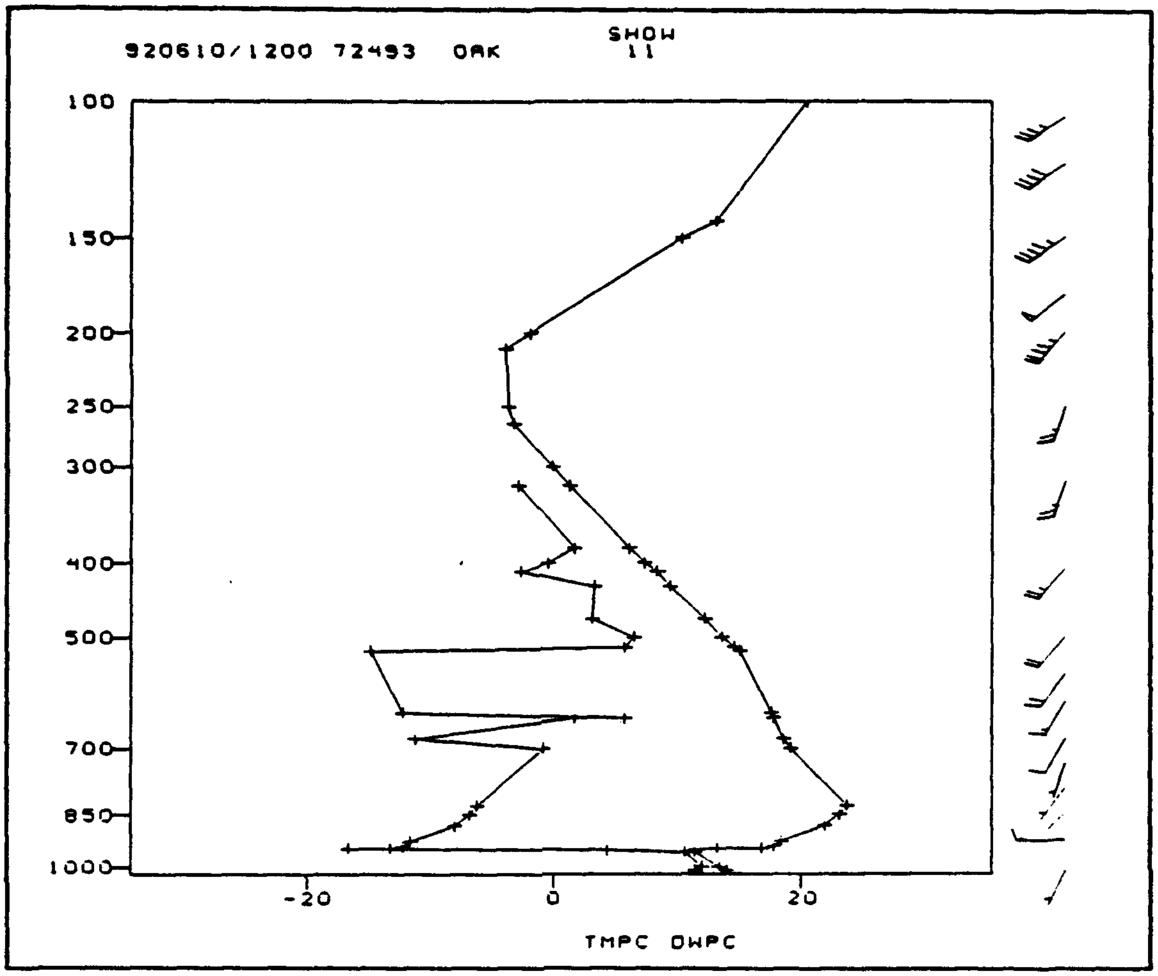


Figure 63. Oakland sounding for 1200 GMT, 10 June 1992.

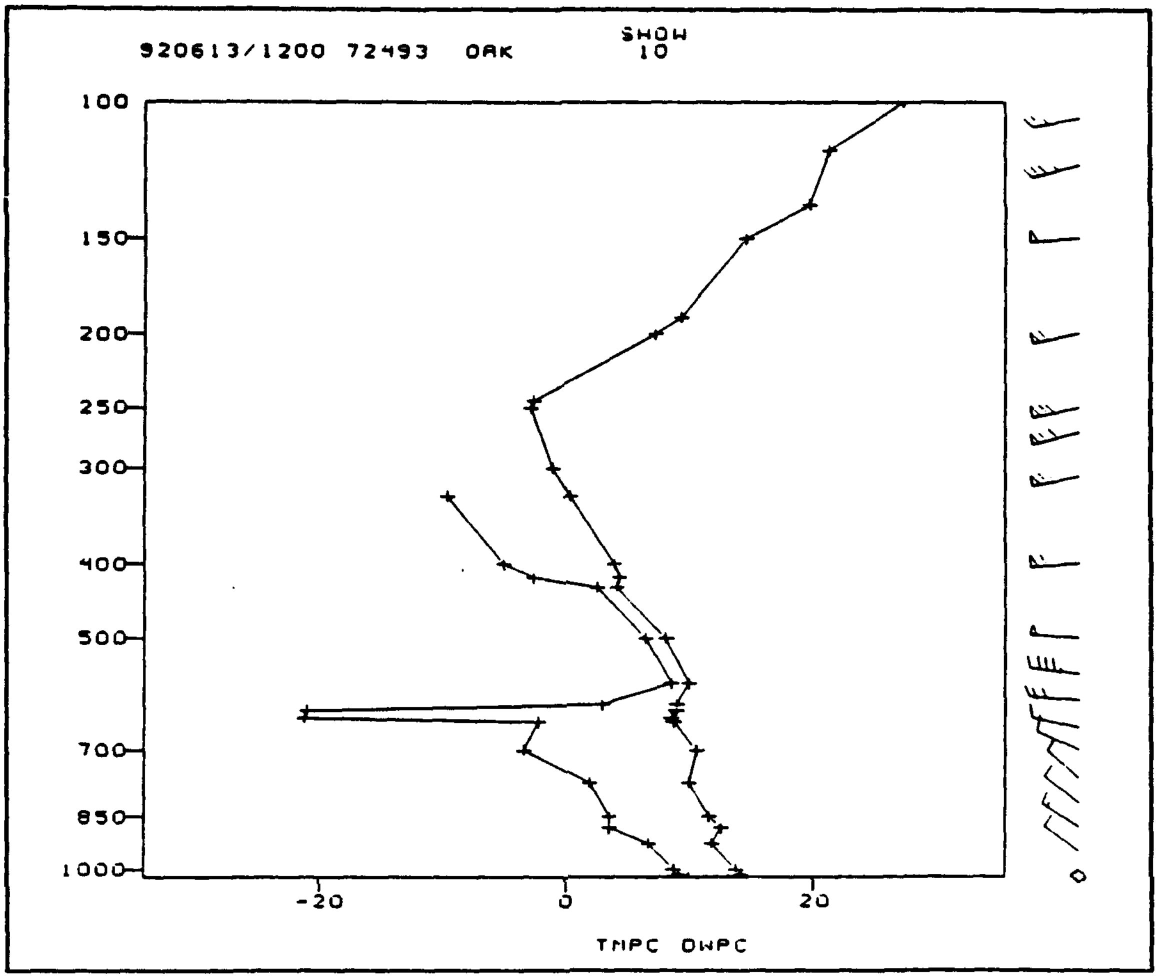


Figure 64. Oakland sounding for 1200 GMT, 13 June 1992.

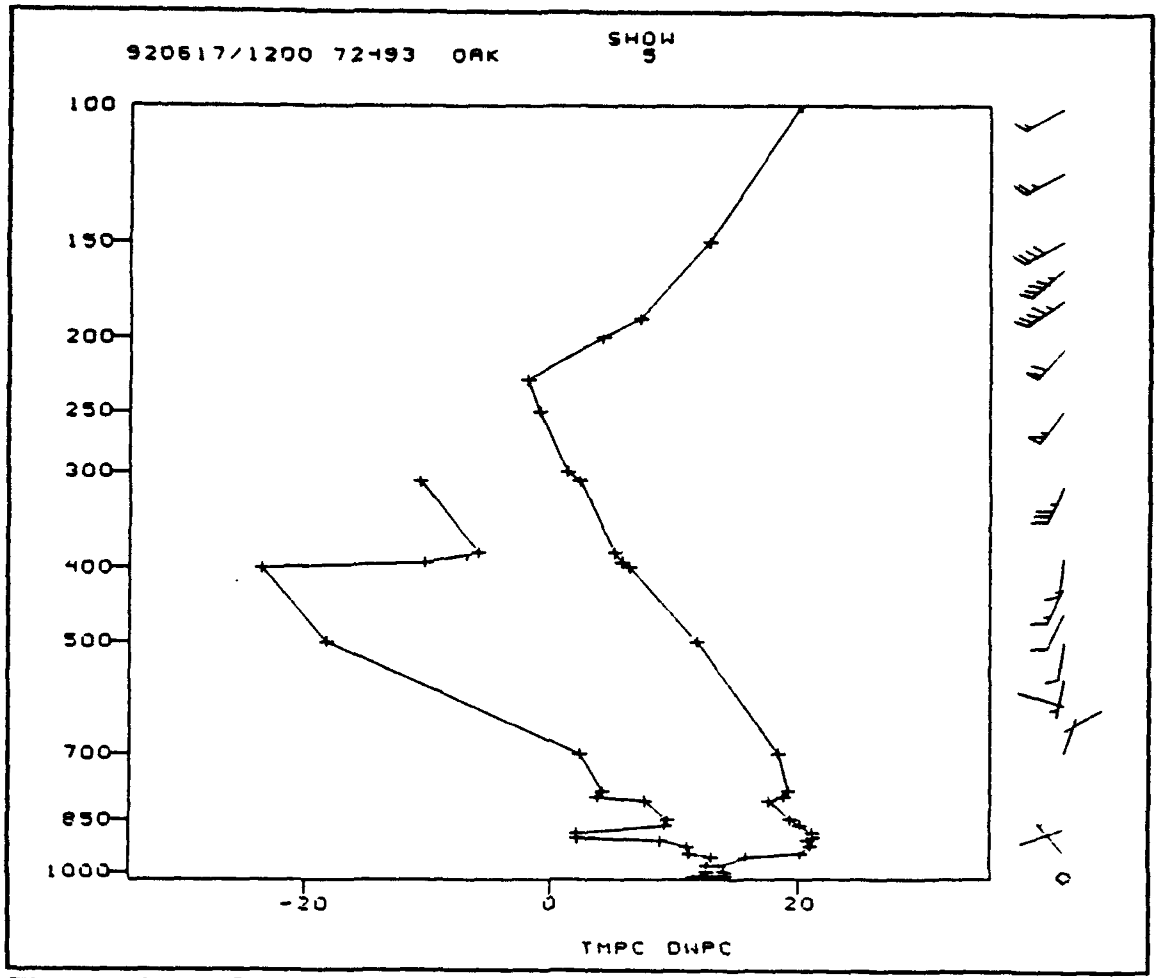


Figure 65. Oakland sounding for 1200 GMT, 17 June 1992.

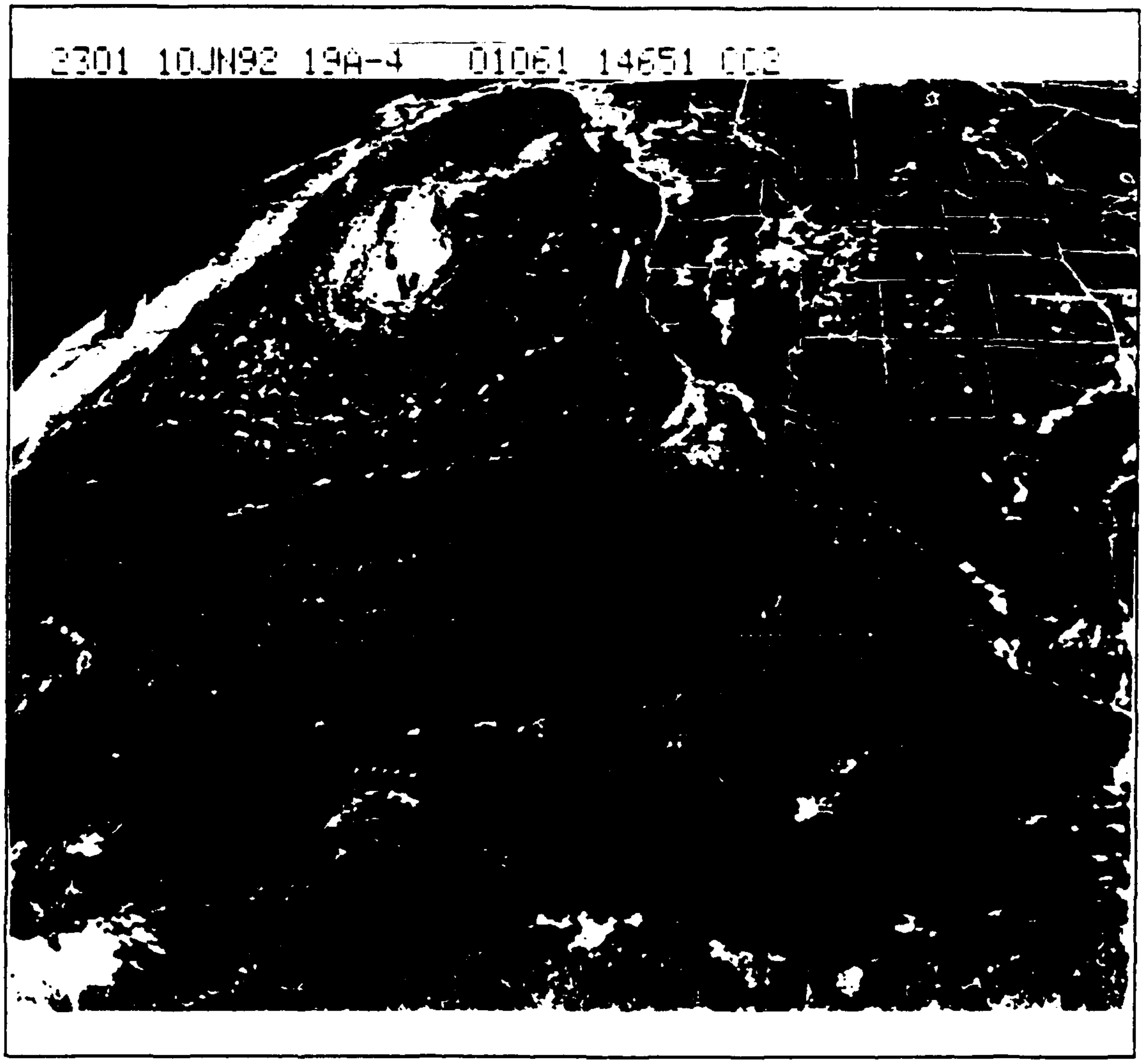


Figure 66. GOES visible satellite image for 2300 GMT, 10 June 1992 showing offshore flow and stratus penetration.

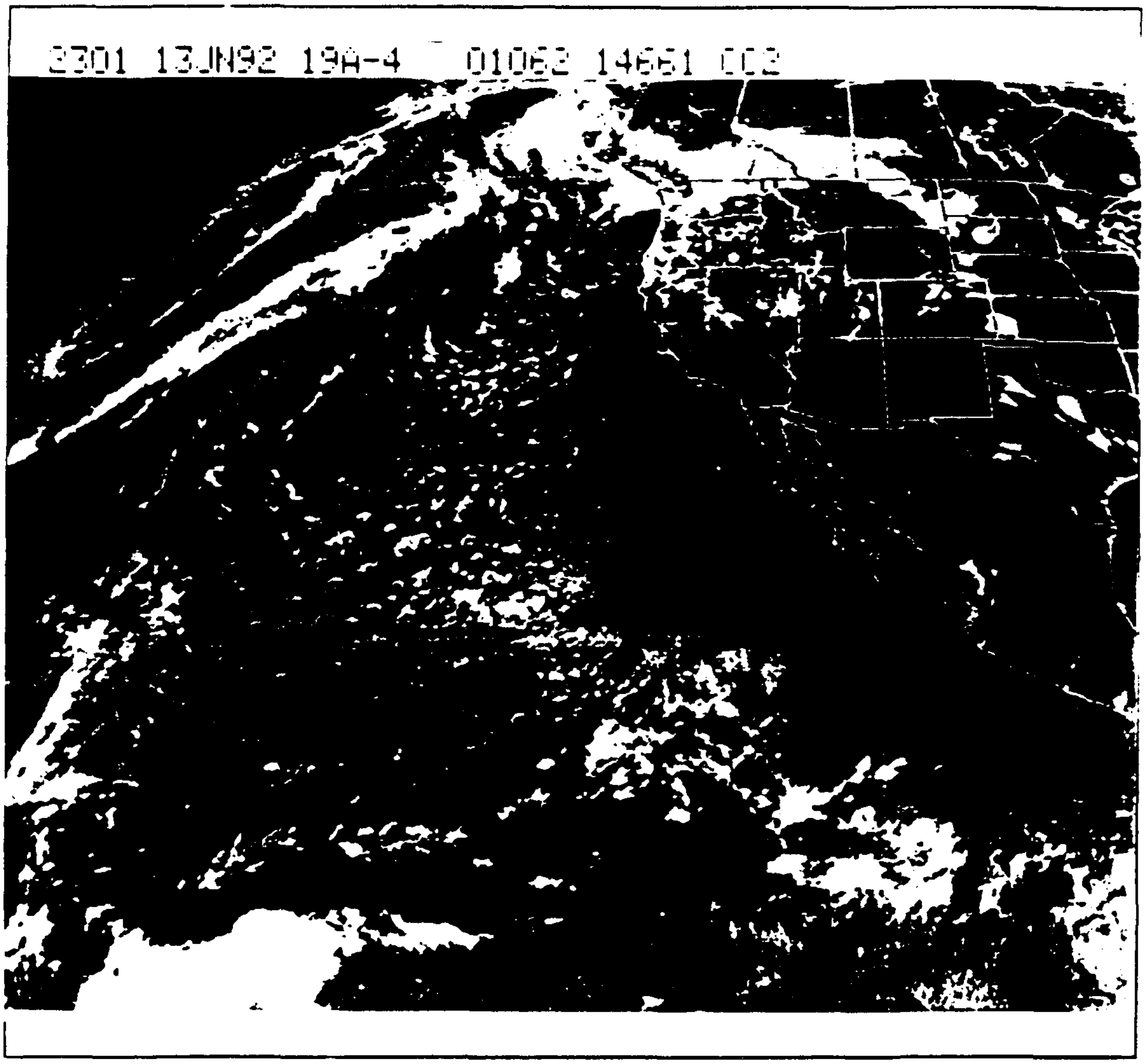


Figure 67. GOES visible satellite image for 2300 GMT, 13 June 1992 showing offshore flow and stratus penetration.

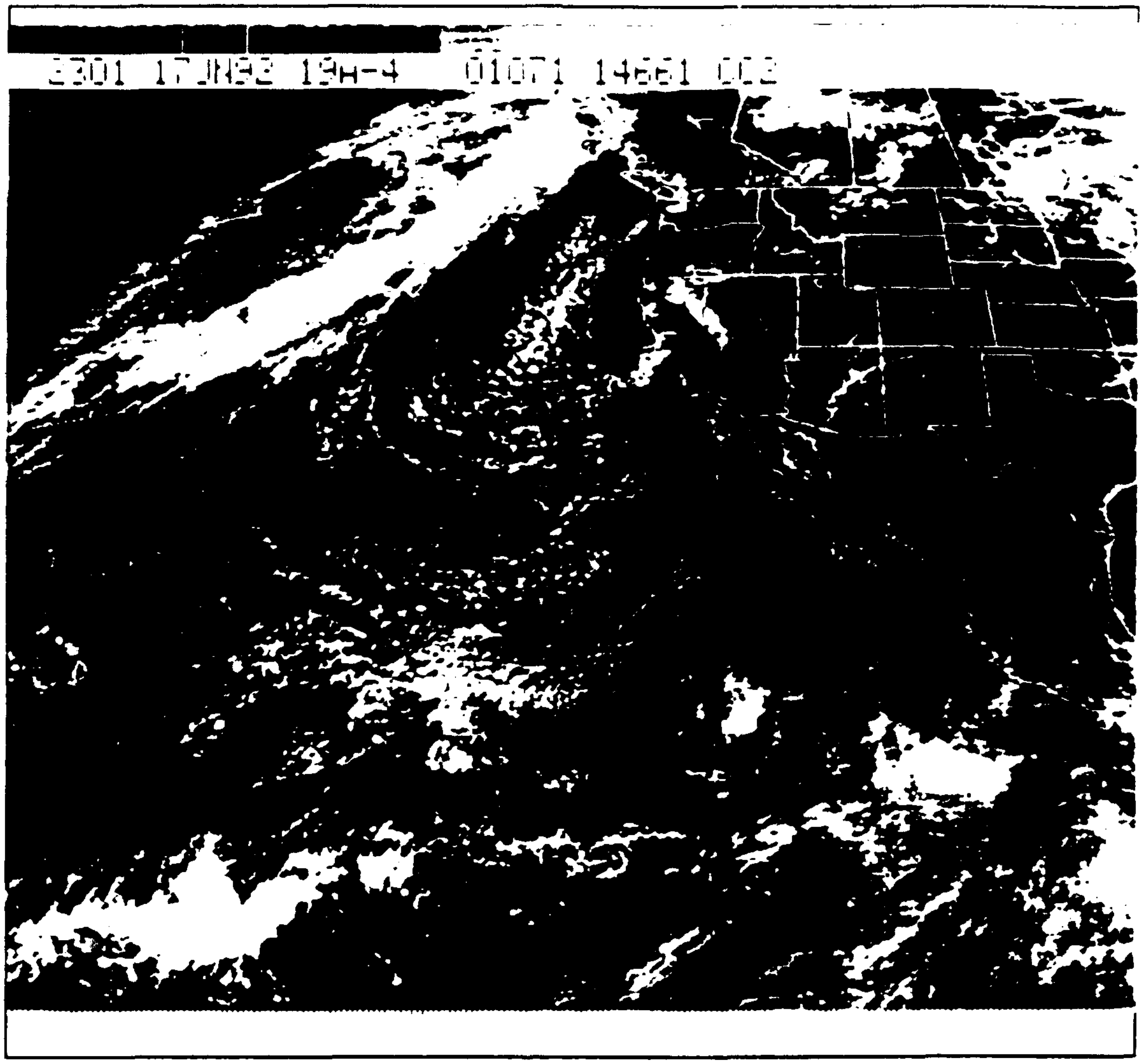


Figure 68. GOES visible satellite image for 2300 GMT, 17 June 1992 revealing the return of coastal stratus.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The results presented in this study demonstrate one example in a broad range of applications of continuous surface meteorological data. Continuous observation systems permit the quantification and analysis of rapidly changing, small-scale meteorological events such as the sea breeze. This study used two-minute continuous records of surface data to quantify hourly maximum and minimum averaged windspeeds and the time they occurred. This allowed the computation of a measure of diurnal windspeed enhancement in a speed index which provided insight into daily sea breeze intensity. The data also provided almost instantaneous changes in wind direction and a means to calculate the number of hours of stratus coverage at the sensor site through the evaluation of a minimum longwave irradiance threshold. Finally, daily graphical representations of the data revealed significant variations in sea breeze intensity furnishing a means to categorize recurring patterns.

Four separate sea breeze categories were identified in the surface data. Of these four; gradual development, clear onset, frontal and double surge, two categories predominantly appear. The gradual development sea breeze was most common occurring approximately 36 % of the days examined in the climatological study. This circulation was shown to primarily be of weak to moderate intensity associated with onshore flow. The frontal sea breeze followed the gradual development in frequency of occurrence at 29 % of the days during the six-month period. In contrast to the gradual development, this is a stronger intensity circulation overcoming large-scale offshore flow.

The daily variation in sea breeze intensity shown in frequency distributions and time-series of speed index demonstrate periods of an inverse relation between sea breeze intensity and hours of stratus coverage. Case studies showed significantly high deviations in speed index accompanied low values in hours of stratus with the reverse occurring as well. Further examination through an analysis of GOES visible satellite imagery and temperature soundings for 10 cases extended this relationship to include depth of the marine boundary layer. Minimal stratus penetration inland occurred with a shallow boundary layer depth and short periods of stratus coverage. This allowed adequate heating of the coastal region to produce strong diurnal windspeed enhancement reflected in the appearance of a strong intensity sea breeze. When stratus penetrated deeply inland with deep boundary layers as reflected by longer periods of stratus coverage, the coastal thermal contrast between land and water was evidently reduced leading to weaker diurnal windspeed enhancement and weak sea breezes. This pattern of speed index, stratus coverage and boundary layer depth does not exclusively explain variations in sea breeze intensity, as shown in the second case study, but dominated in the examination of the majority of the cases investigated.

Lacking the capability of taking local soundings, satellite imagery provided a means to analyze the trend in boundary layer depth through examination of the trend in stratus coverage. Though not ideal, this procedure does allow a crude estimation of the magnitude of sea breeze intensity. This technique should be useful in connection with the rapid deployment of Automated Surface Observation Systems (ASOS) and other complimentary continuous surface observation systems.

The expansion of ASOS and similar systems offers a network of stations which continuously monitor meteorological surface data. These assets will permit similar analyses of the surface environment at high frequency promoting increased emphasis on mesoscale analysis. The development of standard analysis methods of this data should greatly further the understanding of small-scale phenomena.

B. RECOMMENDATIONS

The necessity of taking local temperature soundings in the determination of boundary layer depth was demonstrated in this thesis. A reliance on supporting observational data from different sites prevents a complete analysis of the local data and the determination of how singular continuous observation systems can be used to interpret the local environment. The implementation of a 915 MHz profiler with the capability of taking temperature soundings hopefully will solve this problem. It will also permit a higher spatial resolution analysis of the structure of the winds throughout the boundary layer.

This thesis also showed the need to continue a detailed mesoscale climatology with two-minute data resolution over multiple years. The ASOS network should also be incorporated into the climatology and analysis as it becomes available. A thorough understanding of mesoscale phenomena using these systems is needed to solve aviation and other meteorological forecast problems.

LIST OF REFERENCES

Anthes, R.A., 1978: "The Height of the Planetary Boundary Layer and the Production of Circulation in a Sea Breeze Model." J. Atmos. Sci., 35, 1232-1239.

Arrit, R.W., 1993: "Effects of Large-Scale Flow on Characteristic Features of the Sea Breeze." J. Appl. Met., 32, 116-125.

Banta, R.M., Olivier, L.D., & Levinson, D.H., 1992: "Evolution of the Monterey Bay Sea-Breeze Layer as Observed by Pulsed Doppler Lidar." Unpublished manuscript presented to Journal of the Atmospheric Sciences.

Beardsley, R.C., Dorman, C.E., Friehe, C.A., Rosenfeld, L.K. & Winant, C.D.,1987: "Local Atmospheric Forcing During the Coastal Ocean Dynamics Experiment 1. A Description of the Marine Boundary Layer and Atmospheric Conditions Over a Northern California Upwelling Region." J. Geo. Res., 92, 1467-1488.

Biggs, W.G. & Graves, M.E., 1962: "A Lake Breeze Index." J. Appl. Met., 1, 474-480.

Elliot, D.L. & O'Brien J.J., 1977: "Observational Studies of the Marine Boundary Layer over an Upwelling Region." Mon. Wea. Rev., 105, 86-98.

Estoque, M.A., 1962: "The Sea Breeze as a Function of the Prevailing Synoptic Situation." J. Atmos. Sci..,19,244-250.

Fett, R.W. & Tag, P.M., 1984: "The Sea-Breeze-Induced Coastal Calm Zone as Revealed by Satellite Data and Simulated by a Numerical Model." Mon. Wea. Rev., 112, 1226-1233.

Fisher, E.L., 1960: "An Observational Study of the Sea Breeze." J. Met., 17, 645-660.

Haurwitz, B., 1947: "Comments on the Sea-Breeze Circulation." J. Meteor., 4, 1-8.

Hsu, S., 1970: "Coastal Air-Circulation System: Observations and Empirical Model." Mon. Wea. Rev. 98, 487-509.

Johnson, A. & O'Brien, J.J., 1973: "A Study of an Oregon Sea Breeze Event." J. Appl. Meteor., 12, 1267-1283.

Neal, T.C., 1992: *Analysis of Monterey Bay CODAR-derived Surface Currents, March to May 1992*. M.S. Thesis, Naval Postgraduate School, Monterey, California, 95 pp.

Nuemann, J. & Mahrer, Y., 1974: "A Theoretical Study of the Sea and Land Breezes of Circular Islands." J. Atmos. Sci., 31, 2027-2039.

Pearce, R.P., 1955: "The calculation of a sea-breeze circulation in terms of the differential heating across the coastline." Q. Jl. R. met. Soc., 81, 351-381.

Pielke, R.A., 1974: "A Three-Dimensional Numerical Model of the Sea Breezes Over South Florida." Mon. Wea. Rev., 102, 115-139.

Ramis, C. & Alonso, S.,1988: "Sea Breeze Convergence Line in Majorca." Weather, 43, 288-293.

Rosenfeld, L.K., 1988: "Diurnal Period Wind Stress and Current Fluctuations Over the Continental Shelf off Northern California." J. Geo. Res., 93, 2257-2276.

Segal, M. & Arrit, R.W., 1992: "Nonclassical Mesoscale Circulations Caused by Surface Sensible Heat-Flux Gradients." B. Am. Met. Soc., 73, 1593-1604.

____, Purdom, J.F.W., Pielke, R.A., Mahrer, Y. & Song, J.L., 1986: "Evaluation of cloud shading effects on the generation and modification of mesoscale circulations." Mon. Wea. Rev., 114, 1201-1212.

____, Avissar, R., McCumber, M. & Pielke, R.A., 1988: "Evaluation of vegetation effects on the generation and modification of mesoscale circulations." J. Atmos. Sci., 45, 2268-2292.

Simpson, J.E., 1964: "Sea-breeze fronts in Hampshire." Weather, 19, 208-220.

________, 1967: "Aerial and radar observations of some sea-breeze fronts." Weather, 22, 306-316.

________, Mansfield, D.A., & Milford, J.R., 1977: "Inland penetration of sea-breeze fronts." Q. Jl. R. met. Soc., 103, 47-76.

Skupniewicz, C.E., Glendening, J.W., & Kamada, R.F., 1991: "Boundary-Layer Transition across a Stratocumulus Edge in a Coastal Zone." Mon. Wea. Rev., 119, 2337-2357.

Wallington, C.E., 1965· "Gliding through a sea-breeze front." Weather, 20, 140-145.

Wexler, R., 1946: "Theory and Observations of Land and Sea Breezes." B. Am. Met. Soc., 27, 272-287.

Yetter, J.A., 1990: *The nature of the propagation of sea breeze fronts in central California*. M.S. Thesis, Naval Postgraduate School, Monterey, California, 65 pp.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Technical Information Center Cameron Station Alexandria, VA 22304-6145	2
2.	Attn: Library, Code 52 Naval Postgraduate School Monterey, CA 93940-5000	2
3.	Superintendent Attn: Chairman, Department of Meteorology (Code MR/HY) Naval Postgraduate School Monterey, CA 93940-5000	1
4.	Superintendent Attn: Chairman, Department of Oceanography (Code OC/CO) Naval Postgraduate School Monterey, CA 93940-5000	1
5.	Superintendent Attn: Professor C.H. Wash (Code MR/WX) Naval Postgraduate School Monterey, CA 93940-5000	1
6.	Superintendent Attn: Assistant Professor W. Nuss (Code MR/NU) Naval Postgraduate School Monterey, CA 93940-5000	1

7. Lieutenant Robert D. Round 1
12713 Overbrook Rd.
Leawood, KS 66209

8. Superintendent 1
Naval Research Laboratory
7 Grace Hopper Avenue Stop 2
Monterey, CA 93943-5502

9. Chairman 1
Oceanography Department
U.S. Naval Academy
Annapolis, MD 21402

10. Office of Naval Research (Code 420) 1
800 N. Quincy Street
Arlington, VA 22217

11. Library 1
Scripps Institution of Oceanography
P.O. Box 2367
La Jolla, CA 92037

12. Chief, Technical Procedures Branch 1
National Weather Service
National Oceanic and Atmospheric Administration
Silver Springs, MD 20910

13. NOAA Library 1
7600 Sand Point Way NE
Building 3
Seattle, WA 98115