Wind Forecasting for Yacht Racing at the 1991 Pan American Games

Mark D. Powell
NOAA/AOML/Hurricane Research Division,
Miami, Florida

Abstract

The U.S. Sailing Team competed successfully at the 1991 Pan American Games despite having no previous experience with the sailing conditions off Havana, Cuba. One of the key factors in the team's success was meteorological support in the form of wind climate analysis; application of sea breeze forecasting typical of the south Florida area, modified by tropical weather systems; and effective preregatta briefing.

1. Introduction

This paper describes the author's effort to provide meteorological support to the U.S. Sailing Team in preparation for and during the XI Pan American Games held in Havana, Cuba, in 1991 (Fig. 1a). The purpose is to inform fellow meteorologists of an approach toward meeting the forecast needs of major one-design yachting competitions that may improve service to this segment of the marine community.

Yacht racing at the Olympic and Pan American games involves competition among several classes of sailboats that are designed to challenge athletes in different ways. Each class is "one design"; all yachts are of identical design and rig. The one-design classes include sophisticated windsurfers, single-handed dinghies, double-handed dinghies, a double-handed catamaran, and small keel boats that can carry a crew of two or three. The 1991 format included three classes for women and six open classes (men or women). The yachting competition consisted of one race per day in each class from 7 to 13 August. Medals were awarded to the top three teams in each class based upon the best total score for all races.

Yacht racing is unique among all Olympic sports in that success depends greatly on an intuitive understanding of the wind. When preparing for regatta competition, the sailor must know what wind, weather, tide, current, and wave conditions to expect at the race site. Such knowledge helps in training the crew, selecting and testing sails and equipment, and determining optimum crew weight. On the day of a race, the sailor needs a forecast for expected wind conditions. Special attention must be given to factors that can produce large wind shifts over the 1–4 h of a race.

Although the host nation often provides forecasts for major competitions, many nations send team meteorologists to provide additional assistance. Team meteorologists analyze the wind climate of the race site, make observations of wind and weather conditions at the sailing venue, interpret how forecasts could affect the races, hindcast actual conditions that occurred in the races, and advise the sailors on how to nowcast wind changes as they appear. Their job is made much easier when the host nation makes available climate analysis, observations and forecasts, such as those provided by the National Weather Service Forecast Office (WSFO) in Los Angeles for the 1984 Olympic Games sailing events (Staff, WSFO 1983). When it became obvious that little information of this type would be available for Havana (about 2 months before the Pan American Games), the U.S. Olympic Yachting Committee requested the author's assistance as team meteorologist.

2. Preparations for the regatta

Most sailors rely on past experiences or tips from local sailors to learn about expected conditions for upcoming races. This was a special problem for Havana (Fig. 1b), which was the site of few international competitions since the 1950s. Nevertheless, important information was gleaned from interviews with Cuban-Americans who had raced and, in one case, forecasted in the Havana area. Additional information was acquired from weather atlases and climate summaries. Unfortunately, these sources were unable to describe the typical hour-by-hour wind changes during August afternoons. If anything, the wind speeds in the atlas could be interpreted as deceivingly weak, because monthly wind roses consisted of winds averaged from 0700–1900 Local Daylight Time (LDT = UTC – 4) that included the weak winds following sunrise and the stronger sea-breeze winds during the afternoon.

Atlas data, satellite imagery, and the author's expe-

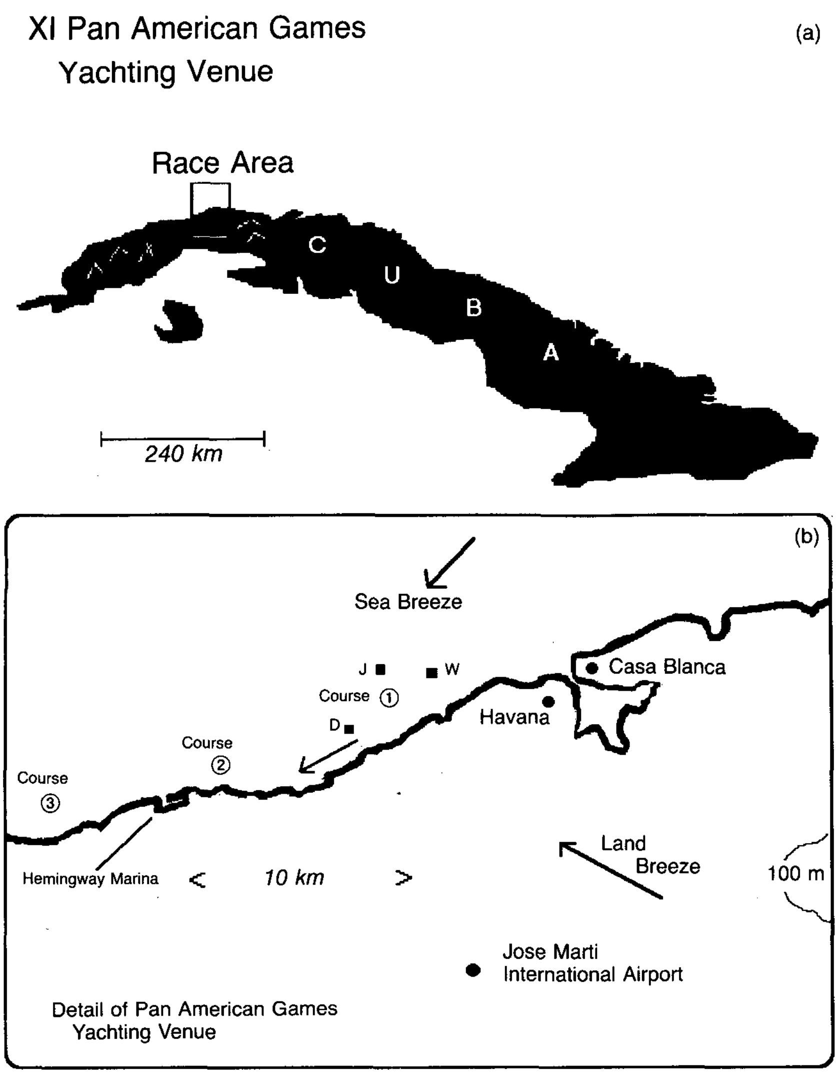

FIG. 1.(a) Location of yachting venue for the 1991 Pan American Games. (b) Detail of inset from (a). Circled numbers indicate individual race courses. Filled squares labeled W, D, J, represent typical mark locations. Arrows represent wind directions, and the 100-m topographic contour is shown to the right.

rience sailing in south Florida suggested that the wind climate of Cuba has many similarities to that of south Florida: the sea breeze would be the dominant feature; its interaction with afternoon thunderstorms and tropical weather features would be the most demanding forecast challenge. Since the sea breeze is the predominant local wind feature in many popular sailing areas in summer (Watts 1967), some of the following will be applicable at other sites.

In the months before the games, the author proceeded to

1) review literature on the south Florida sea breeze and its interaction with convection;

2) acquire and analyze several years of surface wind observations from sites closest to the race area, and prepare a wind climate and weather summary for team use;

3) find out as much as possible about the race site, including topography, bathymetry, location relative to the climate data sites, tide tables, and currents;

4) begin a trial forecast period for the race site using high-resolution visible satellite imagery; and

5) brief the team before their departure, and work out communications between the race site and the forecast base at the Miami National Weather Service Forecast Office, collocated with the National Hurricane Center.

a. *Pertinent information on the sea breeze*

The peninsular-scale forcing of the south Florida sea breeze is responsible for almost daily thunderstorms over the interior of the state. Satellite imagery identifies sea-breeze-front cloud lines that move inland from both coasts and merge to form large thunderstorm complexes that can modulate the sea breeze. Several investigations, including the Thunderstorm Project and the Florida Area Cumulus Experiment (FACE), resulted in a wealth of information on the south Florida sea breeze. Findings by several authors are summarized below, including: Pielke (1974), Frank et al. (1967), Burpee (1979), Burpee and Lahiff (1984), Cooper et al. (1982), and Blanchard and Lopez (1985). On a typical day, peninsular-scale convergence associated with sea breezes on each coast starts at 1000 LDT, becomes a maximum at 1400 LDT, and remains negative until 1900 LDT. The sea-breeze convergence band on each coast moves inland to initiate showers by 1500; convection begins earlier on days with high midtropospheric humidity. By 1600, thunderstorms produce maximum rainfall, outflows, and inland divergence zones. Outflow interaction acts to initiate new convective cells, while the outflows and spreading anvil cloud work to decrease the peninsular-scale convergence from 1600 LDT well into the evening.

The onset time of the sea breeze and the position of deep convection is related to the larger-scale, lower-tropospheric flow direction, hereafter referred to as ambient flow. The onshore coast (relative to the ambient flow) sea breeze develops earlier, but is weaker, while the offshore coast sea breeze forms later, with a stronger circulation reinforced by the ambient flow. Relatively strong (> 5 m s^{-1}) ambient flows from the east and southeast tend to move the east-coast sea-breeze line well inland, often merging with the west-coast sea-breeze line and producing deep convection close to the west coast or inland. A westerly ambient flow confines the east-coast sea-breeze front to the shoreline or slightly inland, causing coastal thunderstorms. A southerly ambient flow concentrates the land/sea temperature gradient, resulting in a stronger sea breeze.

Experience sailing in Biscayne Bay off Miami indicated that the sea-breeze onset occurs sometime between 1100 and 1300 LDT, with the sea-breeze front or convergence band visible as a line of growing cumulus (cu) clouds just offshore or on the coast. As this sea-breeze front propagates inland, the cu grow into towering cu (now visible in satellite imagery) and then into cumulonimbus (cbs). During this stage the sea breeze accelerates as enhanced inflow into the growing cells. The breeze continues building until the inland cells display evidence of outflows (rain shafts and arc clouds; according to the above-mentioned studies, 1500–1600 LDT) or until the anvil spreads over enough land surface to cut down the land/sea temperature gradient. Occasionally, the thunderstorm line moves out over the water, the cells moving with the 970–700-mb mean flow (Woodley et al. 1982) or an outflow moves out toward the water and terminates the sea breeze. With these facts in mind, we initiated a wind climate study of the race area.

b. The wind climate of Havana

A study of the wind climate is essential for proper race preparation by the sailors and for providing a baseline for wind forecasts. It is also important for determining the location of selection trials to attempt matching the climate of the Olympics site. The nearest climate data sources for the Pan American Games were the Cuban National Meteorological Observatory at Casa Blanca (CSB) and the Jose Marti International Airport (MUHA). The data were for August of each year, from 1973 to 1990. Preliminary atlas data from CSB suggested a northeast sea breeze and a southeast land breeze, but gave little indication as to the timing and peak speeds of the sea breeze. CSB is located ~15 km to the northeast of the race site (Fig. 1b), on the east shore of Havana Harbor, on a small hill ~50 m above sea level. The wind data are 10-min averages at the 10-m level (60 m above sea level). Disadvantages of this site included the hilltop exposure (tendency to overestimate wind speeds) and the surrounding urban terrain (tendency to underestimate wind speeds). Despite these disadvantages, CSB's near-coastal location produced surface wind measurements that displayed a very well-defined sea-breeze circulation, in contrast with MUHA (not shown).

Percentage wind-speed and wind-direction frequency diagrams were created for each hour, from 0800 to 1700 LDT, as a three-dimensional plot in Fig. 2. As depicted in the plot, the land and sea breezes are very well defined, suggesting that at the CSB site exposure problems are minimal. The land breeze is predominantly from 120° at 1.5–3.0 m s^{-1} through the morning until 1100 LDT; between 1100 and 1200 LDT, the sea breeze begins as a 3–4.5 m s^{-1} breeze from 050°. Throughout the afternoon, the direction remains 040°–050° and the breeze gradually builds to 6–8 m s^{-1}, with significant percentages of speeds at 8–9 m s^{-1} between 1500 and 1600 LDT. Since the effects of larger-scale, tropical disturbances are contained in the wind-climate database, the data were arranged (not shown) into thunderstorm and nonthunderstorm days and further delineated into sea level pressure above and below 1015 mb, the mean pressure for August. The undisturbed classification was given to observations ≥ 1015 mb (64%) of all observations); the remaining 36% were assumed to represent winds influenced by weather features with below-normal pressures. Burpee and Lahiff (1984) classified nondisturbed and disturbed summer sea-breeze days according to morning areal cloud cover from satellite images and found 69% of the days undisturbed and 31% disturbed, consistent with our findings for Havana. On thunderstorm days with above-normal pressure (1148 observations) the progression of the wind direction and speed frequency distribution was similar to Fig. 2. Nonthunderstorm days with greater-than-normal pressure (2421 observations) are indicative of undisturbed but perhaps suppressed conditions and showed a tendency for stronger wind speeds (8–9 m s^{-1}) at 1500 and 1600 LDT. Nonthunderstorm (1137 obs) or thunderstorm (877 obs) days with below-normal pressure were classified as disturbed conditions and indicated a later and less well-defined sea

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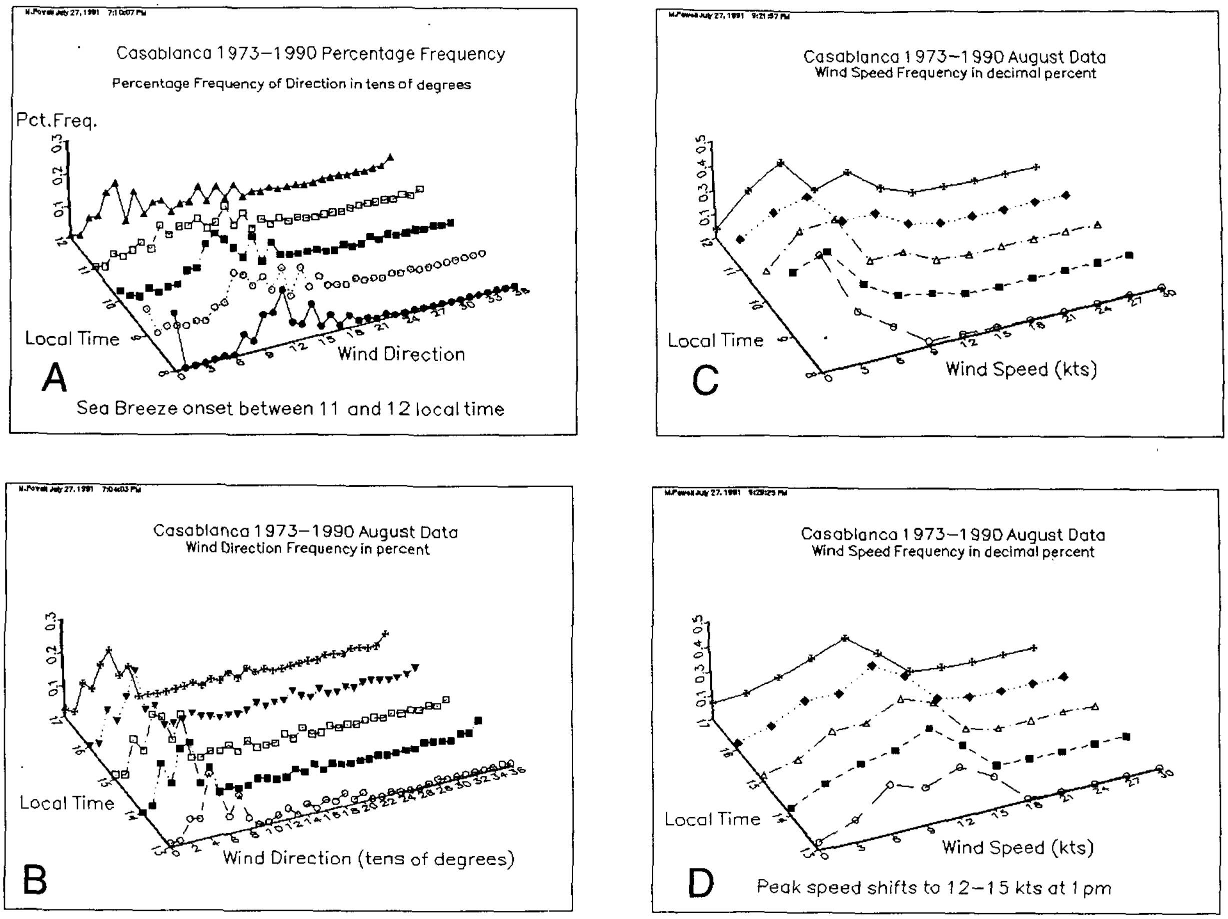

FIG. 2. Percentage frequency distribution of wind direction and speed from 0800–1700 LDT at Casa Blanca for August 1973–1990. The *x* axis represents wind direction or wind speed, the *y* axis represents local daylight time, and the *z* axis represents percentage frequency of all observations at the corresponding time that are from a particular wind direction or at a particular wind speed.

breeze starting between 1200 and 1300 LDT, with speeds of 4.5–6 m s^{-1}, increasing to 6–8 m s^{-1} from 1500 to 1600 LDT.

c. The race site

Details of the race site are shown in Fig. 1b. The nine classes shared three courses, labeled 1–3. The design of Olympic courses requires yachts to start in the vicinity of the D mark, sail upwind to W, then follow the sequence J-D-W-D-finish at W. Navigation charts indicated water depths to > 300 m within 2 km of the coast, forcing courses to be very close to shore to allow anchoring marks. The races were scheduled to begin at 1300 LDT and last 1.5–2 h. The Gulf Stream current was prevalent in the deeper water, running toward the northeast at 0.5 m s^{-1} or more, according to NOAA pilot charts. There was some evidence from past experiences of Cuban–American sailors that the coastline shape causes the wind to veer more parallel to the shore, as depicted by the arrow below D in Fig. 1b. The deep water offshore would help to build a swell through the afternoon, compounded by the sea breeze opposing the Gulf Stream, but the wind would not maintain an onshore flow long enough for large seas to become a major consideration close to shore. The race area was at the narrowest part of Cuba, with the height of some hills > 100 m a few kilometers inland to the southeast and another range of hills farther to the southwest. The topography is generally higher in the middle of the island and is a factor in the development of daily convection.

d. Trial forecasts

During 25 days, between 12 July–6 August, practice forecasts were issued for the race site. A major difficulty involved the lack of verification data for the forecasts due to communication problems. Synoptic (3-h) data were available from CSB on only 10 days, and the 3-h resolution could not validate sea-breeze onset time and hour-to-hour changes. Data were available from MUHA for five other days, but these data were often too far inland to receive the sea breeze. High-resolution (1 km) GOES visible satellite imagery at 30-min intervals was looped over several hours from 1030 to 1630 LDT and gave a reasonable estimate of sea-breeze onset time according to the appearance of the sea-breeze cloud front on the shoreline. Actual onset of the sea breeze was probably up to 30 min earlier. Thunderstorm development over Cuba and subsequent movement into the Florida Straits was monitored over the trial period by the Key West (EYW) Weather Service Office's WSR-57 radar. Disturbed conditions (days with external forcing from larger-scale systems) occurred on 8 of the 25 days. On three days, a low developed in the northeast Gulf of Mexico, producing strong southerly flow; on three other days, tropical waves amplified convective activity on the sea-breeze front, and finally, a 700-mb trough in the extreme eastern Gulf of Mexico caused a northwest sea breeze on two days.

Of the 17 nondisturbed days, deep convection on the sea-breeze front typically began around 1430-1530 LDT. The sea-breeze front usually formed on both coasts. When the direction of the 850–700-mb winds was from the west-southwest clockwise through east-northeast, the north-coast sea-breeze front moved inland, while the south-coast front was quasi-stationary. For 850–700-mb flow from southeast through southwest, the south-coast sea-breeze front moved inland while the north-coast front was stationary; for easterly flow or very weak flow, both fronts moved slowly inland. Mergers of the sea-breeze convergence lines occurred on or inshore of the offshore coast; secondary mergers formed when the lines intercepted convection forming independently on the interior ranges of hills and when arc clouds that had propagated from one line intersected another. These mergers were accompanied by a sudden increase in convection, resulting in spreading anvil clouds and arc clouds associated with thunderstorm outflows. Outflows were evident on five days as wind shifts from onshore to offshore at CSB or MUHA and/or as arc-shaped lines propagating from the parent thunderstorm complex (according to satellite imagery); on another five days, cells forming on the sea-breeze front actually moved out onto the coastline or offshore. Anvil cloud spreading from inland thunderstorm complexes visibly weakened the sea breeze on five days, and anvils from offshore convection delayed sea-breeze onset on two days.

The trial period represented a reasonable example of the complexity of the forecast problem and indicated the products that would be helpful. Climatology provided a good estimate of the sea-breeze onset time and direction. Any extensive early-morning high cloudiness visible on satellite could be expected to delay the sea breeze. The mean 850–700-mb wind indicated the coast that would be downwind for sea-breeze front mergers and the direction that cells would move. The 200-mb flow and/or satellite water vapor channel loops gave a good indication of the direction of anvil spread and upper-tropospheric subsidence zones. The trial period provided many examples of possible interactions between the sea breeze and the sea-breeze-front thunderstorms. Forecasting of downdraft interactions and arc cloud propagation was impossible, because the forecast was due before any convection was evident. The determination of disturbed days caused by easterly waves and upper cold lows and their interaction with the sea-breeze fronts was very difficult. Waves were extremely difficult to track, and their position or existence often depended on which forecaster was consulted. Prominent wind shifts in the upper-air soundings from the central Caribbean, Florida, and the Bahamas were the best indicator; however, many satellite cloud lines that were thought to be waves were not detectable in the soundings, and at times, wind shifts were not accompanied by significant weather.

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e. Team briefing

At the completion of the wind-climate analysis and the trial forecast period, a written summary was prepared for the team and results presented in the form of a briefing. The briefing included viewgraphs, video footage from visible satellite loops, and cloud slides describing the development of sea-breeze-front convection, front movement and mergers, anvil effects, and downdraft outflows. The sailors were briefed on what to look for to "nowcast" these features during a race and how the sea breeze might be affected. They were also familiarized with the forecast format.

3. Forecast support during the Pan American Games

In an ideal operations environment, the team meteorologist should be able to prepare a forecast using detailed information available on site, brief the team each day before they embark for the race course, use an instrumented support boat to take detailed wind and current observations on the race course that could be radioed to the coaches' support boats on the individual courses (to allow updating the forecast for the sailors before the start), continue to take on-the-water observations during the race for hindcast analysis, and finally brief the team on actual conditions after the race. Because of a lack of support craft, on-site weather information, and communication facilities, the team meteorologist's duties were performed by the author in Miami, using the facilities of the Miami Weather Service Forecast Office.

A team alternate was designated to document race-course wind and weather conditions each hour with a hand-held anemometer and compass; these verification data were transmitted to Miami each evening. Due to transportation and communication problems in Havana and communication difficulties between Havana and Miami, the forecast deadline was 0845 LDT; the forecast was polled (accessed by phone from Havana to Miami) by U.S. Olympic Committee fax transmission from Havana. If conditions warranted, forecast updates were forwarded before 1030 LDT. The forecast included: 1) tides for Havana harbor, 2) a hindcast on factors that affected the previous day's wind conditions, 3) general weather pattern for the day (large-scale factors affecting the day's weather), 4) local weather pattern for the day (sea-breeze onset time, speed, likelihood of convection), 5) conditions to look for on the race course (cell movements, anvil spread directions, indicative cloud types), and 6) outlook for tomorrow. A 0500 LDT surface map with wind observations and an isobaric analysis was included with the forecast.

Beginning at 0500 LDT, the forecast procedure was to 1) review conditions and hindcast for the previous day; 2) analyze the previous evening's 2000 LDT (0000 UTC) sounding data for the region to determine the 850–700-mb wind for the area, for effect on sea-breeze onset and convergence-line movement; 3) examine nested-grid model (NGM) (Hoke et al. 1989) and aviation model results from the 2000 LDT run (especially 500-mb vorticity, 700-mb heights, and vertical velocity) to assess the synoptic situation and large-scale changes; 4) examine aviation model 24- and 48-h surface wind forecasts (Rao 1989) for the region and the grid point closest to Havana; 5) review the NGM model boundary-layer wind forecast for the region and Havana grid point for 18, 24, 36, and 48 h; 6) review the NGM 24-h quantitative precipitation forecast (QPF-6) and low-level moisture convergence; 7) check the Havana Jose Marti International Airport terminal wind forecast for the period 0800–0800 LDT, if available; 8) analyze the 0500 LDT surface map and note differences from yesterday's analysis [later surface wind observations for the region were monitored and compared with the previous day's conditions especially at the Coastal Marine Automated Network (CMAN) stations in the Florida Keys]; 9) consult with NHC's tropical satellite and analysis group for potential easterly wave or upper cold-low interaction, upper-level winds or subsidence zones evident from the water vapor imagery, and any local or offshore convection that might affect development of the sea breeze; 10) discuss the forecast situation with the lead forecaster if time allowed; and 11) examine a few of the early 0800 LDT upper-air data for major changes from the previous evening's 2000 LDT analysis.

The forecast form was then filled out and set up for fax polling. After the forecast was transmitted, the later 0800 LDT upper-air data were examined and regional satellite loops were monitored.

Table 1. Observed winds at the race site.

Date	Observed		Observed			
	land breeze		*mean sea breeze onset time, gust*			
	Wd[1] deg	Ws[2] $m\ s^{-1}$	Wd deg	Ws $m\ s^{-1}$	Time LDT	Gust $m\ s^{-1}$
7 Aug.	120	5–6	060	8.5	1430	G 12
8 Aug.	120	2–4	043	6.5	1245	G 8
9 Aug.	130	2–4	039	4.5	1245	G 7
10 Aug.	120	2	040	4.0	1130	G 5
11 Aug.	120	4	040	5.1	1130	G 8
12 Aug.	120	2	032	4.5	1055	G 8
13 Aug.	135	2–3	043	5.0	1320	G 7

[1]Wd = wind direction, [2]Ws = wind speed

4. Observed conditions

Observed and forecast conditions at the race site are listed in Table 1. Forecast winds were assumed to apply to the mean conditions that would be experienced by the sailors on all courses at about the 3-m level from 1300 to 1600 LDT. It is conceivable that

TABLE 1 (continued). Observed winds at the race site compared to forecast winds by various methods.

Date	Persistence		Climatology		NGM 6-h		NGM 18-h		Havana		Forecast		Forecast			
					2 PM LDT		2 PM LDT		*terminal forecast*		*land breeze*		*mean sea breeze onset time, gust*			
	Wd deg	Ws m s^{-1}	Wd deg	Ws m s^{-1}	Wd deg	Ws m s^{-1}	Wd deg	Ws m s^{-1}	Wd deg	Ws m s^{-1}	Wd deg	Ws m s^{-1}	Wd deg	Ws m s^{-1}	Time LDT	Gust m s^{-1}
7 Aug.	055	6.5	045	7.0	055	5	080	5	120	5	120	5–8	045	6	1300–1500	G 8
8 Aug.	060	8.5	"	"	060	5	070	5	120	6	100	6	045	6–8	1300	G 9
9 Aug.	030	6.5	"	"	060	5	065	3	NA		090	3	015	4–6	1200	G 8
10 Aug.	035	4.5	"	"	040	5	095	3	NA		100	4	020	3–5	1200	G 7
11 Aug.	040	4.0	"	"	050	5	070	5	070	8	120	2	035	5	1200	G 6
12 Aug.	040	5.1	"	"	045	5	050	5	070	7	120	3	040	3–5	1200	G 8
13 Aug.	035	4.5	"	"	035	3	045	3	060	7–8	120	3	030	5	1200	G 7

[1]Wd = wind direction, [2]Ws = wind speed

verification data could vary with observing position over one course or between courses at any particular time. Unfortunately, it was not possible to take wind measurements out on the race courses; observed conditions are hand-held anemometer observations taken from a hotel rooftop (= 50 m height) overlooking course 1 (Fig. 1b). In order to minimize variability, the observed winds in Table 1 represent a mean of 4-h (5-min average) observations from 1300 to 1600 LDT. Although not an ideal exposure for measurement, the U.S. coaches believed these measurements were representative of mean wind conditions experienced on the three race courses; main differences between the courses were related to current velocity.

With the exception of the first and last days of the regatta, undisturbed and suppressed conditions prevailed due to the proximity of a lower-tropospheric high-pressure ridge over south Florida or the Florida Straits. Surface pressures were 1–3 mb above normal throughout the week of racing. The first race was associated with disturbed conditions produced by a surge in the easterlies following a tropical wave on 7 August. On this day the gradient flow was strong, as evidenced in Fig. 3 by cloud streets oriented east-southeast to northwest throughout Cuba. The prevailing flow was strong enough to delay the sea breeze to 1430 LDT; the incipient sea-breeze front is barely visible at the head of the line from "race area" in Fig. 3. Conditions for races 2–6 differed from the trial forecast period in that an apparent subsidence region (as indicated by a dry zone in water vapor imagery) prevented deep convection throughout all but western Cuba. Race 3 on 9 August was typical of these conditions as indicated in Fig. 4 a,b. At 1230 LDT (Fig. 4a), scattered cumulus had developed throughout the island, with the beginning of the sea-breeze front indicated by cloud lines paralleling the coast. By 1600 (Fig. 4b), under weak easterly lower-tropospheric flow, the north- and south-coast sea-breeze lines moved inland without convective development. With sea breeze and topography available to force daily convection, the absence of deep convection on the sea-breeze lines was very difficult to forecast. Indeed, the NGM guidance indicated low-level moisture convergence maxima and associated quantitative precipitation maxima inland of Havana for race 3. Overforecasts of precipitation extent associated with sea breezes by the NGM have been noted by Junker et al. (1989). This was further complicated by a lack of upper-air data in the region. The closest upper-air observing site, EYW, was often on the other side of the lower-tropospheric high-pressure ridge.

The effect of a weak westerly wind component at 700 mb on the position and movement of the sea-breeze front is illustrated in Fig. 5 during race 5 on 11 August; the north-coast sea breeze formed at noon

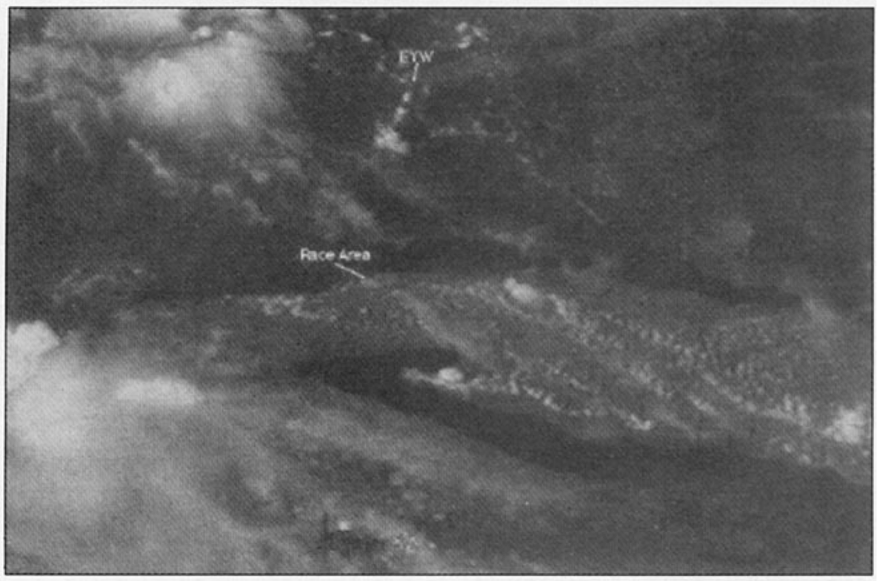

FIG. 3. High (1-km) resolution visible GOES imagery for race 1, on 7 August 1991 at 1500 LDT. Locations of the race site and Key West are indicated at the end of lines from "Race Area" and "EYW" respectively. Image has been edited to enhance coastline contrast.

and propagated across to the south coast of Cuba by 1600 LDT. Deep convection developed on the front, well west of the race site. On 12 August (race 6), lower- to midtropospheric humidity levels rose enough to allow convection to develop on the north side of the island. At 1230 LDT (Fig. 6a), the sea-breeze front was restricted to the north coast by east-southeast lower-tropospheric flow. By 1600 LDT, the resulting anvil (Fig. 6b) was spreading out over the race area and weakened the sea breeze from 6 to 4 m s^{-1}, based on measurements overlooking the race site, and to a calm at MUHA. Conditions for the last race on 13 August were apparently affected by the proximity of an upper cold low over western Cuba. Relatively strong southeasterly flow produced cloud streets (Fig. 7, 1430 LDT) similar to Fig. 3, which delayed the sea breeze until 1320 LDT and restricted the sea-breeze front to the north coast. Towering cu developed on the front close to the coast between 1500 and 1600 LDT, coinciding with the strongest winds of the day at the race area.

5. Forecast performance

In Table 1, persistence refers to mean conditions that occurred from 1300 to 1600 LDT during the previous day, and climatology refers to the mean conditions for the same time period suggested by Fig. 2. The NGM 6-h boundary-layer wind forecast for the coastal grid point about 15 km northeast of the race site (valid for 1400 LDT) was from the 0800 LDT (1200 UTC) initial data and unavailable for forecast guidance. The NGM 18-h boundary-layer wind forecast for the same grid point (also valid for 1400 LDT) from the previous evening's 2000 LDT initial data was available for forecast guidance. According to Junker et al. (1989), both NGM wind products apply to the middle of the lowest model layer (≅150 m). Aviation-model surface wind forecasts were not available for valid times during the races. The Havana MUHA terminal forecast

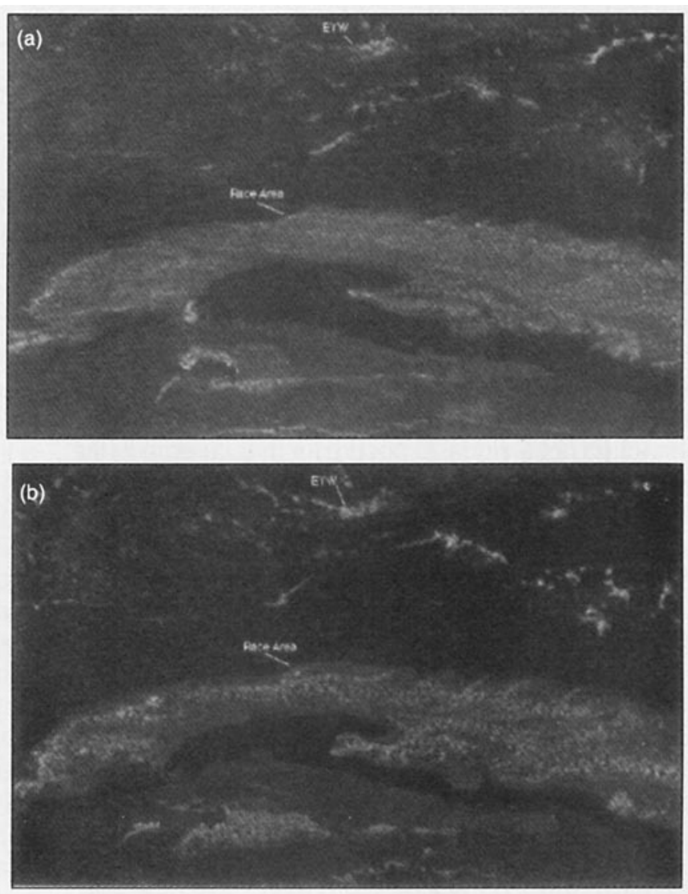

Fig. 4. (a) Same as Fig 3, but for race 3, on 9 August 1991 at 1230 LDT; sea-breeze front not visible. (b) Same as (a), but for 1600 LDT; sea-breeze fronts near center of the island

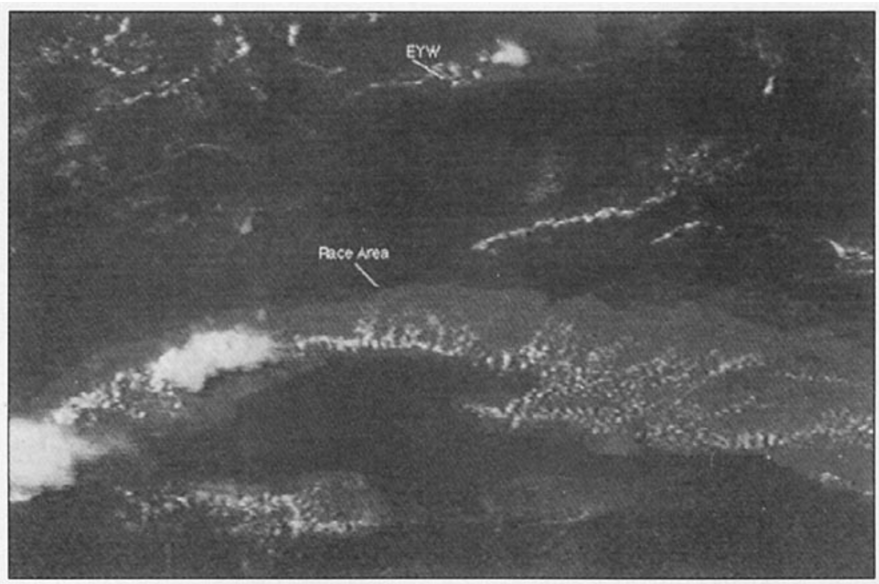

FIG. 5. Same as Fig. 3 but for race 5 on 11 August 1991 at 1600 LDT; sea-breeze fronts merged near south coast.

The quality of the NGM boundary-layer wind field forecasts appeared to improve as a result of changes to the Regional Analysis and Forecast System (RAFS) (Petersen et al. 1991). These changes were effective the day before the regatta began, and consisted of an expansion of the high-resolution 80-km subgrid, which previously terminated near Hispaniola, and an improved regional data-assimilation system capable of incorporating asynoptic data sources. The new version showed a more realistic diurnal wind oscillation between the land breeze (0800 LDT) and the sea breeze (1400 LDT). Earlier NGM boundary-layer wind fields showed a tendency to form is for mean surface wind conditions at Jose Marti International Airport for the daylight portion of the 24-h period from 0800 to 0800 LDT.

The forecast performance of a particular method cannot be quantitatively assessed on the basis of a 1-week period. The best methods will perform well over a large range of background synoptic conditions that require years to assess. Forecast performance for the week of the Pan American Games is displayed in Table 2 according to mean absolute difference, bias, and standard deviation between observed and forecast winds. Due to the limited time period, no attempt was made to determine skill or significance testing of one method over another. All wind-direction forecast methods displayed larger mean absolute differences than both climatology and persistence. For wind speed, the team, NGM 6-h, and NGM 18-h forecasts showed smaller mean absolute differences than climatology, and only the team forecast differences were smaller than persistence. Despite the large differences exhibited by the wind-direction forecasts, the NGM 6-h and team forecasts were close to the typical measurement accuracies for wind direction (+/– 10°). Both NGM boundary-layer wind forecast models displayed a negative mean difference or bias in wind direction, in agreement with the expected veering of the wind with height; neither displayed a bias toward higher wind speed expected above the surface layer.

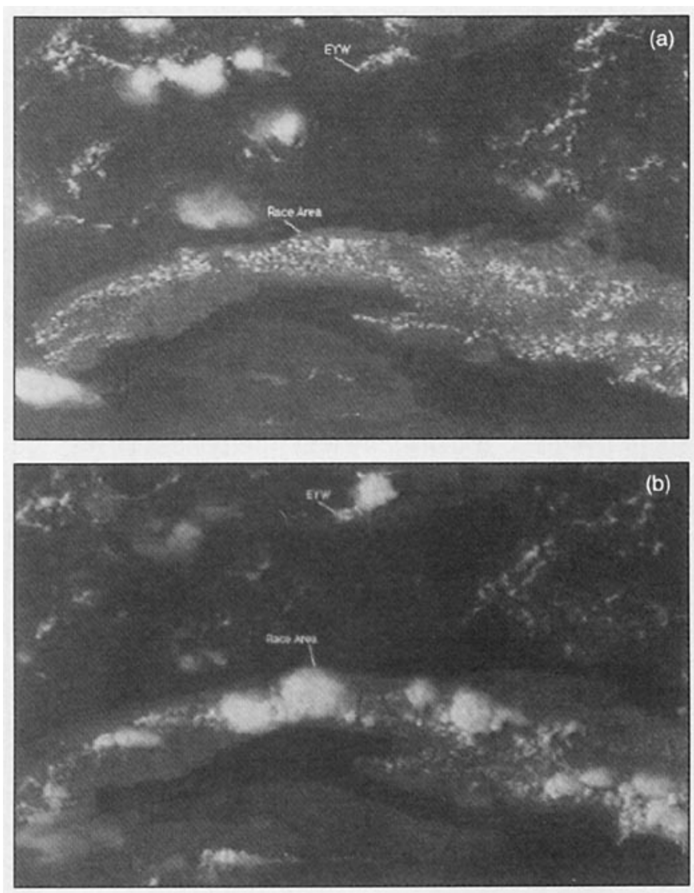

FIG. 6.(a) Same as Fig. 3 but for race 6 on 12 August 1991 at 1230 LDT; north-coast sea-breeze front restricted just inland. (b) Same as (a) but for 1600 LDT; sea-breeze fronts have merged.

TABLE 2. Wind speed and direction prediction differences (observed – predicted).

	Persistence		Climatology		NGM 6-h		NGM 18-h		Havana terminal team forecast			
Date	Wd[1] deg	Ws[2] $m\ s^{-1}$	Wd deg	Ws $m\ s^{-1}$	Wd deg	Ws $m\ s^{-1}$	Wd deg	Ws $m\ s^{-1}$	Wd deg	Ws $m\ s^{-1}$	Wd deg	Ws $m\ s^{-1}$
7 Aug.	5	2	15	1.5	5	3.5	–20	3.5	–60	3.5	15	2.5
8 Aug.	–17	–2	–2	–0.5	–17	1.5	–27	1.5	–77	0.5	–2	–0.5
9 Aug.	9	–2	–6	–2.5	–21	–0.5	–26	1.5	NA	NA	24	–0.5
10 Aug.	5	–0.5	–5	–3	0	–1	–55	1	NA	NA	20	0
11 Aug.	0	1.1	–5	–1.9	–10	0.1	–30	0.1	–30	–2.9	5	0.1
12 Aug.	–8	–0.6	–13	–2.5	–13	–0.5	–18	–0.5	–38	–2.5	–8	0.5
13 Aug.	8	0.5	–2	–2	8	2	–2	2	–17	–2.5	13	0
Abs. diff.	7.43	1.24	6.85	1.98	10.57	1.3	25.4	1.44	44.4	2.38	12.42	0.59
Mean diff.	0.29	–0.21	–2.57	–1.56	–6.86	0.73	–25.43	1.30	–44.4	–0.78	9.57	0.30
Std. dev.	9.55	1.51	8.58	1.56	11.25	1.65	15.98	1.30	24.01	2.76	11.70	1.03

[1]Wd = wind direction, [2]Ws = wind speed

a persistent cyclonic circulation over western and west-central Cuba.

The large mean absolute difference and positive bias of the team wind-direction forecast were caused by inaccurate estimation of the preexisting pressure gradient and its effect on the sea-breeze direction. On the first day, with a strong pressure gradient, it was not clear that the sea breeze would even occur. Under the very weak surface pressure-gradient conditions of 9 and 10 August, a more northerly (perpendicular to shore) sea breeze was expected, but failed to occur. For wind speed, the team forecast displayed the lowest absolute difference of 0.6 m s^{-1}. The other methods showed absolute differences of 1–2 m s^{-1}. A mean wind-speed difference of this magnitude can account for large differences in boat speed among competitors related to their choice of equipment and crew weight. The team forecast of time of sea-breeze onset and maximum sea-breeze wind gust (Table 3) showed smaller absolute differences than persistence and climatology. Sea-breeze onset time is especially critical when the sea breeze is late and the race is started in prevailing or land-breeze wind conditions.

6. Forecast impact and conclusions

Since it was not possible for the meteorologist to assess the usefulness of the forecasts through direct interaction with team members during the regatta, the sailors completed a questionnaire after the regatta. Responses indicated that the individual day's forecasts were used to select sails and set up rigging before each race. The most important information was contained in the weather and climate summary given to the team at the preregatta briefing. The percentage frequency diagrams from the wind climate analysis gave them a good idea of the steadiness of the breeze and the likelihood of wind shifts during the race. The summary and preregatta briefing concentrated on the conditions that should be observed to nowcast sea-breeze interaction with convection and anvil clouds. In the daily briefings, sailors would discuss wind and current variations experienced on each course. Hindcasts helped to explain differences between the forecasts and observed conditions.

The performance of the U.S. Sailing Team at the Pan American Games was the most successful in history; the team received eight medals out of a possible nine, including four gold, one silver, and three bronze. Although the winning of any one race could not be attributed to an individual forecast, the net effect of the wind climate and weather summary, nowcasting training at the prerace briefing, hindcasts, forecasts, and on-site team discussions of wind behavior on the courses each day was beneficial. In essence, the analyses gave the team members "local knowledge" before they even saw the racing site. In retrospect, they would have liked to have had access to the climate analysis months earlier to help their training and crew and equipment selection; this can be corrected by requesting meteorological support much earlier.

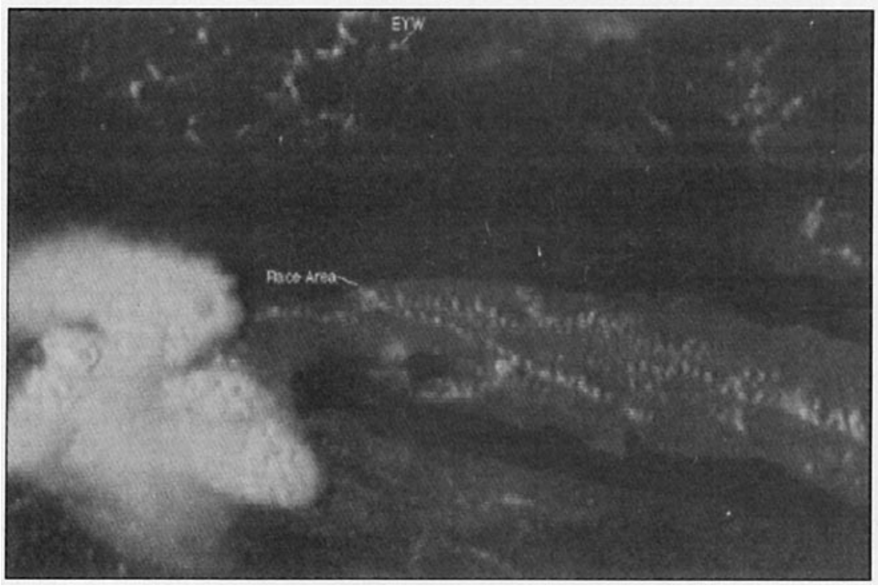

FIG. 7. Same as Fig. 3 but for race 7 on 13 August 1991 at 1430 LDT; north-coast sea-breeze front barely visible in vicinity of race area.

The approach followed here need not be implemented to give one team advantage over another. Host nations could provide this type of support to all teams competing, such as was done prior to the 1984 Summer Olympics in Los Angeles (Staff, WSFO 1983). Forecast performance in future events could be improved by access to three-dimensional mesoscale models (e.g., Xian and Pielke 1991), which could be initialized with the latest soundings and run for a particular locality. The recent television coverage of the America's Cup competition hinted at the extent to which competing syndicates valued weather information. Although little specific information was released to the public, each syndicate employed their own team of meteorologists and even went so far as to fly helicopters out over the courses to observe wind patterns over the race course before the start. These multimillion-dollar funded syndicates also equipped their yachts and support boats with sophisticated instrumentation and computers. Marine meteorologists could learn much from their forecasting approaches, but it is doubtful that such "trade secrets" will be published.

TABLE 3. Sea-breeze onset time and average-gust prediction differences (observed – predicted).

	Persistence		Climatology		Team forecast	
Date	**Onset time** (hours)	**Gust** ($m\ s^{-1}$)	**Onset time** (hours)	**Gust** ($m\ s^{-1}$)	**Onset time** (hours)	**Gust** ($m\ s^{-1}$)
7 Aug.	1.5	3	2.5	2.7	0.5	4
8 Aug.	−1.75	−4	0.75	−1.3	−0.25	−1
9 Aug.	0	−1	0.75	−2.3	0.75	−1
10 Aug.	1.25	−2	−0.5	−4.3	−0.5	−2
11 Aug.	0	3	−0.5	−1.3	−0.5	2
12 Aug.	−0.6	0	−1.1	−1.3	−1.1	0
13 Aug.	2.4	−1	1.3	−2.3	1.33	0
Abs. error	1.07	2.00	1.06	2.21	0.70	1.43
Mean error	0.40	−0.29	0.46	−1.44	0.03	0.29
Std. dev.	1.41	2.56	1.25	2.12	0.85	2.06

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