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A CLIMATOLOGY OF THE SEA BREEZE AT CAPE CANAVERAL, FLORIDA

By

JEFFREY DAVID CETOLA

A thesis submitted to the
Department of Meteorology
in partial fulfillment of the
requirements for the degree of
Master of Science

Degree Awarded:

Summer Semester, 1997

The members of the Committee approve the thesis of Jeffrey D. Cetola defended on July 1, 1997.

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ABSTRACT

A climatology of the Cape Canaveral, Florida sea breeze has been established using data from the warm seasons of 1995 and 1996. Data from the Cape Canaveral mesoscale tower network were used to locate the sea breeze, determine its inland penetration, and assess its time of passage. Visible satellite imagery centered over Melbourne, Florida also were used for this purpose. Radiosonde data were used to determine the large-scale flow over the region. A total of 357 days was analyzed. These days were classified as sea-breeze days, non-sea-breeze days, or undetermined. Undetermined days (40) were removed from the final sample, leaving a total of 317 days. River breezes and other local circulations were analyzed and related to the sea breeze, and the presence of convection was related to sea-breeze occurrence and large-scale flow.

An onshore sea breeze was observed on 194 of 317 days (61%) during the warm season. It was likely to form on days with large-scale flow from any direction but northeast. The average time of sea-breeze passage at tower 112 was determined to be 1528 UTC. The sea breeze penetrated the entire Cape Canaveral tower network (30 km) on 81% of the 194 sea-breeze days investigated. Inland penetration was reduced, and passage time was delayed, for offshore flow greater than 4 m s^{-1}. The river breezes that were observed on 116 days tended to occur when the large-scale flow was weak. A trailing convergence line was observed behind the sea-breeze front on 30 days. This line formed on days with weak large-

scale forcing. Thunderstorms were observed on 53% of the sea-breeze days, and storms were most likely when the large-scale flow was from the southwest.

Thresholds were established for the onshore and offshore large-scale wind components associated with inland sea-breeze occurrence. Observations indicated an offshore maximum of 12.9 m s^{-1} and an onshore maximum of 6.7 m s^{-1} for the Cape Canaveral area. In general, sea breezes occur over the Cape Canaveral area for onshore flow no greater than 6 m s^{-1} and offshore flow no greater than 10 m s^{-1}. These values are somewhat higher than those derived from previous, numerical studies. Current results indicate that some findings from two-dimensional sea-breeze modeling studies are not applicable to Cape Canaveral's complex land/sea interface.

1. INTRODUCTION

a. Background

The sea breeze is a thermally-direct mesoscale circulation that occurs in coastal regions primarily during the warm season. That is when the daytime land temperature is most likely greater than the temperature of the adjacent water. A sea breeze forms when the temperature difference between the land and sea is large enough to overcome any forcing by the large-scale wind (Reible et al. 1991; Zhong and Takle 1992; Simpson 1994).

After sunrise, the land heats more rapidly than the nearby ocean. This heating produces a shallow thermal low over the land. Since the air over the adjacent water remains relatively cool, a shallow thermal high forms over the water. When there is a sufficient temperature gradient between the land and water, the sea breeze forms and moves toward the shore. Sea-breeze related wind speeds increase during the day reaching a peak near the time of maximum heating--the time of greatest temperature difference between land and sea. After sunset, land temperatures decrease, and the temperature gradient between the land and water diminishes. As a result, the sea-breeze circulation ends, and the large-scale flow becomes predominant. If the land temperature decreases to become sufficiently cooler than the water temperature (which cools much more slowly), a reverse of the sea breeze, called a land breeze, can develop. Since the land-sea temperature gradient during the evening is not as great as during the day, land-breeze circulations are weaker than their daytime counterparts.

The leading edge of the sea breeze, called the sea-breeze front, is a region of enhanced low-level convergence and vertical motion that is often associated with convection (e.g., Gentry and Moore 1954; Nicholls et al. 1991). The sea-breeze front often has the shape of the nearest coastline. If the coastline is curved, there can be localized regions of even greater convergence over land in some locations (Laird et al. 1994; Pielke 1974; Neumann 1951; Laird et al. 1995). Furthermore, as the sea breeze moves onshore, interactions with other locally-induced circulations, such as river breezes, can produce areas of enhanced convergence and convection (Pielke et al. 1991; Zhong and Takle 1992; Laird et al. 1995).

The river breeze is a mesoscale circulation that forms in the same manner as the sea breeze (Simpson 1994). When the temperature of the land increases and sufficiently exceeds the temperature of the river, low-level flow from the water body to the land begins. This produces divergent flow over the river. The same effect is seen with lakes and other large water bodies. In general, the temperature of the river is warmer than that of the nearby ocean. As a result, river breezes are not as strong as sea breezes.

b. Previous Studies

The sea breeze is one of the most studied meteorological circulations. Both numerical and diagnostic studies have been performed.

The majority of sea-breeze studies have utilized two-dimensional numerical models (e.g., Walsh 1974; Arritt 1993; Estoque 1962; Bechtold et al. 1991; Nicholls et al. 1991; Xian and Pielke 1991). Although this research has provided an excellent explanation of general sea-breeze characteristics and large-scale forcing thresholds, it cannot account for three-dimensional features such as coastline curvature and inland water bodies. These factors can have a dramatic impact on the behavior of the sea breeze and its associated convection.

Three-dimensional numerical models of the sea breeze account for coastal irregularities, and several researchers have studied the sea breeze using them (e.g., McPherson 1970; Pielke 1974; Zhong et al. 1991; Zhong and Takle 1993; Lyons et al. 1995). These models have further enhanced our understanding of sea-breeze characteristics in regions with complex coastlines.

In addition to the numerical studies, many diagnostic studies have been completed. Case studies spanning one to two days (Laird et al. 1994; Zhong and Takle 1992; Kingsmill 1995; Laird et al. 1995; Guillory and Jedlovec 1994; Wakimoto and Atkins 1994) and climatological studies (Gentry and Moore 1954; Intrieri et al. 1990; Simpson et al. 1977; Blanchard and Lopez 1985) have provided detailed information about observed sea-breeze characteristics.

c. The Cape Canaveral Sea Breeze

The Cape Canaveral region of central Florida has a complex coastline (Fig. 1) that complicates sea-breeze behavior. The convex coast of the Cape Canaveral region is surrounded by the Atlantic Ocean and several inland water bodies--the Indian River, the Banana River, and the Mosquito Lagoon. Land features include mainland Florida, Merritt Island, and a barrier island known as Cape Canaveral Proper. The area is home to the National Aeronautics and Space Administration (NASA) Kennedy Space Center (KSC) and the United States Air Force Eastern Range. Space shuttle and other spacelift activities at

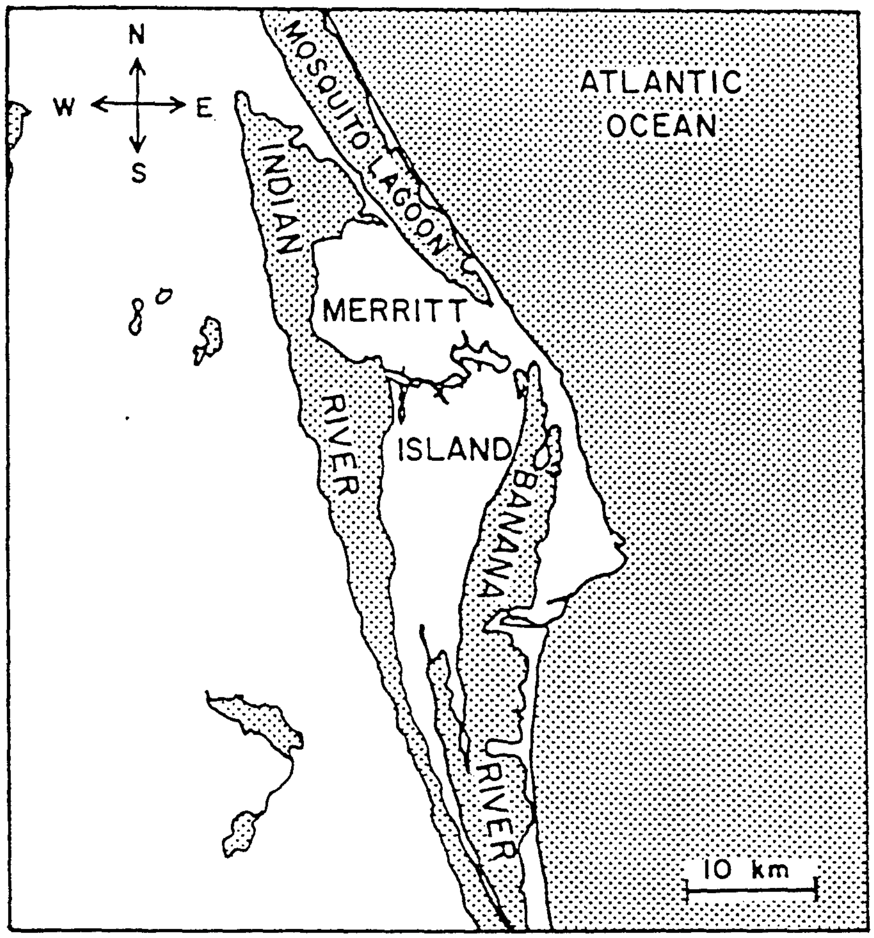

Fig. 1. Physiographic features near Cape Canaveral, Florida.

these sites are extremely weather sensitive, especially to convection.

The Cape Canaveral region has an extensive network of meteorological sensing equipment for use in research and operational forecasting. Numerous diagnostic and numerical studies of the Cape Canaveral area sea breeze have utilized this information (Zhong and Takle 1993; Laird et al. 1994; Laird et al. 1995; Zhong and Takle 1992; Guillory and Jedlovec 1994; Reed 1979; Watson et al. 1991). Nonetheless, an extensive climatology of the sea breeze in this area has not been performed.

Convection is a major operational consideration in the Cape Canaveral area. Florida has the greatest concentration of thunderstorm activity of any of the United States, with locations in eastern and central Florida having between 70 and 80 thunderstorm days per year (Court and Griffiths 1986). The climatological daily expectancy of thunderstorms at Cape Canaveral during the warm season varies from a low of near 10% in early May to over 50% in August (Neumann 1970). The sea breeze has been shown to be the dominant factor influencing thunderstorm development over Florida during the warm season (Laird et al. 1994; Taylor et al. 1990; Lyons et al. 1992; Pielke 1974; Byers and Rodebush 1948; Nicholls et al. 1991; Guillory and Jedlovec 1994).

The complex land/water interface near Cape Canaveral influences convection over the region. Specifically, enhanced convergence associated with the sea breeze, its interactions with various river breezes (Indian River breeze and Banana River breeze), as well as the coastal shape in the Cape Canaveral region help determine the probability and location of convection. The direction and strength of the large-scale wind also play important roles in determining the likelihood and location of thunderstorms during the warm season (Cooper and Smith 1993; Laird et al. 1994; Neumann 1970; Gentry and Moore

1954; Lopez and Holle 1987a; Lopez and Holle 1987b; Nicholls et al. 1991; Watson et al. 1991).

Another zone of convergence that can affect the formation of convection in the Cape Canaveral region is called the trailing convergence line (TCL). First documented by Laird et al. (1994), they found that sea-breeze frontal movement produced a quasi-stationary trailing convergence line behind the sea-breeze front. Specifically, on days with weak synoptic forcing, the sea breeze follows the shape of the coastline in the Cape Canaveral region, producing two separate sea breezes--SB1 and SB2 (Laird et al. 1994; Laird et al. 1995). Due to the convex shape of the coastline in the area, a zone of convergence develops in the wake of these two sea breezes as they advance inland.

d. Objectives

This research has four major objectives. The primary objective is to establish a climatology of the Cape Canaveral area sea breeze to include passage time and degree of inland penetration. This is believed to be the first detailed sea-breeze climatology for the region. The research also establishes relationships between the sea breeze and several meteorological parameters (e.g., large-scale flow, cloud cover, and maximum temperature). Additionally, relationships between these parameters, the sea breeze, and thunderstorm activity are detailed. Finally, current results are compared with those from numerical simulations to determine their applicability to the Cape Canaveral area.

2. DATA AND METHODOLOGY

The Cape Canaveral area has an exceptional amount of mesoscale meteorological data with which to examine the sea breeze and other small-scale circulations. In the current study, the primary data source for analyzing the sea breeze was the network of 44 meteorological towers. The principal towers used in the current study are indicated (Fig. 2). These towers encompass Cape Canaveral and extend approximately 30 km inland, covering more than 1500 km^2. The tower sensors measure multiple meteorological parameters at heights between 2 and 150 m. Measurements at 16.5 m were used in this study since this is the highest available level at all the sites. This level also is high enough to avoid surface effects (Watson et al. 1991). The study period encompassed two warm seasons--May - October, 1995 and May - October, 1996. A total of 357 days was investigated.

a. Sea Breeze

The sea breeze was detected using several data sources; however, the tower data were the primary means for resolving it. This network has been used to identify the sea breeze in several prior studies (Taylor et al. 1990; Zhong and Takle 1993; Laird et al. 1994; Laird et al. 1995; Reed 1979; Zhong et al. 1991). The tower data were analyzed using McIDAS and the TWRJ and XPLOT software provided by the Spaceflight Meteorology Group (SMG) at NASA Johnson Space Center, Houston, Texas. The tower parameters that were analyzed included: 5 min average wind and 10 min peak wind, as well as

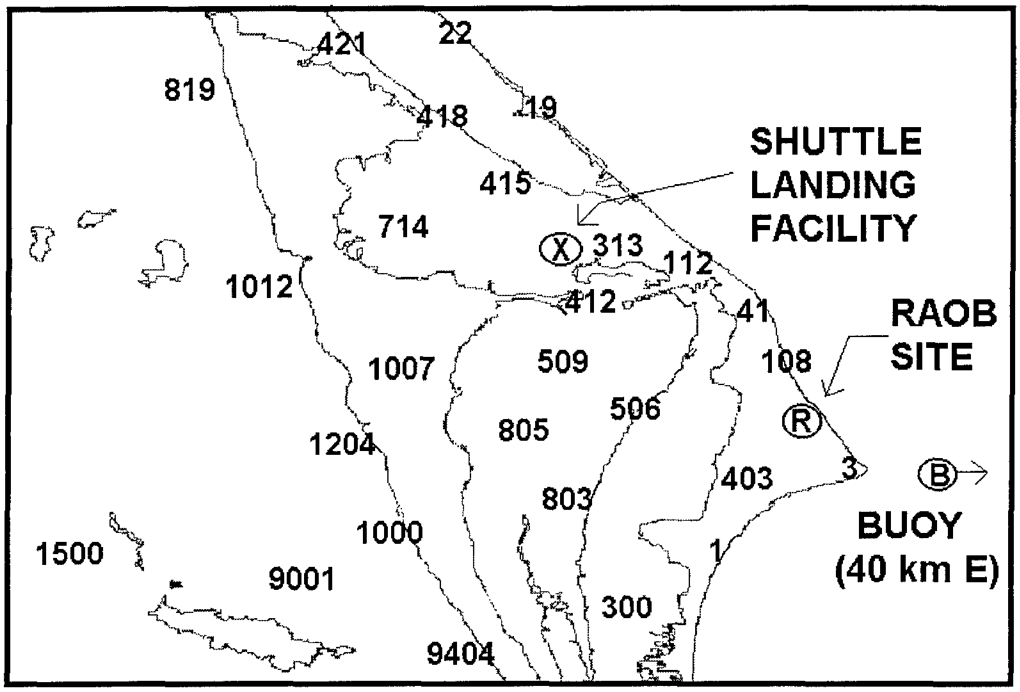

Fig. 2. The Cape Canaveral tower network. Locations of the Shuttle Landing Facility, radiosonde (RAOB) release site, and offshore data buoy (buoy 41009) are also indicated.

temperature, dewpoint, relative humidity, and pressure at 5 min intervals. The TWRJ software plotted horizontal charts of the various parameters in standard format. The XPLOT software provided time series (meteograms) of wind direction and wind speed.

Tower 112, located approximately 2 km inland and near the NASA Shuttle Landing Facility (SLF) and radiosonde (RAOB) site (see Fig. 2), was chosen as the primary location for determining the time of sea-breeze passage. This tower had the fewest missing days of data and is located far enough from inland water bodies to avoid significant river-breeze influences. Additionally, the tower is located east of the NASA Shuttle Landing Facility and close enough to the coast to provide advance notice of sea-breeze passage to stations located further west.

Sea-breeze passage was determined to have occurred when there was an identifiable wind shift (i.e., from offshore to onshore flow) or for the case of large-scale onshore flow, an increased onshore component. In most cases, these were accompanied by an identifiable increase in wind speed. Fig. 3 shows an example of sea-breeze passage at 1440 UTC 16 August 1996. The brief wind shift at 1030 UTC is not accompanied by an increase in wind speed (wind is essentially calm), and other data confirm that this wind shift does not represent the sea breeze. This method for locating the sea breeze is somewhat subjective, and, in some instances (particularly onshore flow), sea-breeze identification was difficult. These days were investigated further using satellite imagery as well as temperature and dewpoint analyses. For example, temperatures generally decrease and dewpoints increase with sea-breeze passage; however, this is not as pronounced for cases of onshore flow as for offshore flow.

Propagation of the sea breeze could be identified using successive plots of the tower

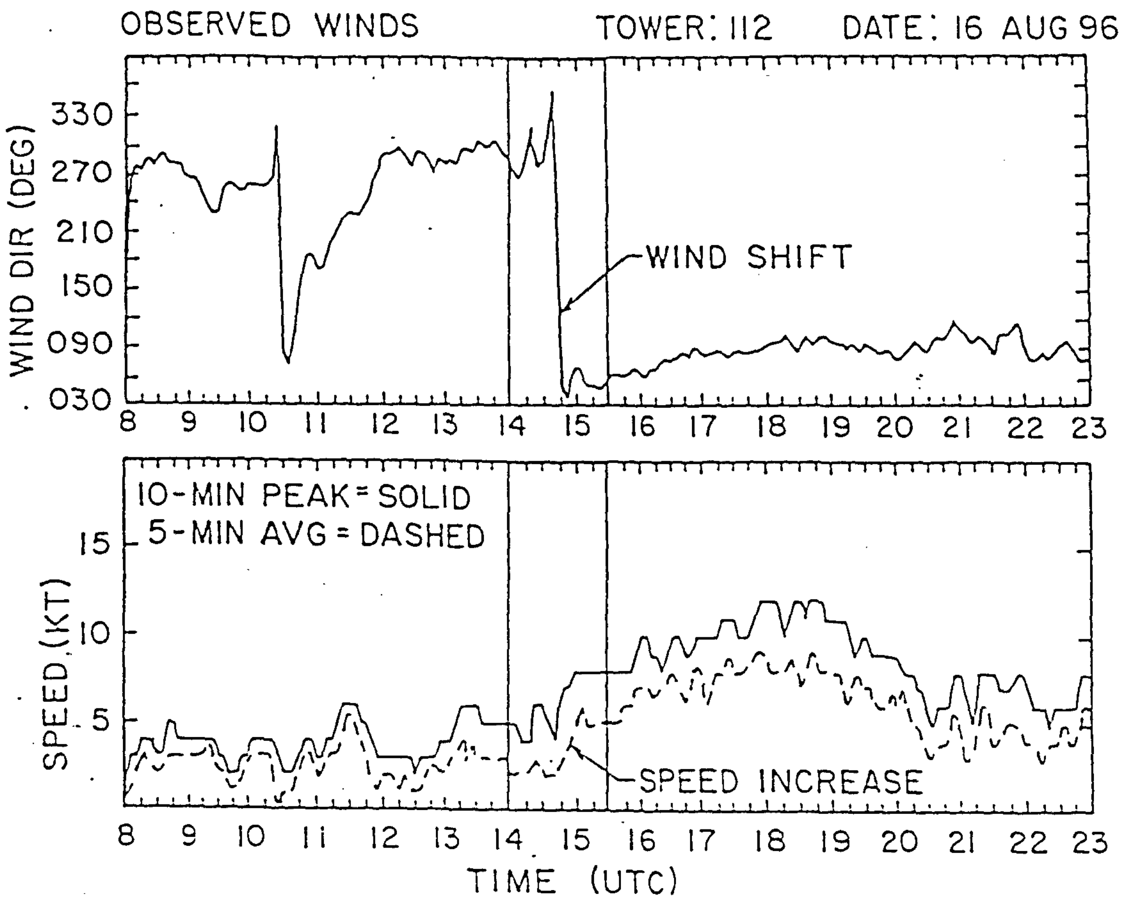

Fig. 3. Meteogram depicting sea-breeze passage on 16 August 1996.

data. For example, Fig. 4 shows hourly plots from 1500 UTC to 1800 UTC 17 September 1995. At 1500 UTC, winds throughout the network are offshore and fairly weak. By 1600 UTC, winds along the coast have shifted to onshore, with the sea-breeze front located just east of the Banana River. The sea breeze continues to move onshore, and by 1700 UTC, is identified over northeast Merritt Island, just east of the Indian River. Finally, by 1800 UTC, the sea-breeze front is located along and west of the Indian River as it progresses toward mainland Florida.

Inland penetration of the sea breeze also was identified using the tower network. When the sea breeze was located over mainland Florida, penetration was considered to be greater than 30 km. When the sea breeze did not propagate through the entire network, penetration was determined by the westernmost tower experiencing passage. Distance was calculated from the coastline and was considered to be the farthest distance orthogonal to the direction from which the sea breeze was moving.

Propagation speed of the sea breeze was calculated simply as distance divided by time using consecutive tower passages. Propagation speed was not always uniform throughout the tower network. These fluctuations have been observed in previous studies (Simpson et al. 1977; Bechtold et al. 1991; Pielke, 1974; Zhong et al. 1991; Wakimoto and Atkins 1994).

In addition to the tower data, 1 km Geostationary Operational Environmental Satellite (GOES) visible imagery (centered over Melbourne, Florida) was used to identify the sea breeze and other circulation features (river breezes, convergence lines, outflow boundaries, convection). Visible satellite imagery has been used for sea-breeze identification in previous studies (Simpson 1994; Pielke 1974). The sea breeze is associated

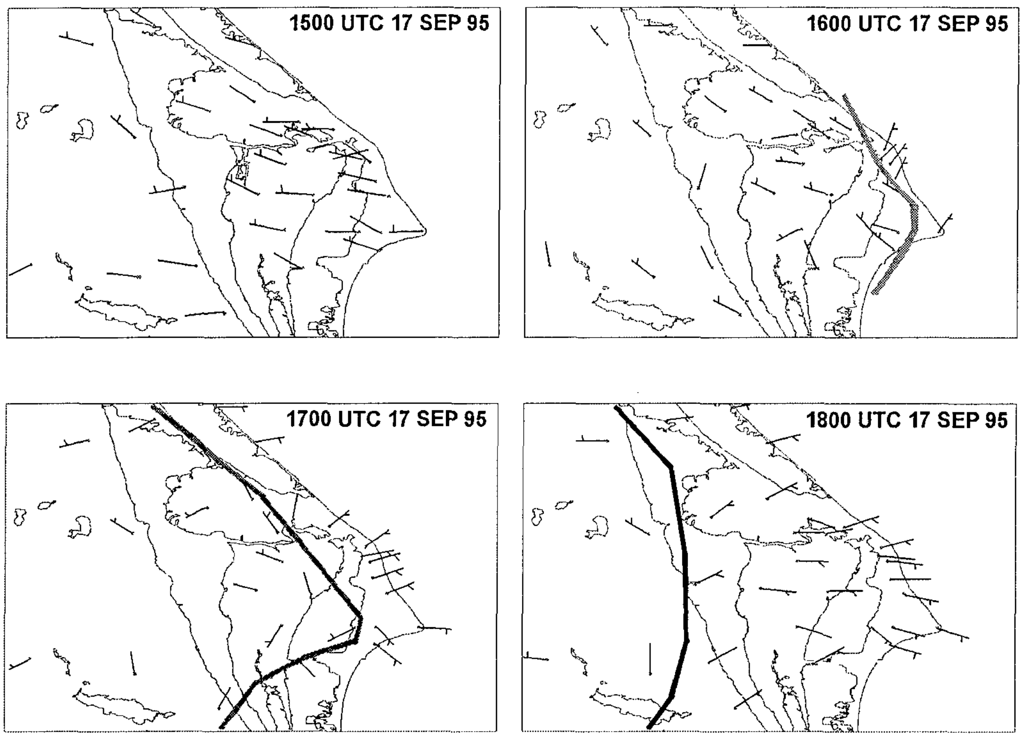

Fig. 4. Tower wind plots indicating sea-breeze propagation from 1500 to 1800 UTC 17 September 1995.

with a linear zone of enhanced cumulus clouds that can be observed in the imagery. These clouds are attributed to the enhanced vertical motions and increased moisture associated with the sea-breeze front. Values of ascent are thought to be approximately 0.7 to 3 m s^{-1} (Simpson et al. 1977). Additionally, there often is clearing behind the sea-breeze front along the coastline. Fig. 5 shows an example of the clouds associated with the sea breeze along the east coast of Florida.

The 1995 satellite imagery was provided by the 45th Weather Squadron at Cape Canaveral and was viewed using McIDAS. Imagery for 1996 was ingested and archived by Florida State University and viewed using the software xanim. The imagery was not always useful for identifying the sea breeze due to cloud cover and, in some instances, the lack of a sea-breeze signature due to the dryness of the boundary layer.

It was not always possible to clearly identify the sea breeze--particularly for cases of onshore flow. In fact, there were 40 days on which it was impossible to determine whether or not a sea breeze occurred. This was due to various factors, including poor or missing satellite imagery, either too much cloud cover or no sea-breeze related cloud feature, as well as the lack of a clear signature in either the meteograms or spatial plots of tower data, especially during cases of onshore flow. To maintain as much objectivity and accuracy as possible, these days were eliminated from all subsequent data analyses. This yielded a total of 317 days that were examined in greater detail.

b. River Breeze

River breezes are associated with both the Indian and Banana Rivers (Fig. 1). These river breezes were diagnosed from divergent flow over the rivers using the tower

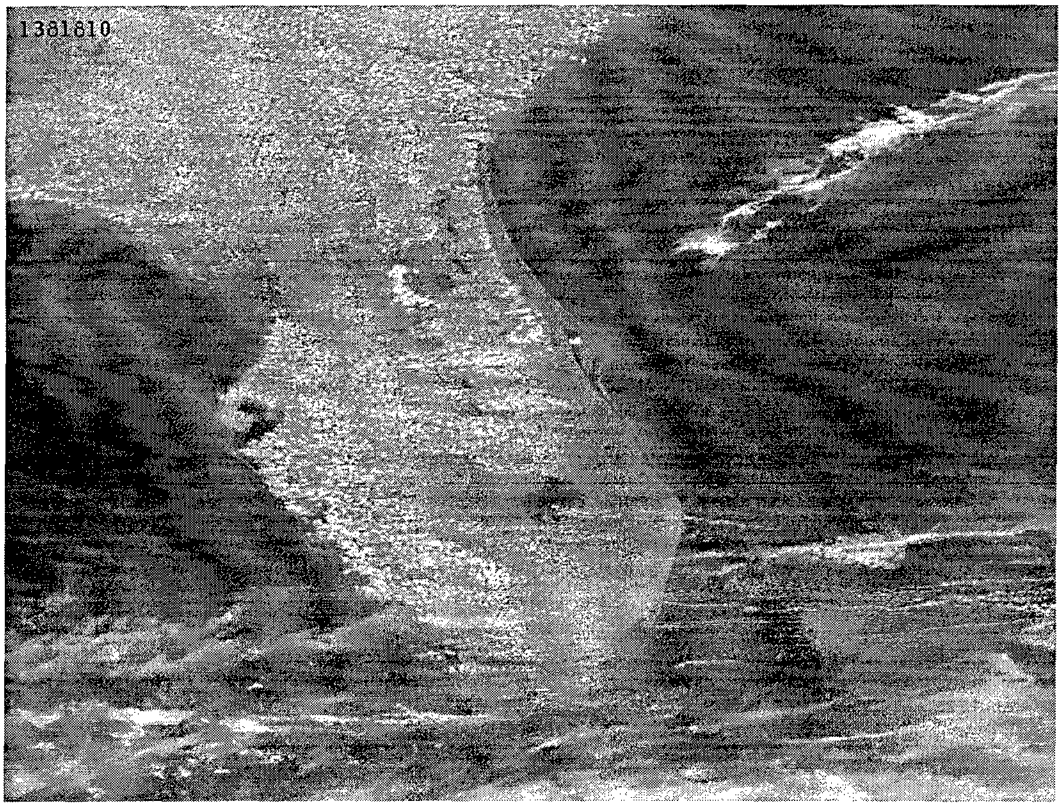

Fig. 5. GOES 1 km visible image for 1810 UTC 17 May 1996. The Atlantic sea breeze is apparent along the east coast of Florida.

wind plots. The example in Fig. 6 shows westerly winds on the eastern shores of the Banana and Indian Rivers, but easterly winds on the western shores. Divergent flow over the rivers is clearly indicated. This divergence corresponds to a clear slot in the 1 km visible satellite imagery (Fig. 7).

Being weaker than the sea breeze, the river breeze generally was more difficult to detect. The problems described earlier for the sea breeze also are applicable here. Additionally, a lack of tower sites along the eastern shore of the Indian River enhanced these difficulties.

c. Trailing Convergence Line

Trailing convergence lines were identified using the tower wind analyses. Specifically, the TCL corresponds to convergent flow along an axis generally extending from central Cape Canaveral toward the eastern boundary of the onshore sea breeze (Fig. 8). The TCL in this figure extends from just west of the central Indian River to Cape Canaveral Proper--just south of tower 3. Winds to the south of the TCL are from the south or southeast, whereas winds to the north are from the northeast. Some trailing convergence lines can be observed in visible satellite imagery as a line of enhanced cloudiness behind the sea-breeze front (Fig. 9).

d. Convection

Surface observations from the NASA Shuttle Landing Facility were used to identify the presence of thunderstorms in the Cape Canaveral area. The Shuttle Landing Facility is located approximately 6 km west of the Atlantic coastline (Fig. 2). A thunderstorm was

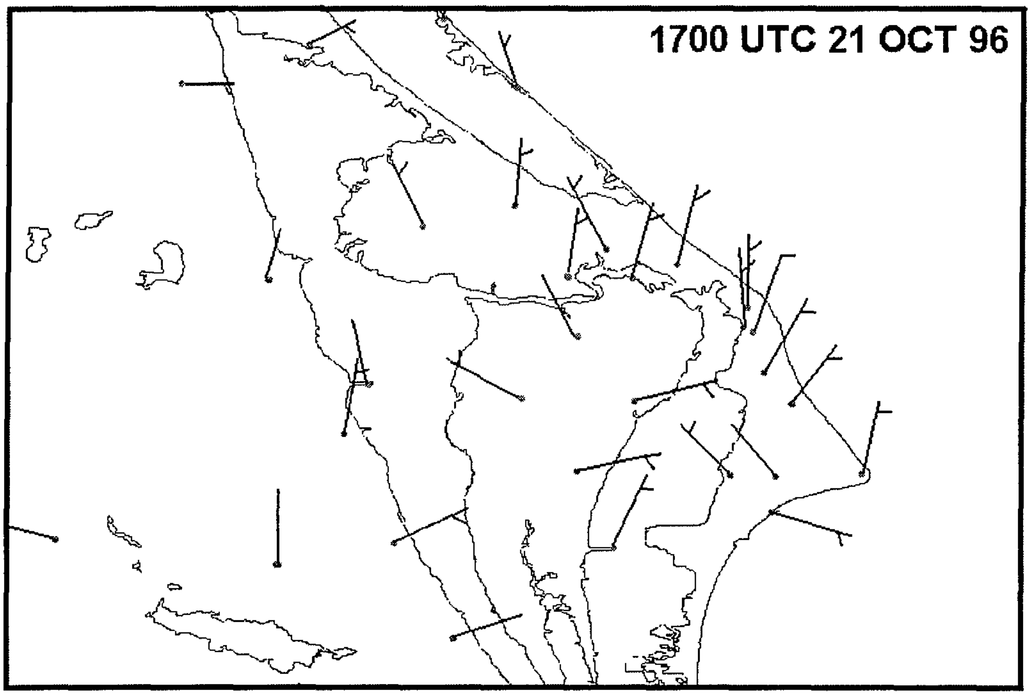

Fig. 6. Tower wind plot indicating Indian and Banana River breezes at 1700 UTC 21 October 1996.

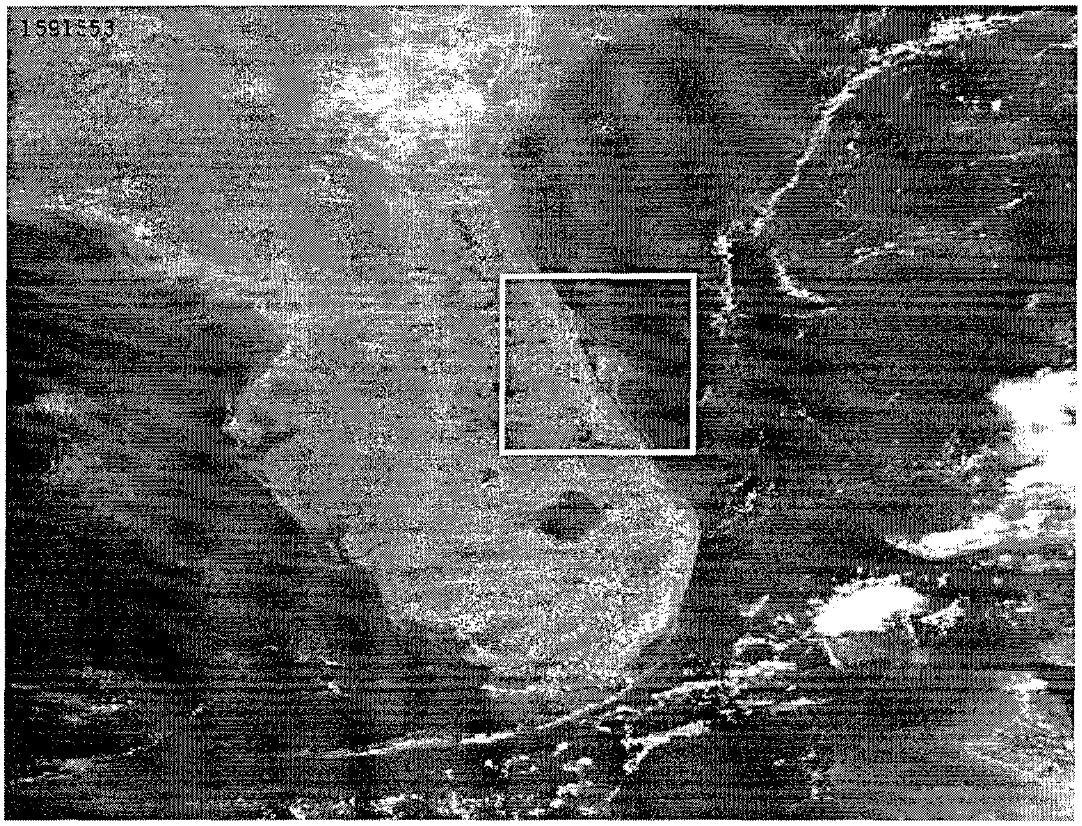

Fig. 7. GOES 1 km visible image for 1553 UTC 7 June 1996. Relatively clear skies over the Indian and Banana Rivers indicate the presence of the Indian and Banana River breezes.

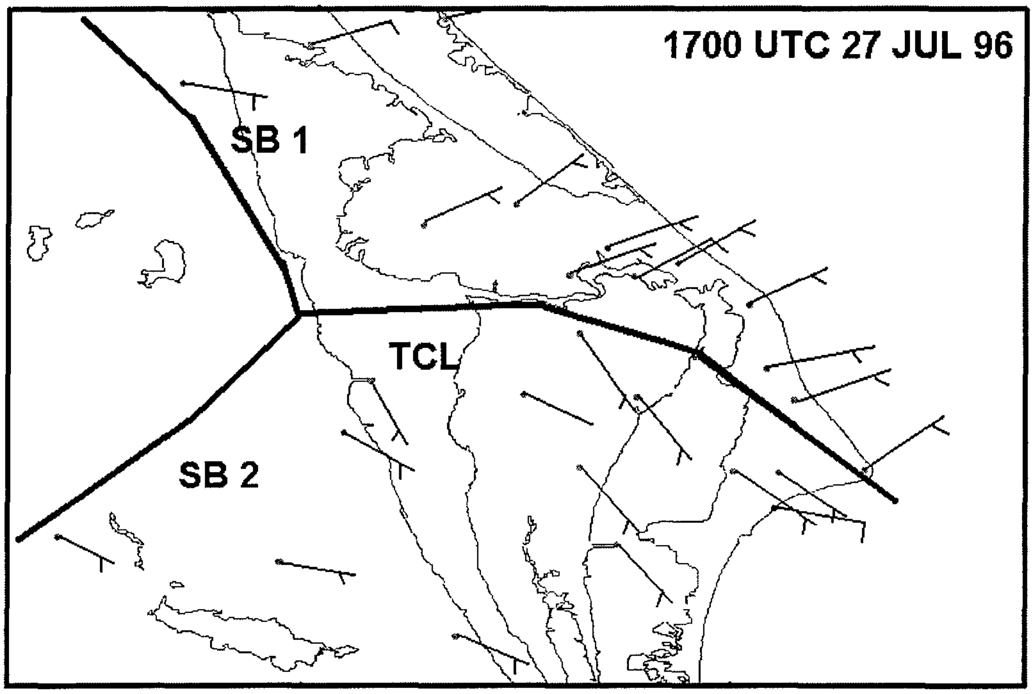

Fig. 8. Tower wind plot indicating the trailing convergence line at 1700 UTC 27 July 1996.

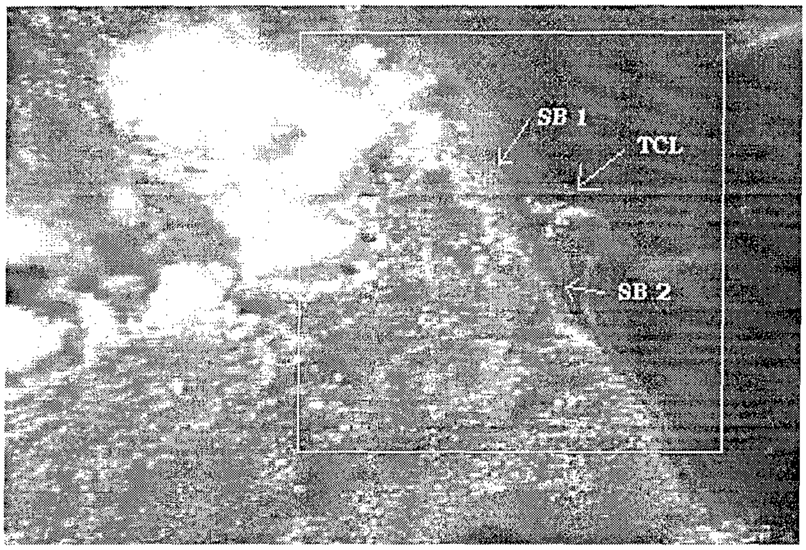

Fig. 9. GOES 1 km visible image for 1851 UTC 25 June 1996. The cloud cover indicates a sea breeze and a trailing convergence line.

considered to have occurred if thunder was reported at the observation site. Additionally, any report of a thunderstorm within 40 km of the SLF was considered convection within the Cape Canaveral region.

This second criterion for thunderstorm occurrence was possible because surface observations at the SLF indicate thunderstorms within a 40 km radius based on radar reports. Including thunderstorms within 40 km provides a better indication of nearby convection than does the small-scale, restrictive and somewhat arbitrary choice of denoting thunderstorms only at the observation site.

e. Other Data

Sea surface temperatures of the Atlantic Ocean were taken from morning readings (0900 to 1200 UTC) at buoy 41009. This buoy is located approximately 40 km east of the eastern tip of Cape Canaveral (Fig. 2). Land temperatures were taken from observations at the SLF, as were maximum daily temperatures. Temperatures of the Banana River were a daily average based on 5 years of data. These temperatures also were used to approximate the temperature of the Indian River.

Sky conditions were observed at the SLF between 1000 and 1600 UTC. This is the period of maximum heating prior to expected sea-breeze passage. Four categories were used--clear, scattered, broken, and overcast--based on the standard definitions. Additional notes on sky conditions were made using satellite analyses.

f. Synoptic Typing

The large-scale flow has a significant influence on the sea breeze (e.g., Zhong and

Takle 1993; Estoque 1962; Arritt 1993; Bechtold et al. 1991; Xian and Pielke 1991; Reible et al. 1991; Neumann 1977; Blanchard and Lopez 1985; Lopez and Holle 1987a; Zhong et al. 1991; Wakimoto and Atkins 1994; Atkins et al. 1995). To investigate this influence in the current study, mean layer winds were calculated for each day. Each day then was categorized by the mean wind direction and also by the wind component perpendicular to the average Cape Canaveral coastline.

The mean, large-scale flow was the average wind between 300 and 900 m on the morning sounding (0900 to 1200 UTC) at Cape Canaveral (see RAOB site, Fig. 2). This layer avoids most surface influences and incorporates the typical depth of the sea breeze. Additionally, it is the same layer used by forecasters at Cape Canaveral to determine large-scale flow (Roeder 1997, personal communication). Some previous investigations of the Cape Canaveral area have used a mean from the surface to 3000 m to describe the large-scale flow (e.g., Watson et al. 1991; Lopez and Holle 1987a; Lopez and Holle 1987b). However, those studies primarily examined the movement of convection, not the sea breeze itself. The 300 to 900 m layer seems most suitable for studying the effects of the large-scale wind on the sea breeze.

The mean winds were categorized according to the coastal geography of the Cape Canaveral region. Specifically, winds were classified using 90° sectors centered on the directions perpendicular to (68° and 248°) and parallel to (158° and 338°) the average coastline near Cape Canaveral (Fig. 10). As a result, flow from 293° to 023° was classified as northwest (alongshore); flow from 023° to 113° was classified as northeast (onshore); flow from 113° to 203° was classified as southeast (alongshore); and flow from 203° to 293° was classified as southwest (offshore). Winds were classified as calm for mean speeds less

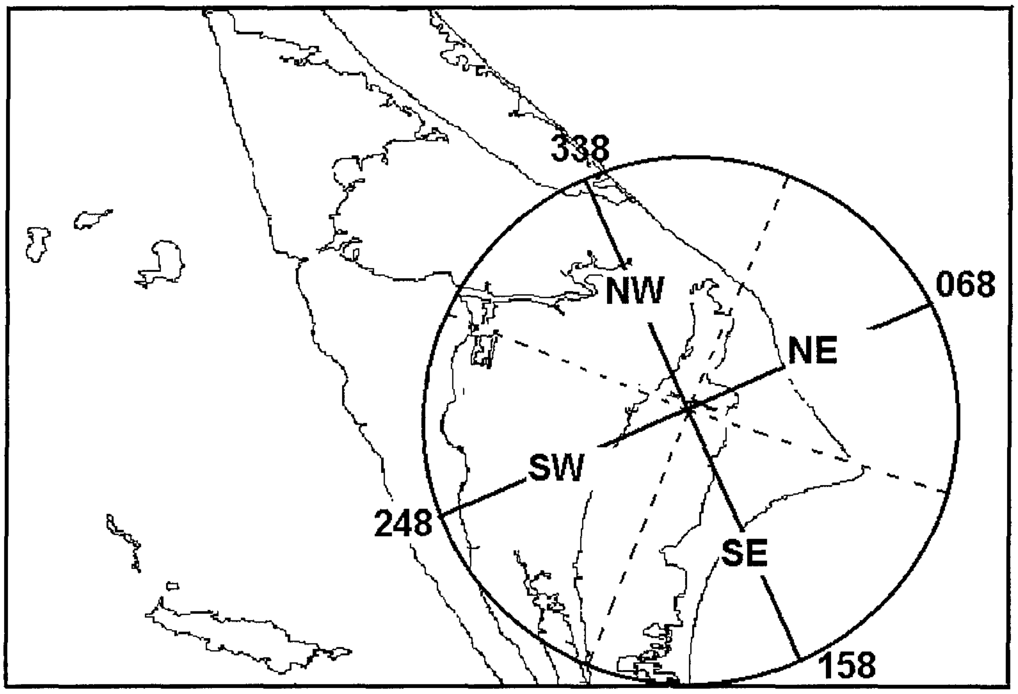

Fig. 10. Quadrants for typing the large-scale wind direction near Cape Canaveral, Florida. For example, the northwest (NW) quadrant ranges from 293° to 023°.

than 2 m s^{-1}. This classification scheme was used previously by Lopez and Holle (1987b) and Watson et al. (1991). In addition to this classification, the wind component perpendicular to the coastline (along the $68^{\circ}/248^{\circ}$ axis) was calculated.

3. RESULTS

a. Large-Scale Flow

A total of 317 days was analyzed for the presence of a sea breeze. Approximately 61% of these days (195) have large-scale flow from the southeast or southwest (Fig. 11). There are fewer days (104) with northeasterly or northwesterly flow. This distribution is similar to that found over a 13 year period by Neumann (1970). Therefore, the two year period of the current study appears to be representative.

Over 60% of the days experience a clearly identifiable sea breeze that extended onshore. There is some seasonal variability for sea-breeze formation in the Cape Canaveral area with June through August having the most sea breezes and October, the least. Frontal passage and stronger winds are more likely late in the warm season. Almost 70% of days with southwest flow have an observable onshore sea breeze. Conversely, when the large-scale flow is from the northeast (Fig. 11), sea-breeze formation is suppressed. Only 21% of these days have observable sea breezes. The alongshore flow (northwest and southeast) cases are similar to each other and the offshore flow case. Specifically, a sea breeze is observed on 66% of southeast-flow days and 77% of northwest-flow days. These results suggest that a sea breeze is unlikely for northeasterly large-scale flow, but is almost equally likely for flow from any other direction.

The speed of the large-scale wind also is related to sea-breeze occurrence. A sea breeze is observed on 94% of days with calm large-scale flow (less than 2 m s^{-1}, Fig. 11).

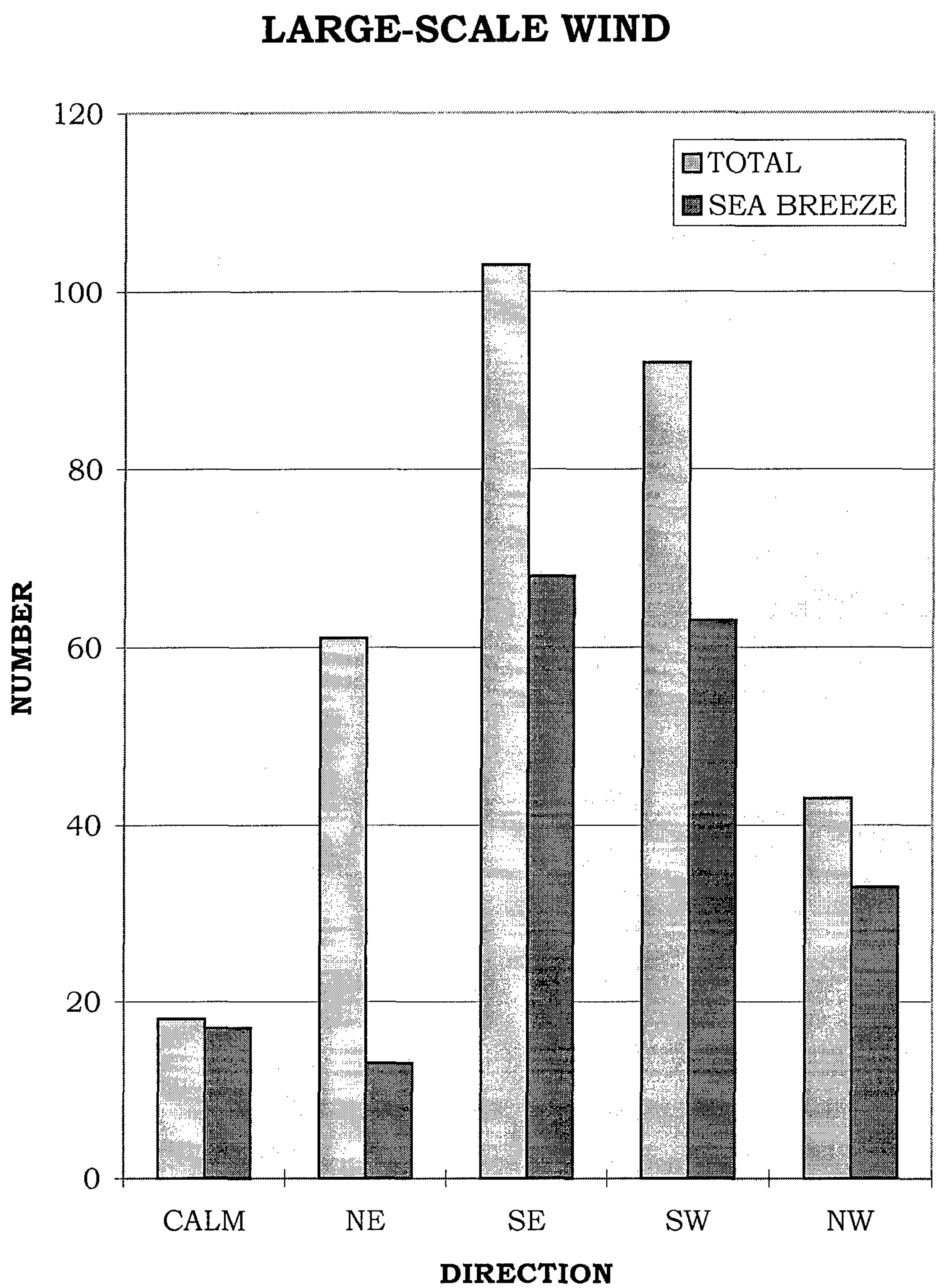

Fig. 11. Number of days with specific large-scale flow (see Fig. 10) and with a sea breeze.

Conversely, when the wind speed is greater than 8 m s^{-1} (not shown), an onshore sea breeze is observed on only 24% of the days. The overall range of wind speeds for sea-breeze occurrence is 0.7 to 14.3 m s^{-1}. The average wind speed on sea-breeze days is 4.8 m s^{-1}. On the other hand, the average on days with no sea breeze is 8.8 m s^{-1}. These results show that a sea breeze is most likely for weak large-scale flow in the Cape Canaveral area.

To further elucidate the effects of the large-scale wind on sea-breeze occurrence, the wind component perpendicular to the coastline was determined (see Section 2). This allows ready comparison with previous numerical studies and provides thresholds for sea-breeze formation. The distribution of the large-scale flow by perpendicular wind component is shown in Fig. 12. Negative values denote offshore large-scale flow, while positive values indicate onshore flow.

Large-scale offshore (negative) flow is more conducive to sea-breeze formation than is onshore flow (Fig. 12)--almost 70% of the sea-breeze days have a perpendicular component that is offshore. Over 73% of the days with an offshore perpendicular component have sea breezes that have penetrated inland. In addition, some sea breezes may remain entirely offshore and are not included in these statistics. Conversely, only 45% of the days with an onshore perpendicular component have an observable sea breeze. The strongest onshore component associated with a detectable sea breeze is 6.7 m s^{-1}, whereas the strongest offshore component that allows the sea breeze to advance onshore is 12.9 m s^{-1}. Only six cases (11%) of onshore large-scale flow greater than 4 m s^{-1} result in an observable sea breeze. On the other hand, there are 49 instances (59%) when a sea breeze is observed with an offshore large-scale component greater than 4 m s^{-1}. An onshore sea breeze even is observed on seven days (26%) with an offshore component greater than 8 m s^{-1}. These

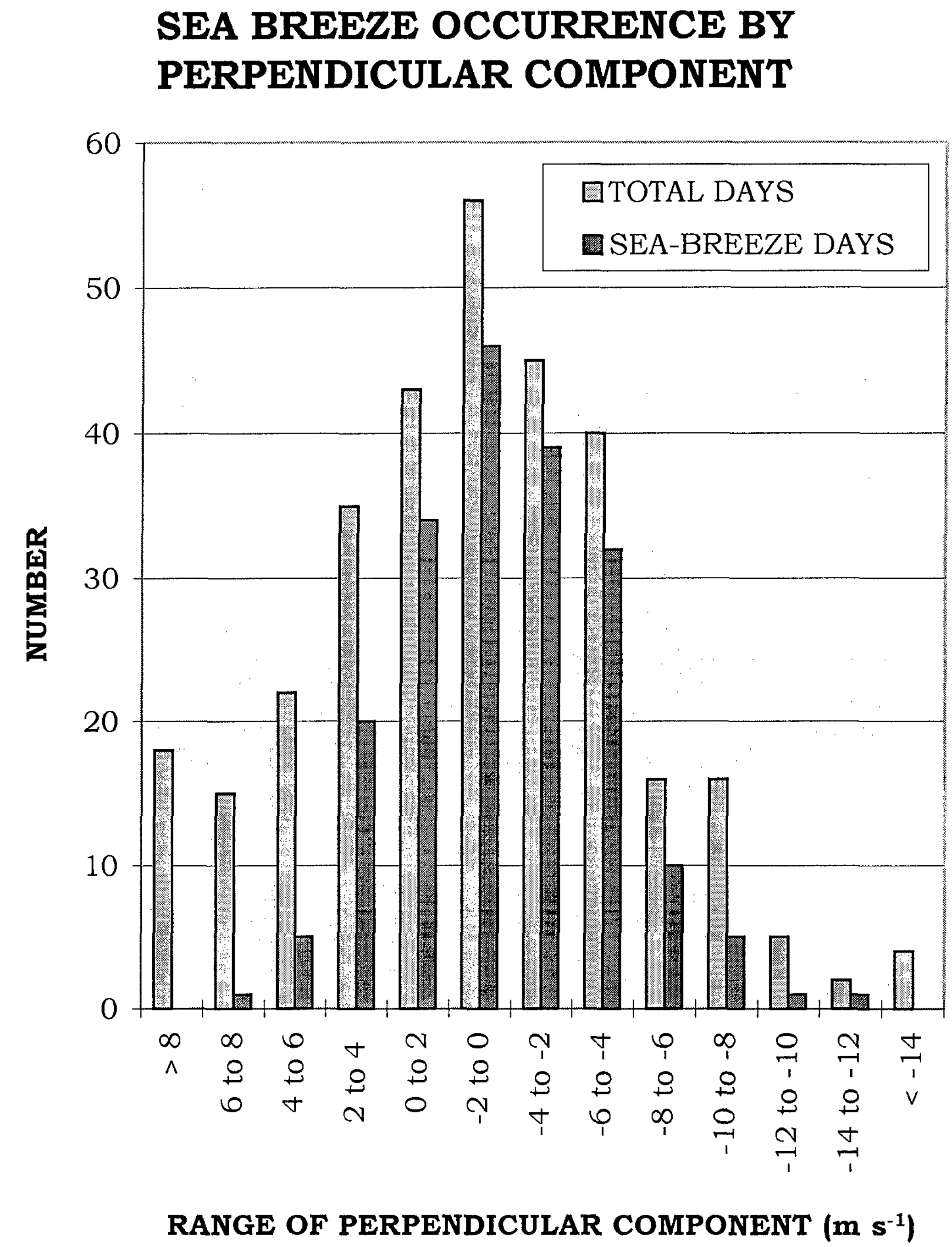

Fig. 12. Sea-breeze occurrence as a function of perpendicular wind component. Onshore wind components are positive. Offshore wind components are negative.

results show that the perpendicular wind component is a strong predictor of sea-breeze occurrence over the Cape Canaveral area.

Some results of the current study agree with those from numerical models. Zhong and Takle' s (1993) three-dimensional modeling of the Cape Canaveral region showed that large-scale offshore winds were most favorable for the development of a sea-breeze perturbation. Onshore winds were least favorable. Several modeling studies have demonstrated that offshore large-scale flow intensifies the sea-breeze by strengthening the horizontal temperature gradient, whereas onshore large-scale winds weaken the temperature gradient and the sea breeze (Estoque 1962; Arritt 1993; Bechtold et al. 1991; Xian and Pielke 1991). The horizontal temperature gradient is enhanced when there is convergence between the cooler, sea-breeze air and the warmer, opposing large-scale flow off the land (Arritt 1993).

Numerous theoretical studies have established thresholds for the perpendicular wind component that is associated with sea-breeze formation (Walsh 1974; Arritt 1993; Estoque 1962; Bechtold et al. 1991; Xian and Pielke 1991; Zhong et al. 1991). However, thresholds in the current study of Cape Canaveral generally are higher than those derived from these models. For example, Walsh (1974) used a two-dimensional linear model to show that a sea breeze rarely occurred for an offshore large-scale component greater than 6 m s^{-1}. Bechtold et al. (1991) concluded that maximum sea-breeze intensity occurred for an offshore component of 5 m s^{-1}, whereas the sea breeze remained entirely offshore for an offshore component of 10 m s^{-1}. Xian and Pielke (1991) detected no well-defined sea breeze for an onshore component of 5 m s^{-1}, but noted an onshore sea breeze for an offshore component of 10 m s^{-1}. Zhong et al. (1991) applied a three-dimensional model to the Cape Canaveral region. They found a well-defined sea breeze for cases of calm winds or weak offshore flow. No sea breeze was noted for onshore flow exceeding 2 m s^{-1}. More recently, Arritt (1993), used a two-dimensional non-linear model to determine that an offshore component of 6 m s^{-1} was strong enough to keep the sea breeze entirely offshore. Conversely, an onshore component of 3 m s^{-1} was sufficient to suppress sea-breeze formation.

Current results indicate that sea-breeze formation is not suppressed for onshore flow until that component exceeds 4 m s^{-1}. Additionally, almost 40% of the current days with offshore flow greater than 6 m s^{-1} experience a sea breeze that moves inland (see Fig. 12). Even more importantly, the sea breeze is able to move inland for offshore values as great as 12.9 m s^{-1}.

With the exception of Zhong et al. (1991), the previously cited studies utilized two-dimensional models. Thus, they did not consider complex coastlines such as that found in the Cape Canaveral area. Current results indicate that local studies are needed in order to account for regional effects.

b. Cloud Cover and Maximum Temperature

Cloud cover plays an important role in the development of the sea breeze since it is directly related to the amount of solar insolation received at the surface. If the land temperature does not sufficiently exceed the water temperature, the sea breeze will not form. On 88% of the sea-breeze days, morning sky conditions are either clear or scattered (total sky coverage less than 3/8, not shown). In contrast, only 61% of non-sea-breeze days have either clear or scattered clouds. Additionally, only 3% of sea-breeze days report morning overcast conditions (8/8 coverage), whereas 16% of non-sea-breeze days have overcast skies. Overall, sea-breeze days are over 30% less cloudy prior to onset of the sea breeze.

Maximum temperature directly influences sea-breeze formation. Since the land experiences greater temperature changes than the nearby ocean, a warmer maximum temperature is more likely to produce a horizontal temperature gradient that is sufficient for sea-breeze development. The average temperature difference between land and sea for sea-breeze days is 5.3° C, but only 3.7° C on non-sea-breeze days. Additionally, the average maximum temperature for sea-breeze days is 1.7° C higher than that of non-sea-breeze days. These results suggest that accurate forecasts of sky condition and maximum temperature can aide in determining the likelihood of a sea breeze on a given day.

c. Sea Breeze Type

There are three types of sea breezes in the Cape Canaveral area based on their direction of movement. The most prevalent is the NE-type (or Type 1) sea breeze. This sea breeze propagates from the northeast throughout the Cape Canaveral region. The SE-type (or Type 2) sea breeze is the second most common. It propagates through the area from the southeast. The least common type of sea breeze is a combination of the NE- and SE-types that Laird et al. (1994) have called the (SB1/SB2)-type. It propagates through the Cape Canaveral region according to the shape of the nearest coastline. Specifically, the northern portion moves from the northeast, while the southern portion moves from the southeast.

The NE-type sea breeze occurs on 57% of sea-breeze days and is observed for all large-scale wind directions. As a result, it is the most common type of sea breeze. The observed lack of directional dependence may be a result of the longer coastline in the northeast section of the tower network (Fig. 2). This type of sea breeze is the least likely to result in thunderstorms (49%). On the other hand, the SE-type sea breeze is found on only 27% of sea-breeze days and is usually only observed when the large-scale flow is from the southeast through southwest. In addition to this directional dependence, the SE-type sea breeze appears to require a stronger large-scale wind (mean of 5.9 m s^{-1} compared to 4.6 m s^{-1} for NE-type and 3.6 m s^{-1} m s^{-1} for SB1/SB2-type). Onset of the SE-type sea breeze is later than the other types due to a larger percentage of offshore (southwest) flow cases. Thunderstorms are observed on 59% of SE-type sea-breeze days. Lastly, the SB1/SB2-type sea breeze occurs on only 16% of sea-breeze days. It usually forms on days with weak large-scale forcing and often results in a trailing convergence line (documented further in Section g). Thunderstorms are observed on 63% of the days with this type of sea-breeze.

Large-scale perpendicular wind components are similar for the NE- and SE-type sea breezes (not shown), with perpendicular components ranging from -11.6 to 6.7 m s^{-1} (mean of -1.8 m s^{-1}) for the NE-type sea breeze and -12.9 to 5.0 m s^{-1} (mean of -2.6 m s^{-1}) for the SE-type. Values are significantly weaker for the SB1/SB2-type sea breeze--ranging from only -4.8 to 3.0 m s^{-1} (mean of -0.4 m s^{-1}). These findings indicate that the sea breeze is more likely to be affected by large-scale flow when that flow is strong. However, when large-scale forcing is weak, sea-breeze propagation is controlled more by local forcing. For example, the sea breeze is more likely to mirror the shape of the coastline for weak large-scale forcing.

d. Time of Passage

The time of sea-breeze passage is important because it indicates a change in meteorological conditions. Sea-breeze passage generally is associated with a wind shift and speed increase, temperature decrease, and dewpoint increase (Simpson et al. 1977; Zhong and Takle 1992; Intrieri et al. 1990; Laird et al. 1995; Zhong et al. 1991; Wakimoto and Atkins 1994). Perhaps most important, sea-breeze passage often is associated with convection.

The large-scale wind plays an important role in determining the time of sea-breeze passage. Onshore flow enhances propagation of the sea breeze. Conversely, offshore flow inhibits propagation, and in some instances causes the sea breeze to become stationary. In the current study, sea-breeze passage was determined at tower 112 in the Cape Canaveral network (Fig. 2). Sea-breeze passage times at this tower are related to large-scale wind direction in Table 1 and to the perpendicular wind component in Table 2. Wind information for a range of passage times is found in Table 3.

Onshore (northeast) flow days have the earliest average passage time (1415 UTC (1015 EDT), Table 1). Offshore (southwest) flow results in the latest average passage time--over 2 h later. Calm flow produces an average passage time that is 10 min later than cases of onshore flow. Average passage times for the alongshore (northwest and southeast) cases fall in between those of the calm and offshore cases. Some previous studies (Xian and Pielke 1991; Arritt 1993; Bechtold et al. 1991) have indicated that alongshore flow results in sea breeze characteristics similar to those for calm large-scale flow. However, Table 1 indicates delayed sea-breeze passage for alongshore flow. Average passage time for southeast flow is 49 min later than that for calm flow, while sea-breeze passage for northwest flow is 42 min later than for calm flow. Of course, when considering alongshore flow, the perpendicular component of the large-scale wind determines the characteristics of the sea breeze.

Table 1. Time of sea-breeze passage at tower 112 according to the large-scale wind. Northwest and Southeast flow are considered alongshore (Fig. 10).

DIRECTION	SEA-BREEZE DAYS	SEA-BREEZE PASSAGE TIME (UTC)
CALM	17	1425
NORTHEAST	13	1415
SOUTHEAST	68	1514
SOUTHWEST	63	1628
NORTHWEST	33	1507
TOTAL	194	1528

Table 2. Time of sea-breeze passage at tower 112 as a function of the perpendicular wind component. Onshore components are positive. Offshore components are negative.

PERPENDICULAR WIND COMPONENT (m s^{-1})	SEA-BREEZE DAYS	SEA-BREEZE PASSAGE TIME (UTC)
> 8	0	N/A
6 to 8	1	1415
4 to 6	5	1437
2 to 4	20	1416
0 to 2	34	1431
-2 to 0	46	1509
-4 to -2	39	1534
-6 to -4	32	1639
-8 to -6	10	1723
-10 to -8	5	1825
-12 to -10	1	1735
-14 to -12	1	1720
< -14	0	N/A
TOTAL	194	1528

Table 3. Wind information as a function of sea-breeze passage time. Onshore wind components are positive. Offshore wind components are negative.

PASSAGE RANGE (UTC)	SEA-BREEZE DAYS	AVERAGE WIND DIRECTION (deg)	AVERAGE WIND SPEED ($m\ s^{-1}$)	PERPENDICULAR WIND COMPONENT ($m\ s^{-1}$)
1200 - 1300	8	069	3.2	1.9
1300 - 1400	20	179	3.4	0.4
1400 - 1500	45	184	4.7	-0.3
1500 - 1600	52	213	4.2	-1.5
1600 - 1700	32	213	4.9	-2.8
1700 - 1800	21	231	7.0	-4.8
1800 - 1900	11	237	5.9	-5.0
1900 - 2000	2	232	9.4	-7.3
2000 - 2100	1	316	10.9	-4.1
2100 - 2200	2	225	7.5	-6.8

The influence of large-scale flow on sea-breeze passage time is better documented by examining the perpendicular component of the wind. The average time of sea-breeze passage for the combination of all wind directions is 1528 UTC (1128 EDT, Table 2). Onshore (positive) wind components are associated with early sea-breeze passage at tower 112, i.e., prior to 1500 UTC (1100 EDT). Conversely, the later passage times occur for offshore (negative) components. For example, an offshore component between -8 and -10 m s^{-1}, produces an average passage time of 1825 UTC (225 PM EDT).

Table 3 presents an alternative representation of passage times. Time of passage ranges from 1205 to 2120 UTC, with 50% of all sea breezes passing tower 112 between 1400 and 1600 UTC (Table 3). For passage times prior to 1400 UTC, the average perpendicular component is onshore (positive). For all other passage times, the average perpendicular component is offshore (negative), reaching a peak of -7.3 m s^{-1} for sea-breeze passage after 1900 UTC.

Current findings are consistent with those of previous studies for the Cape Canaveral region. Zhong and Takle (1993) noted a later onset of sea-breeze flow for stronger offshore winds in the Cape Canaveral region. Reed (1979) noted an average passage time between 1500 and 1600 UTC.

e. Inland Penetration

Several studies have related inland penetration of the sea breeze to the large-scale flow (e.g., Simpson et al. 1977; Arritt 1993; Estoque 1962; Bechtold et al. 1991). Results have shown that stronger opposing large-scale winds produce less inland penetration of the sea breeze. Current findings also indicate a strong relationship between the large-scale wind and inland penetration of the sea breeze. The leading edge of the sea breeze penetrated the entire Cape Canaveral tower network (30 km) on 81% of the 194 sea-breeze days investigated. The average passage time for these days at tower 112 is 1513 UTC--15 min earlier than the average for all days (not shown).

The propagation speed of the sea breeze is closely related to its inland penetration. In general, the more rapidly a sea breeze advances, the farther inland it penetrates. Results from this study indicate an average sea-breeze propagation speed of 1 to 4 m s^{-1}. This value is consistent with those determined in previous studies (Simpson et al. 1977; Laird et al. 1994; Zhong and Takle 1992).

Sea breezes with little inland penetration have important effects on local weather conditions. Only 37 of the 194 sea-breeze fronts (19%) fail to penetrate the entire Cape Canaveral tower network (30 km). The average large-scale wind on these days is from 243 degrees at 6.4 m s^{-1} (not shown), while their average passage time at tower 112 is 1637 UTC--almost 70 min later than the overall average. For the 11 days with sea-breeze penetration less than 10 km, the average wind speed is 8 m s^{-1} and passage time is 1649 UTC. These weakly penetrating sea breezes also have a much higher probability of thunderstorms. Over 80% of sea breezes that fail to advance beyond 10 km result in thunderstorms. Convection is described in greater detail in a later section.

It is useful to relate sea-breeze penetration to the perpendicular component of the large-scale wind (Fig. 13). No sea breeze that forms on a day with onshore flow (positive values) fails to penetrate the entire tower network. The average perpendicular component on days when the sea breeze does penetrate the entire tower network is -1.0 m s^{-1} (offshore). Conversely, the sea breezes that do not penetrate the entire network are associated with

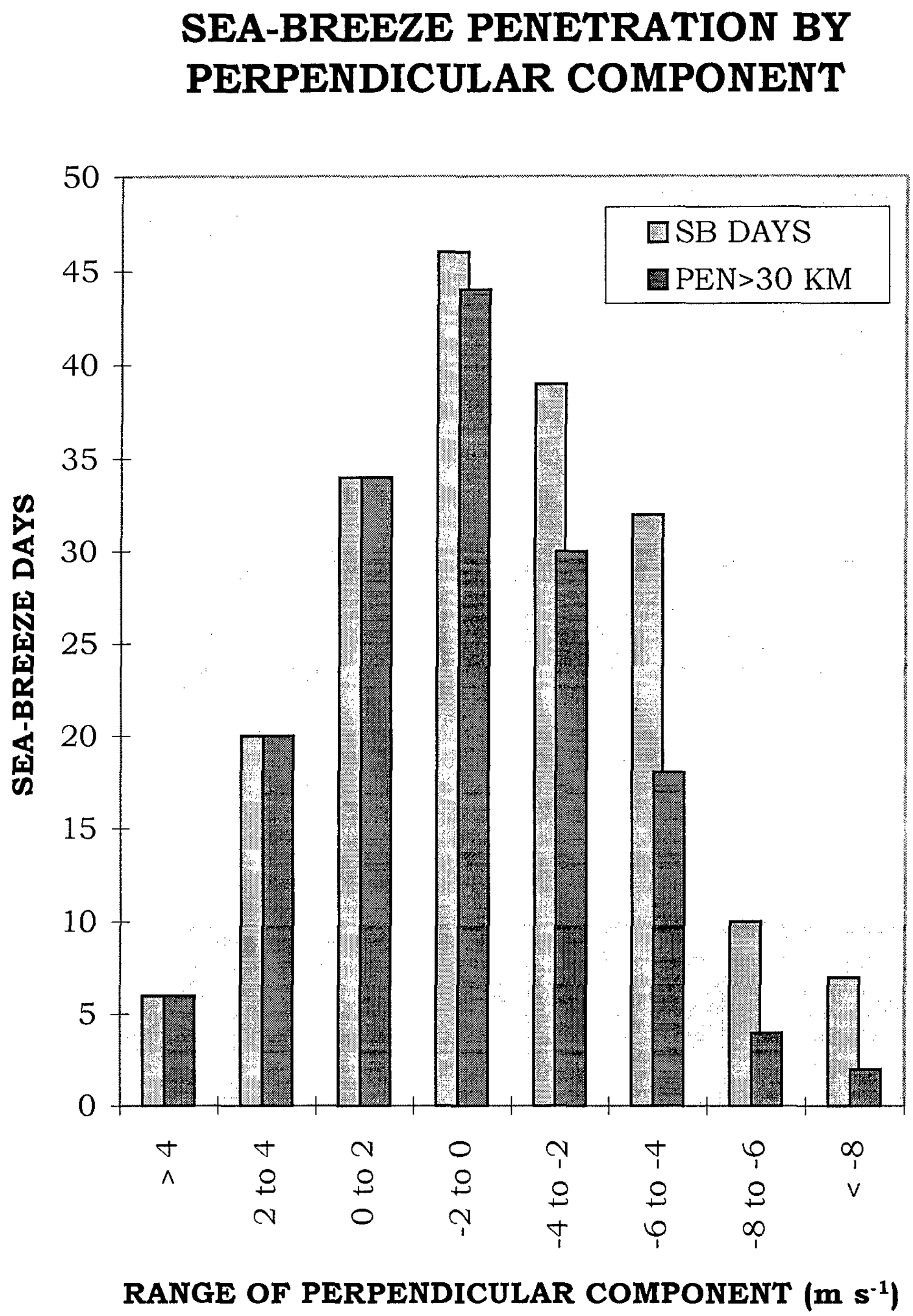

Fig. 13. Sea-breeze penetration as a function of perpendicular wind component. Onshore wind components are positive. Offshore wind components are negative.

strong offshore wind components. For example, the average component for days on which the sea breeze does not penetrate the tower network is offshore at 5.2 m s^{-1}. In fact, 94% of the days when the sea breeze does not penetrate the tower network have a large-scale offshore component greater than 2 m s^{-1}. Similarly, only 35% of sea breezes that form on days with offshore large-scale flow greater than 6 m s^{-1} penetrate beyond 30 km. These results clearly indicate that stronger offshore flow is likely to result in a poorly penetrating, or even stationary, sea breeze.

General findings concerning inland penetration in the Cape Canaveral area agree with those of previous investigations (Estoque 1962; Simpson et al. 1977; Wakimoto and Atkins 1994; Arritt 1993). Estoque (1962) found that inland penetration was greater for calm flow than for offshore flow of 5 m s^{-1}. The majority of sea breezes that penetrated 45 km inland (in southern England) occurred on days with calm large-scale wind or offshore winds less than 3 m s^{-1} (Simpson et al. 1977). Wakimoto and Atkins (1994) concluded that southwest large-scale flow tended to inhibit the inland penetration of the sea breeze along the east coast of Florida and that the sea breeze penetrated farther inland for onshore large-scale wind.

Current thresholds of offshore flow which prohibit the sea breeze from moving onshore do not agree with previous results. Specifically, two-dimensional modeling has indicated that opposing flow greater than 6 m s^{-1} is sufficient to keep the sea breeze entirely offshore (Arritt 1993). However, current results suggest a higher threshold for the Cape Canaveral region since the sea breeze moved onshore and beyond tower 112 on almost 40% of the days with offshore flow greater than 6 m s^{-1}. Although an onshore sea breeze was noted for an offshore wind component as large as 12.9 m s^{-1}, a more realistic threshold for the Cape Canaveral area is 10 m s^{-1}. These findings again indicate that results from two-dimensional models are not necessarily applicable to specific locations such as Cape Canaveral, where the land/sea interface is very complex.

f. River Breezes

Banana and/or Indian River breezes are observed on 60% of sea-breeze days, a total of 117 days. River breezes are less prevalent than the sea breeze because river temperatures generally are warmer than those of the nearby Atlantic Ocean. In the current study, the temperature of the Banana River was approximately 1.5 to 3.0° C warmer than that of the Atlantic Ocean. Thus, the land/river temperature contrast is not as great as that between the land and ocean. As a result of the weaker temperature gradient, river breezes are influenced more by the large-scale wind than are sea breezes.

The Indian and Banana River breezes occur when the large-scale flow is weak. The average wind speed on days with a river breeze is 4.0 m s^{-1}. The average wind speed on days with a sea breeze, but no river breeze, is 6.1 m s^{-1}. Zhong and Takle (1993) found that weak westerly flow was the most favorable for development of the Indian River breeze. However, no strong directional preference is observed in the current study.

In spite of the weak relationship between river-breeze formation and large-scale wind direction, dependence on the strength of the large-scale flow is further reflected in values for the average perpendicular wind component. Specifically, the average component on days with a river breeze is offshore at 1.5 m s^{-1}. Conversely, on days with a sea breeze, but no river breeze, the value is somewhat higher-- offshore at 2.3 m s^{-1}. Nearly 75% of days with an observable river breeze have a perpendicular component between -4 and

+2 m s^{-1} (Fig. 14). This figure indicates that the river breeze is more affected by stronger onshore (greater than 4 m s^{-1}) and offshore flow (greater than 6 m s^{-1}) than is the sea breeze (Fig. 12).

In addition to being less prevalent than the sea breeze, the river breeze tends to initiate later than the sea breeze. Both the Indian and Banana River breezes tend to form approximately 1-2 h after the onset of the Atlantic sea breeze. Once formed, the river breezes remain for 1-4 h before being overtaken by the sea breeze. In general, the Indian River breeze lasts longer than the Banana River breeze due to the former' s greater distance from the coastline. Zhong and Takle' s (1993) numerical simulations showed that the Indian River breeze was generated at about the same time as the sea breeze and lasted for 5-6 h. This discrepancy between current results and modeled results likely occurs because Zhong and Takle assigned the Atlantic Ocean temperature to both of the rivers.

The presence of the Indian and Banana River breezes appears to have little effect on the propagation speed of the sea breeze. In general, propagation speed of the sea breeze in the Cape Canaveral region increases as the sea breeze moves inland. While this non-uniform movement can possibly be attributed to the presence of a Banana River breeze, it is more likely the result of an increased diurnal land/sea temperature gradient since this propagation pattern is apparent even on days without a river breeze. Additionally, there is no indication of decreased propagation speed of the sea breeze in the vicinity of the Indian River. Current results indicate that the Banana and Indian River breezes do not significantly reduce propagation speed of the sea breeze in the Cape Canaveral area. These findings are in agreement with both numerical simulations and previous observations (Zhong et al. 1991; Zhong and Takle 1992).

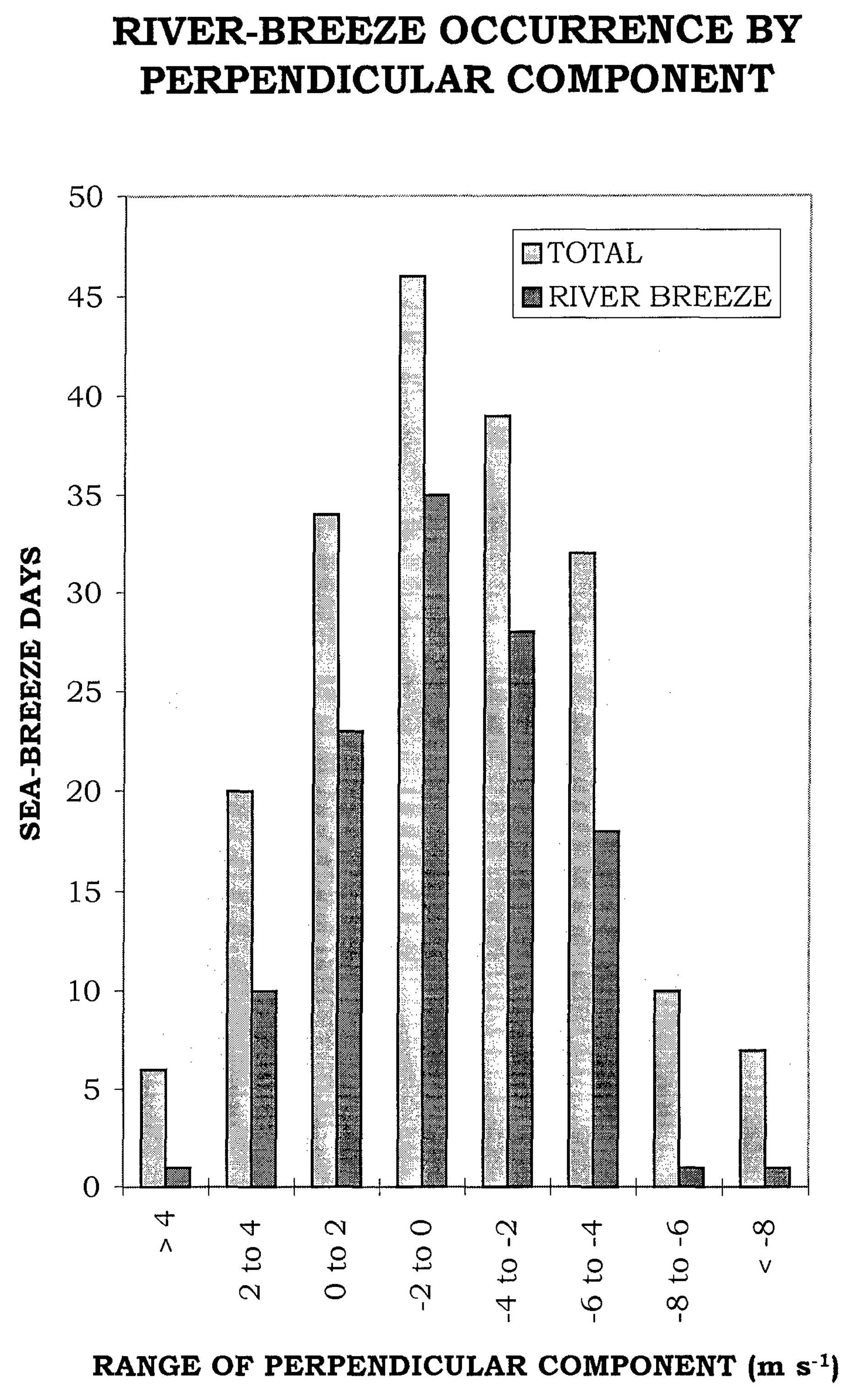

Fig. 14. River-breeze occurrence as a function of perpendicular wind component. Total is the number of sea-breeze days. Onshore flow is positive. Offshore flow is negative.

g. Trailing Convergence Line

The trailing convergence line (TCL) develops only with the SB1/SB2-type sea breeze that occurs with weak large-scale forcing. During the warm seasons of 1995 and 1996, a clearly observable TCL occurred on only 16% of the sea-breeze days (a total of 30 days). The mean large-scale wind speed for TCL development is 3.6 m s^{-1}, while the range of speeds is 0.7 to 8.2 m s^{-1}. This compares to 5.0 m s^{-1}, and 0.9 to 14.3 m s^{-1} for days with a sea breeze but no TCL. This dependence on weak large-scale wind results in the infrequent TCL occurrences; wind speeds on most days are too strong.

The TCL also is related to the direction of the large-scale wind. Results from the current study indicate that a TCL is more likely to form on days with large-scale flow from the southeast (47%). TCL dependence on weak and alongshore (southeast) flow is further demonstrated by average values of the perpendicular wind component (not shown). Specifically, the mean perpendicular component on TCL days is weak and offshore at 0.4 m s^{-1}, with a range of only 4.8 m s^{-1} offshore to 3.0 m s^{-1} onshore. In contrast, the average perpendicular component for sea-breeze days with no observable TCL is offshore at 2.0 m s^{-1} with a range of 12.9 m s^{-1} offshore to 6.7 m s^{-1} onshore. This dependence on weaker large-scale flow is similar to that found for the river breezes. In fact, 90% of all TCLs occur on days with an observable river breeze.

The TCL usually extends eastward from the intersection of the two sea breezes (SB1/SB2 type) toward the outer coast of Cape Canaveral in the vicinity of tower 3 (see Fig. 8). However, on occasion it is located north of this position. Fig. 15 indicates a TCL that formed north of its typical position. The location of the TCL depends on the position of the two separate branches of the sea breeze. If this intersection occurs in the northern

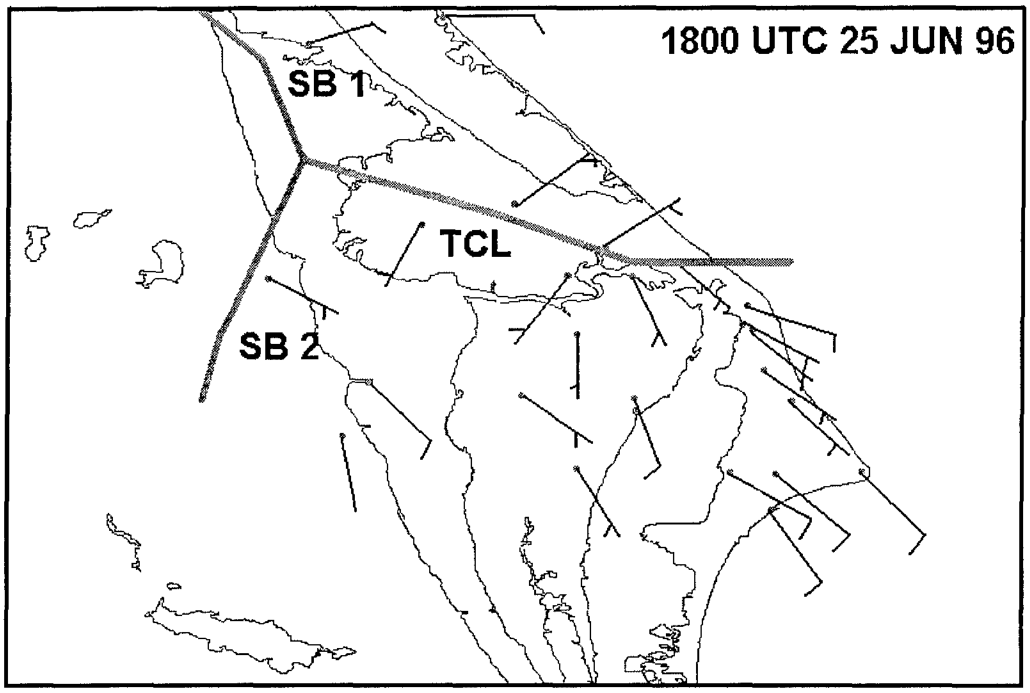

Fig. 15. Tower wind plot indicating a trailing convergence line at 1800 UTC 25 June 1996. This location is north of the typical position shown in Fig. 8.

portion of the Cape Canaveral area (as in Fig. 15), the TCL will be located north of its typical position. Results from the 30 TCL days observed in the current study indicate that this northern TCL location is unusual (only 1 case). The TCL was not observed to form south of its typical position. Once the TCL develops, it may move 1-2 km northward or southward, depending on the large-scale flow and the speed of the two sea breezes. However, in most cases it remains stationary.

Laird et al. (1994 and 1995) documented the existence of a trailing convergence line over the Cape Canaveral region during a 1 day case study. Current results indicate that TCLs are relatively uncommon and that they may develop north of the preferred location.

h. Convection

Convection is an important operational consideration in the Cape Canaveral area, and the sea breeze strongly influences its development. Pielke (1974) concluded that sea-breeze convergence patterns are the primary control for the location of clouds and convection on days without significant large-scale disturbances over south Florida. Laird et al. (1994) noted that interacting boundaries, such as the sea-breeze front, outflow boundaries, and convergence lines are associated with the initiation of most warm season deep convection over Florida. Sea breezes favor convection because convergence along the sea-breeze frontal boundary produces vertical motions within the boundary layer (Zhong and Takle 1993; Arritt 1993; Estoque 1962).

Thunderstorms are observed in the Cape Canaveral area on 53% of the days with an observable sea breeze. This compares to only 38% for days with no detectable sea breeze. Thunderstorms observed on sea-breeze days are not necessarily the result of sea-breeze passage or sea-breeze enhanced convergence, although all occurred in the afternoon or evening. On days without a sea breeze, most (83%) of the thunderstorm cases are clearly attributed to large-scale influences, e.g., fronts, tropical systems, or surface and upper air troughs. The remainder are due to subtle forcing mechanisms which cannot be resolved with the available data.

The large-scale flow plays an important role in determining the likelihood of convective development along the sea breeze front. In addition to affecting convergence along the sea breeze, the large-scale flow influences the humidity and stability of the atmosphere, and, therefore, the likelihood of convection. Thunderstorms are observed on 70% of the sea-breeze days with southwest flow. Conversely, only 15% of the sea-breeze days with northeast flow result in convection. Almost 80% of all sea-breeze days with thunderstorms have large-scale flow from the southeast or southwest.

These findings agree well with those of previous researchers. Neumann (1970) used 13 years of data to show that southwesterly winds at 850 mb are highly favorable for thunderstorm development over the Cape Canaveral area. Lightning flashes in the Cape Canaveral region also are most abundant for southwest flow (Watson et al. 1991). Fewest flashes occurred under northwest and northeast large-scale flow. The direction of the large-scale flow affects the stability and humidity of the atmosphere and the likelihood of convection. Days with southwest large-scale flow have been found to be the most humid and unstable and most favorable for convective development in the Cape Canaveral area (Lopez and Holle 1987). On the other hand, days with northeast flow were the driest and most stable. Additionally, southwest flow can cause thunderstorms over mainland Florida to advect into the Cape Canaveral region from mainland Florida. Southwesterly winds can also cause the west coast sea breeze to propagate toward the east coast where it can interact with the east coast sea breeze (Watson et al. 1991; Holle and Lopez 1987; Cooper and Smith 1993). This can provide an additional region of convergence, further enhancing the likelihood of convection.

Convection over Cape Canaveral is highly dependent on the perpendicular component of the large-scale wind (Fig. 16). Over 62% of the sea-breeze days with an offshore (negative) component experience convection. The stronger offshore flow cases are associated with a greater likelihood of convection. Conversely, only four sea-breeze days with a large-scale onshore component greater than 2 m s^{-1} (15%) experience convection. Results clearly indicate that offshore flow is most likely to result in convection over the Cape Canaveral region on days with an observable sea breeze.

Current results are consistent with those from previous research. An early diagnostic study of the southeast Florida coast revealed maximum convective activity for offshore large-scale flow (Gentry and Moore 1954). More recently, Nicholls et al. (1991), utilizing a two-dimensional model, noted that most convection over the east coast of south Florida occurred for offshore large-scale flow. Additionally, two-dimensional modeling of the sea breeze has shown that offshore flow produces the strongest low-level convergence along the sea-breeze front (Bechtold et al. 1991; Arritt 1993; Zhong and Takle 1993; Xian and Pielke 1991; Atkins et al. 1995).

The likelihood of convection also is related to the inland penetration of the sea breeze. Convection within 40 km of Cape Canaveral occurs on only 49% of the days when the sea breeze penetrates the entire Cape Canaveral tower network. Conversely, when the sea breeze fails to penetrate beyond 30 km, nearby thunderstorms are observed on 70% of

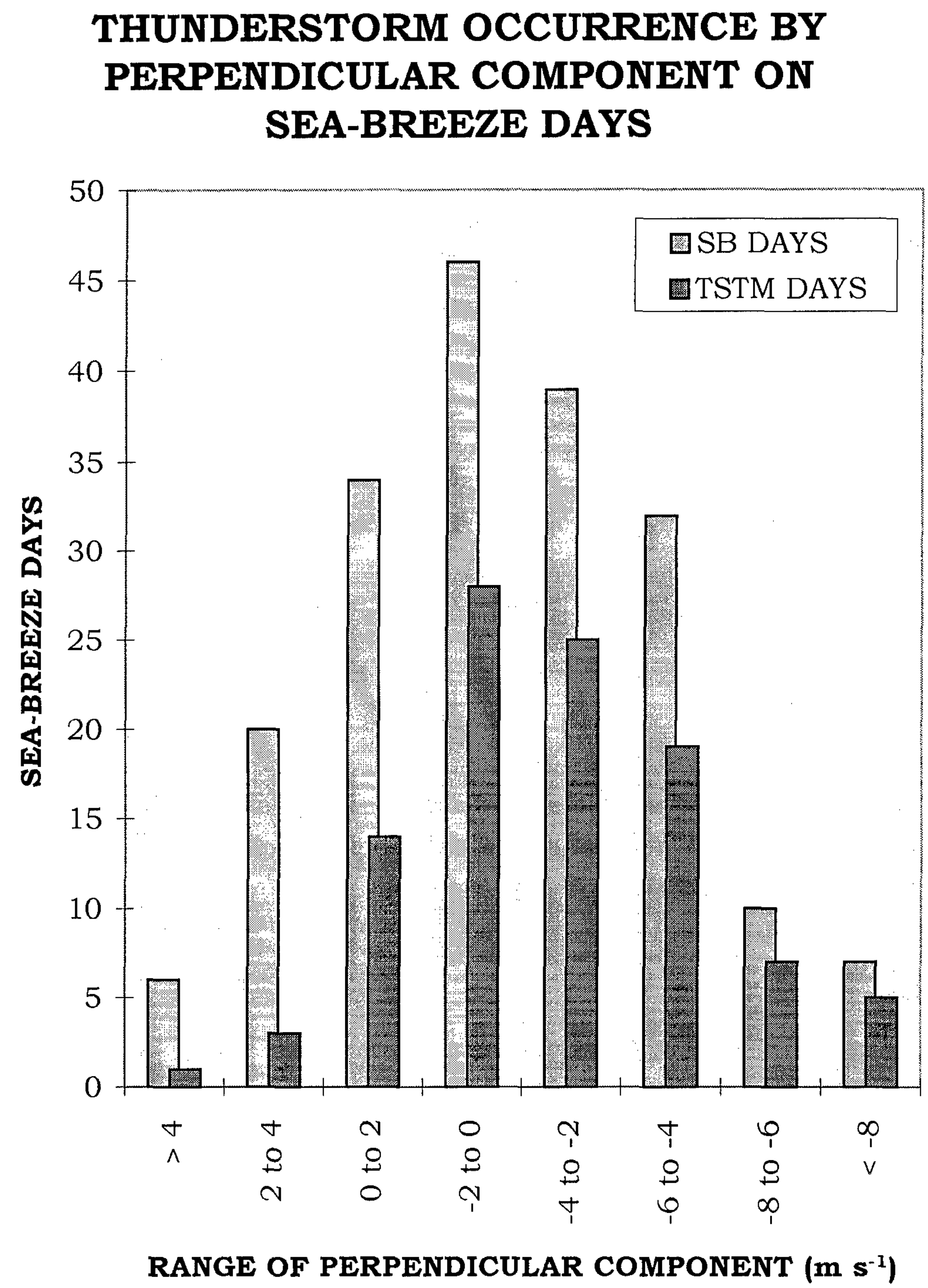

Fig. 16. Thunderstorm occurrence as a function of perpendicular wind component on sea-breeze days. Onshore components are positive. Offshore components are negative.

the days. For inland penetration less than 10 km, thunderstorms are observed on 82% of the days.

Results of the current study indicate little relation between convection and the presence of the Indian and/or Banana River breezes. This may be due to the weaker large-scale forcing present on river-breeze days or, more probably, the larger percentage of southwest flow cases for non-river breeze days.

Conversely, the presence of a TCL increases the likelihood of convection. Thunderstorms are 13% more likely to occur on sea-breeze days with an observable TCL than on sea-breeze days without a TCL. This agrees with Laird et al. (1994 and 1995) who noted that the TCL played an important role in the initiation of convection.

4. SUMMARY AND CONCLUSIONS

This study has investigated the sea breeze in the Cape Canaveral, Florida region during the warm seasons of 1995 and 1996. Meteorological data from the Cape Canaveral mesoscale tower network were used to locate the sea breeze, determine its inland penetration, and assess its time of passage. One kilometer, half-hourly GOES visible imagery centered over Melbourne, Florida also was utilized for this purpose. Upper air data from the Cape Canaveral radiosonde site were used to determine the large-scale flow over the region. A total of 357 days was examined. They were classified as sea-breeze days, non-sea-breeze days, or undetermined. Undetermined days (40) were removed from the final sample, leaving a total of 317 days. River breezes and other local circulations were analyzed and related to the sea breeze. Additionally, the presence of convection was related to sea breeze occurrence and large-scale flow.

A sea breeze was observed on 194 of the 317 days (61%). The sea breeze was most likely to form on days with large-scale flow from any direction but northeast. Inland penetration was greater, and passage times were earlier for onshore large-scale flow. Conversely, inland penetration was reduced and passage times delayed for offshore large-scale flow.

River breezes were observed on 117 of the sea-breeze days (60%). River breezes were not observed on days without a sea breeze. A river breeze was more likely to develop when the large-scale flow was less than 4 m s^{-1}. A trailing convergence line was observed behind the sea breeze on 30 days. It formed on days with very weak large-scale forcing (average perpendicular wind component offshore at 0.4 m s^{-1}). Thunderstorms were observed on 53% of all sea-breeze days and were most likely for large-scale flow from the southwest. Thunderstorms occurred on over 70% of the sea-breeze days with an offshore large-scale wind component. The probability of convection increased to a maximum of 82% for inland sea-breeze penetration less than 10 km.

Thresholds of the large-scale perpendicular wind component producing an onshore sea breeze were established. Values determined from the current study were greater than those from previous numerical studies. Current observations indicated sea-breeze occurrence between an offshore maximum of 12.9 m s^{-1} and an onshore maximum of 6.7 m s^{-1}. Almost all (99%) sea breezes occurred within thresholds of 10 m s^{-1} for offshore flow and 6 m s^{-1} for onshore flow.

The average sea-breeze passage time at tower 112 was 1528 UTC. The range of passage times for the sea breeze was found to be 1205 to 2120 UTC. This range is highly dependent on the large-scale flow.

This study considered two warm seasons at Cape Canaveral, Florida. The research should be continued with an expanded data base. It is suggested that cloud cover and temperature be incorporated further. With an increased data base, a forecast tool could be created for sea-breeze probability and passage time based on amount of cloud cover, temperature, and large-scale wind. Diagnostic climatological studies of this type are important because two-dimensional numerical sea-breeze models, and even some three-dimensional models, do not adequately account for the complex land/sea interface near Cape Canaveral.

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BIOGRAPHICAL SKETCH

Jeffrey David Cetola [redacted] graduated from J.E.B. Stuart High School in Falls Church, Virginia in 1984. He received a Bachelor of Science degree in Electrical Engineering from Clemson University in 1988. He was commissioned a 2nd Lieutenant in the United States Air Force in December, 1988 and was assigned to the Air Force Institute of Technology's Basic Meteorology Program. He completed the 1-year program at Florida State University in 1989 and was assigned to Carswell Air Force Base, Texas as a weather officer. In 1992 he was transferred to Royal Air Force Mildenhall, United Kingdom where he worked as chief of the Special Support Cell until July of 1995. Captain Cetola returned to the Air Force Institute of Technology to pursue a Masters Degree in Meteorology in the autumn of 1995. This thesis is the result of two years of research in accomplishing that goal.