Marine Forecasting at the 1996 Centennial Olympic Games

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ABSTRACT

A team of meteorologists from the United States, Canada, and Australia provided marine weather support to the sailing events of the 1996 Centennial Olympic Games, held in Wassaw Sound near Savannah, Georgia. The team conducted research on the weather and climate and developed a set of forecast products designed to inform athletes, volunteers, and race managers of the wind, tidal current, wave, and weather behavior expected each day during the pre-Olympic and Olympic periods. The Olympic period proved to be a challenge with thunderstorms delaying, abandoning, or postponing races on half of the days. Thunderstorm development and movement was linked to the timing and strength of the sea breeze as well as the direction and speed of the gradient wind. Numerous thunderstorm warnings were issued with the assistance of the WSR-88D radar and the Warning Decision Support System. Frequent lightning was a legitimate safety concern due to the long distances between race courses and lack of suitable shelter; fortunately no one was injured during the lightning episodes. Forecasters benefited from access to a variety of monitoring tools and models including real-time Olympic buoy wind and current time series displays; satellite and radar imagery animation; 2-, 8-, and 10-km resolution mesoscale models; a live video feed of race coverage; and communications with forecasters aboard patrol craft offshore. Official wind forecasts, mesoscale models, and a simple vector addition model performed better than climatology and persistence as defined by mean vector error and rms wind direction error. Climatology was difficult to beat on the basis of wind speed error.

1. Introduction

The yachting (sailing) competition for the 1996 Atlanta Centennial Olympic Summer Games was held in the vicinity of Wassaw Sound, on the Atlantic Ocean southeast of Savannah, Georgia. The competition consisted of races in 10 classes of identical ''one design'' boats including windsurfers, dinghies, small keelboats, and catamarans. Several hundred competitors, team personnel, and volunteers were involved. Because of the large number of competitors, the location of the competition several miles from the major launch venue and accessible shelter, and the length of time needed to conduct races, sailing athletes, officials, and spectators were among the most weather-exposed groups taking part in the Olympics. Hence, the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) was asked by the Atlanta Committee for the Olympic Games (ACOG) to provide a Marine Olympic Weather Support Office (OMWSO) on the site of the sailing venue.

Sailing is extremely sensitive to the wind and weather; indeed the sailing events of the first Olympics of the modern era in 1896 were canceled due to lack of wind. One hundred years later, significant changes in weather and wind contributed to the outcome of many medals while several races were postponed or abandoned due to thunderstorms or lack of wind. Forecasts were required to provide basic information to advise the competition management, volunteers, athletes, and spectators on the hourly wind behavior for the day and whether competition or logistics would be affected by thunderstorms, severe weather, or heat stress. With the exception of specialized forecast services similar to that provided for the America's Cup competition, wind forecasts are rarely conducted on the time and space scales of that provided during the Olympic sailing events. Forecasting weather and wind conditions required a staff of meteorologists with considerable marine forecasting and sailing experience using sophisticated tools including mesoscale atmospheric numerical models, an ocean current model, as well as observation and dissemination systems from many sources. An important result of the

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forecast experience was an evaluation of the utility of these new systems for marine forecasting. Mesoscale models are not normally used to provide detailed, hour-by-hour, local area wind forecasts; hence, the models were evaluated against climatology and persistence to assess skill.

The intent of this paper is to document the 1996 Olympic marine forecast experience. We describe 1) information derived from background studies of the wind climate to determine wind forecast guidelines; 2) the forecast duties and product schedule; 3) the forecast process developed during the pregames period; 4) the conditions experienced during the Olympics, including problems posed by thunderstorms (focusing on 2 days in particular); 5) an evaluation of wind forecast accuracy; and finally 6) a summary and recommendations for weather support during future Olympics.

2. Wassaw Sound climatology

As shown by Powell (1993), information on the atmospheric and oceanographic climate of the competition venue assists athletes with precompetition planning and training. To learn more about the expected oceanic and atmospheric conditions, as well as sea-breeze development and evolution off Savannah, observations were collected in the summers of 1994 and 1995 by a special Olympic buoy deployed by the NWS National Data Buoy Center (NDBC) within one of the race courses and by an automatic weather station sited by the University of Georgia on a barrier island adjacent to the race courses. These data were compared to 9 yr of measurements collected from 1985 to 1993 at the NWS Savannah Light Coastal Marine Automated Network platform located roughly 22 km offshore. The typical wind behavior (Fig. 1) for the offshore buoy 41021 was based on July and August 1994–95 data, which were also used to assess wind forecast skill (compared to climatology and persistence).

a. Sea-breeze behavior

The 1994–95 data suggest that typically a weak offshore southwesterly wind in the morning hours decreases to a minimum between 1000 and 1100 local time (LT). The plot in Fig. 1 shows the relative amount of time the wind blew with a given speed and direction as a series of gray squares; the darker the squares at a particular hour, the greater the percentage of time that the wind blew with that speed or direction. The sea-breeze onset occurs shortly after the wind speed minimum and is evident as a gradual increase to 12–15 kt with a consistent backing to 150°–170° by 1500–1700 LT.

The backing in direction is caused by a superposition of the developing sea-breeze circulation on the existing synoptic flow. As the sea-breeze circulation strengthens, the wind direction turns progressively toward a direction perpendicular to the coastline. Unlike sea breezes in more northern climes, the air–sea temperature differences associated with the Georgia coastal sea breeze are insufficient to provide a uniquely stable flow; considerable mixing occurs with the background gradient flow. The ultimate direction of the sea breeze is dependent on the amount of mixing and the direction and strength of the background gradient flow. Once the sea-breeze direction is stabilized near 1700 LT, the wind veers with time due to a combination of the Coriolis force and increased gradient flow influence.

b. Synoptic categories, including thunderstorm and high wind frequency

To assist in developing wind forecast guidelines, a series of wind regimes based on the strength and direction of the synoptic flow were developed by correlating daily plots of hourly or 10-min wind speed and direction time series patterns at Olympic buoy 41021 with the background synoptic conditions as defined by the daily weather maps published by NOAA's Climate Analysis Center. Five synoptic regimes were identified (Fig. 2, Table 1) and associated with the number of occurances of winds in excess of 20 kt and the number of thunderstorm days observed at Savannah International Airport. All time series traces, surface maps, and soundings for the 1994 and 1995 periods were archived into atlases made available to the forecasters. Descriptions of the synoptic regimes were made available to athletes, coaches, and venue management in the form of climate summaries (Rinard and Powell 1995, 1996). In addition, seminars describing expected synoptic conditions were conducted for athletes and coaches prior to the competition by members of the OMWSO staff.

1) DISTURBED CONDITIONS

Weather disturbances of many kinds may affect Savannah during the summer including cold fronts, upper-level instabilities, or nearby tropical disturbances (tropical waves, depressions, tropical storms, and even hurricanes). Over the summers of 1994 and 1995, disturbances were evident in the vicinity 37% of the time (Table 1). On some of these days (16), the disturbance was weak or too far away to substantially affect Savannah's weather and a well-defined sea breeze was able to develop. Thunderstorms were observed at Savannah's airport on 17 days and winds above 25 kt occurred on 4 days with winds above 20 kt on 8 days.

2) HIGH PRESSURE RIDGE TO THE SOUTH

This condition was produced by the location of the axis (or ridge) of the Bermuda high extending to the south of Savannah, usually over Florida (Fig. 2a). This orientation is responsible for gradient winds near parallel to the coastline from the southwest. A flow parallel

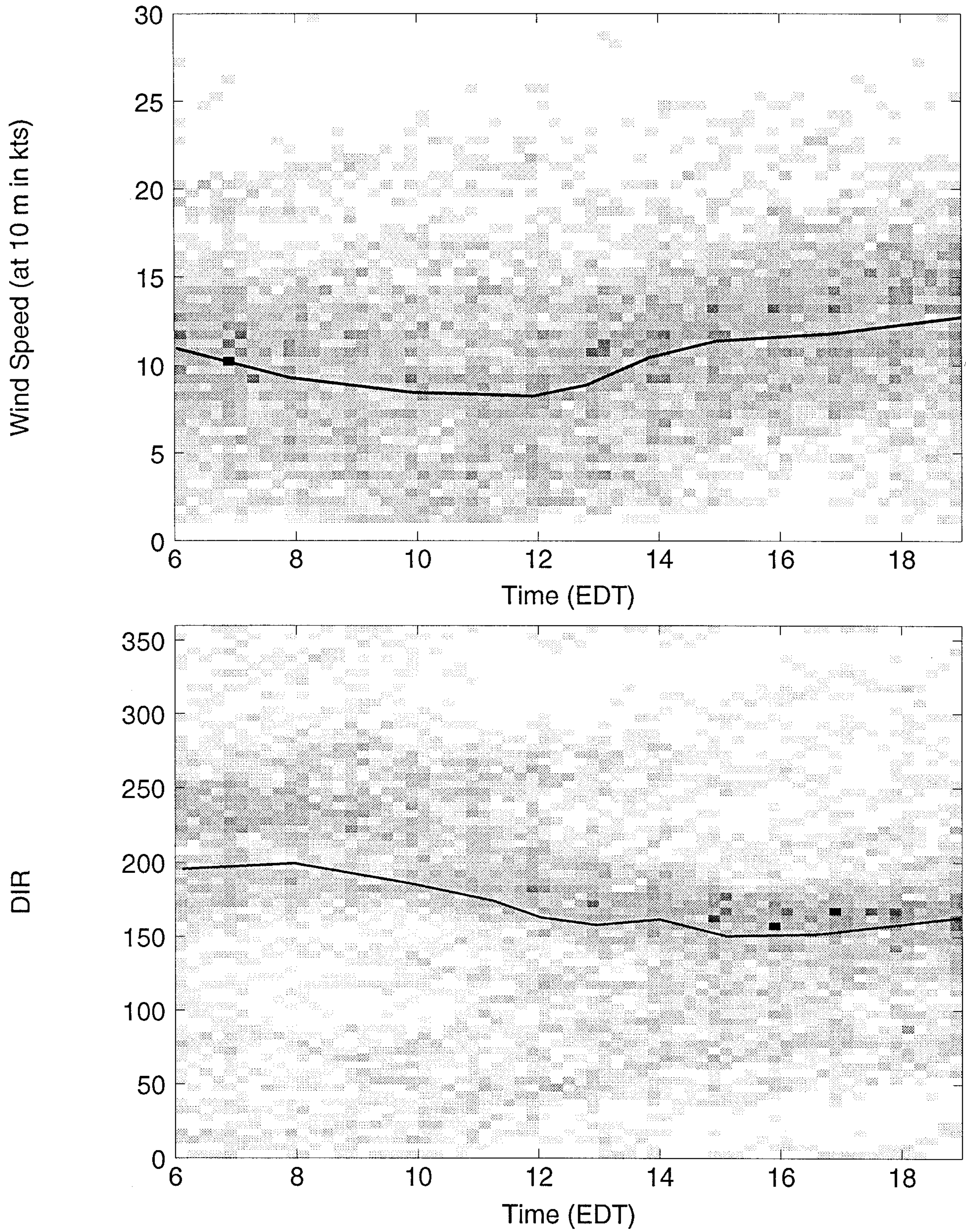

FIG. 1. Percentage frequency plots for (top) wind direction (°) and (bottom) wind speed (kt) vs time (EDT or LT) at NOAA Olympic buoy 41021 during July and August of 1994 and 1995 (based on 10-min continuous data). Darker gray shades indicate higher frequency of occurrence at a particular time. Curved line is a subjective fit to mean observations for each hour.

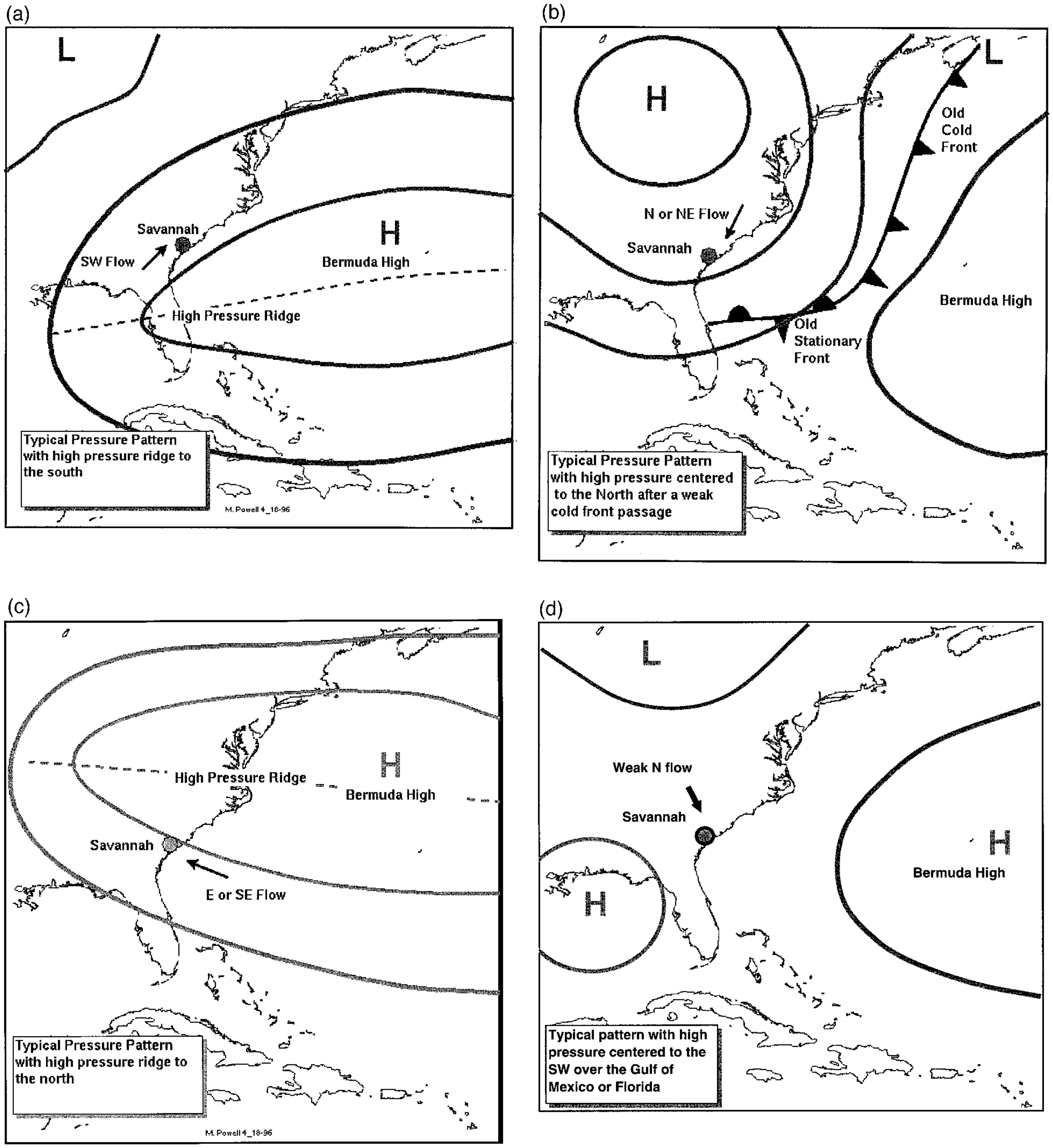

FIG. 2. Depiction of surface synoptic weather map features and resulting gradient flow directions: (a) high pressure ridge to the south, (b) high pressure centered inland to the north or northwest, (c) high pressure ridge to the north, and (d) high pressure centered to the southwest.

to the coastline may help maintain a larger land–sea temperature difference as well as an orientation needed to generate a well-defined, strong sea breeze through mixing with the gradient wind. This orientation is consistent with observations of stronger sea-breeze activity on the southeast Florida coast during southerly flow (Burpee 1979). Occasionally (Table 1) the sea breeze exceeds 20 kt (two days). Thunderstorms developing inland along the sea-breeze front are common during this category and were observed at the Savannah airport on 14 days over the two summers.

3) HIGH PRESSURE INLAND TO THE NORTH

Weak cold fronts can affect south Georgia during the summer. A high pressure center following such a front

TABLE 1. Wassaw Sound climatology for July–August 1994–95 (108 days).

Synoptic regime	Percent of total, no. days	Days with thunderstorms	Winds >20 kt	Winds > 25 kt
Disturbed	37%, 46	17	8	4
High ridge to the south	24%, 30	14	2	0
High center inland to the north	21%, 26	4	1	0
High ridge to the north	10%, 13	4	1	0
High centered to the southwest	7%, 9	4	0	0

was typically located to the northwest or north of Savannah. North or northeasterly flow (Fig. 2b) is associated with this category and may occasionally produce thunderstorms (four days) or winds above 20 kt (once). A sea breeze may be apparent as a wind veering from a north or northeast direction to the east or southeast with time.

4) HIGH PRESSURE RIDGE TO THE NORTH

Sometimes the Bermuda high moves such that the ridge is located north of Savannah (Fig. 2c). This synoptic condition produces winds from the southeast or east with little direction change during the day. The sea breeze is often superimposed on this flow pattern but is difficult to observe if the pressure gradient is strong. A strong pressure gradient allows the sea-breeze component to propagate quickly inland and is only discernible by a cloud line moving well inland and an absence of clouds seaward. This condition produced winds above 20 kt on one occasion over the two summers. If the gradient flow from the high is weak, an offshore land breeze may be apparent in the morning hours (especially if the evening has been clear and cool), which will be replaced by a well-defined sea breeze near noon. This category was associated with thunderstorms observed inland at the Savannah airport on four days.

5) HIGH PRESSURE TO THE SOUTHWEST

Occasionally a high pressure center will develop to the south or southwest of Savannah separated from the Bermuda high by a region of slightly lower pressure (Fig. 2d). Under this condition the synoptic-scale wind is frail and a weak to moderate sea breeze may form. Within this category (Table 1) over the two summers, no winds in excess of 20 kt were observed during daylight hours and thunderstorms were observed inland at the Savannah airport on four days.

c. Other conditions

Comprehensive cloud-to-ground lightning climatologies were prepared for the Olympic Weather Support Offices (Livingston et al. 1996; Watson and Holle 1996). These studies suggested a diurnal maximum in activity near 1500 LT and a high correlation of flash density with the sea-breeze convergence zone with a relative minimum offshore.

The combined, discomforting effect of high temperature and high humidity on a lightly clothed, shaded individual is known as the heat index or apparent temperature (Rothfusz 1990). People in high risk groups for sunstroke, heat stroke, and muscle cramps are advised to limit physical activity when the heat index exceeds 41°C.

3. Forecast office design and function

The OMWSO was located in a mobile home (Fig. 3) supplied with several workstations with access to an impressive array of observational platforms including: the Charleston WSR-88D radar, the special installation of the NOAA Environmental Technology Laboratory (ETL) wind profiler (Ecklund et al. 1988) on nearby Fort Pulaski, a special Olympic mesonet consisting of stations throughout coastal and inland Georgia (Garza and Hoogenboom 1997), a line-of-sight access to real-time measurements collected by three NDBC Olympic buoys (Fig. 4) deployed adjacent to the race course ''field of play'' (NDBC 1996), and satellite imagery products delivered via the RAMSDIS system (Molenar et al. 1995). The requirement of localized forecasts specific to various sports venues established a need for unique, very high resolution, mesoscale numerical weather prediction models including a 10-km version of the Eta Model (Dimego 1998, manuscript submitted to *Wea. Forecasting*), the Local Analysis and Prediction System (LAPS) (Stamus and McGinley 1998), and both 8-km (for state coverage) and 2-km (for Savannah marine application) versions of the Regional Atmospheric Modeling System (RAMS) model (Snook et al. 1998). Additional personal-computer-based forecast and analysis tools included the SHARP software for analyzing soundings and cross sections (Hart and Korotky 1991), the PC GRIDS system for viewing model output (Petersen 1992), and the JT sea-breeze model developed by an OMWSO forecaster (J. Townsend).

The OMWSO depended on a T1 communications line from the Olympic Weather Support Office in Atlanta (Rothfusz and McLaughlin 1997; Rothfusz et al. 1998) for delivery of graphical numerical model products, satellite images, AFOS text products, and mesonet data [which in turn received the data from National Centers

FIG. 3. OMWSO forecaster workspace within the trailer showing Meteorologist-in-Charge Rinard (seated second from left) briefing an ACOG manager (left) in radio contact with the field of play director during a thunderstorm warning episode on 23 July 1996. The WDSS workstation and meteorologists (Scott Spratt and Mario Valverde) are to the right, with Systems Specialist Bruce Marchak in the center background.

for Environmental Prediction (NCEP) via another T1 line]. AFOS text products, graphical products generated from numerical weather prediction models, and satellite imagery were displayed using National Advanced Weather Information and Processing System (N-AWIPS) software (desJardins et al. 1997). A 128-KB communications line from the newly commissioned Charleston Weather Surveillance Radar-1988 Doppler (WSR-88D) radar site delivered data required for the Warning Decision Support System (WDSS; Johnson et al. 1998). During the competition a live video feed from races filmed for television distribution by Atlanta Olympic Broadcasting was helpful for monitoring weather conditions. Table 2 provides additional details on tools and guidance available to the marine forecasters.

A map of the general area is shown in Fig. 5. The OMWSO office was located at the Olympic marina (not shown) about 9 km up the Wilmington River. The OMWSO operated from 0500–1900 LT daily and the staff of six forecasters operated according to a schedule that distributed duties among two morning forecasters, one afternoon forecaster, and two marine shift forecasters each day. The marine shift worked on the day marina with venue management and aboard a dedicated weather patrol boat that traveled within the field of play. The meteorologist-in-charge, scientific operations officer, the Canadian meteorologist (who also served as a French language interpreter), the technical support specialist, and the NDBC technical support specialist remained on duty or available at all times.

Competition was scheduled to begin at 1300 LT each day and usually two races were scheduled per day for each class. Staggered rest days were built into the schedule for each class to allow days off, to make up postponed races, and to facilitate television coverage of the finals in each class. The OMWSO executed the following forecast schedule.

1) A series of morning forecasts and briefings were issued to race officials and venue managers (0700, 0730, 0800 LT), and to the athletes and coaches of all participating nations (0830, 1130 LT). Due to the distance of the race course areas from the Olympic and day marinas, athletes and volunteers usually shuttled to the day marina shortly after the 0830 briefing, prepared their boats, and then left the day marina between 1030 and noon to reach their respective course areas before start time. Hence, the most important products for athletes were the 0830 LT (Fig. 6) and 1130 LT forecasts.
2) Beginning at noon, nowcast updates were issued hourly. The National Weather Service Office (NWSO) in Charleston issued a special Olympic broadcast from the Savannah NOAA weather radio between 1100 and 1400 LT, which repeated the OMWSO forecasts and hourly updates. Unique NOAA weather radio receivers with speakers were installed for competitor and volunteer use at the Olympic and day marinas.
3) At 1800 LT, a forecast outlook was issued for the

FIG. 4. Former NWS Director Dr. E. Friday conducts an offshore television news conference during the 2 Aug 1996 marine weather patrol to one of three NDBC 3-m moored buoys deployed in the field of play. The buoys provided real-time wind, wave, and current measurements to the OMWSO and were visited each day by the weather patrol boat, which called in observations from throughout the field of play.

following day. At the end of each day (about 1900 LT), an observation package containing tables and time series plots of the winds, waves, and currents observed each day by the Olympic buoys was delivered to team leaders from each country.

Watches and warnings were issued for high heat index, frequent lightning, winds in excess of 12.5 m s^{-1}, and severe weather associated with thunderstorms within 9.2 km (5 n mi) of the Olympic marina, Wassaw Sound–day marina, and the three offshore race course areas. Watches and warnings (Fig. 7) were issued by radio to venue management and then by fax to a central venue communications center (VCC) and additional locations. Warnings were updated every 30 min. The marine shift consisted of forecasters sharing duty on the day marina launch venue site or a dedicated weather patrol boat (Fig. 4). The marine duty forecasters (equipped with cellular phones and hand-held anemometers) traveled throughout the field of play and called in frequent observations to the OMWSO. With respect

TABLE 2. Marine forecasting tools and guidance.

Product	Purpose
National Advanced Weather Information and Processing System (N-AWIPS)	Display model fields, AFOS emulation, display satellite imagery
Warning Decision Support System (WDSS)	Display NEXRAD reflectivity and velocity fields
Radar Algorithms and Display System (RADS)	Display lightning strikes, track reflectivity cells, indicate severe weather potential
RAMSDIS	Display satellite imagery
LAPS	Display mesoscale analyses, initialize RAMS
RAMS 2 km and 8 km	Sea-breeze forecasts, convection development
Eta 10 km and 29 km	Sea-breeze forecasts, synoptic-scale features
SHARP	Display soundings
JT model	Sea-breeze forecasts
Synoptic category atlases	Sea-breeze forecasts
PC Grids	Backup display of model output

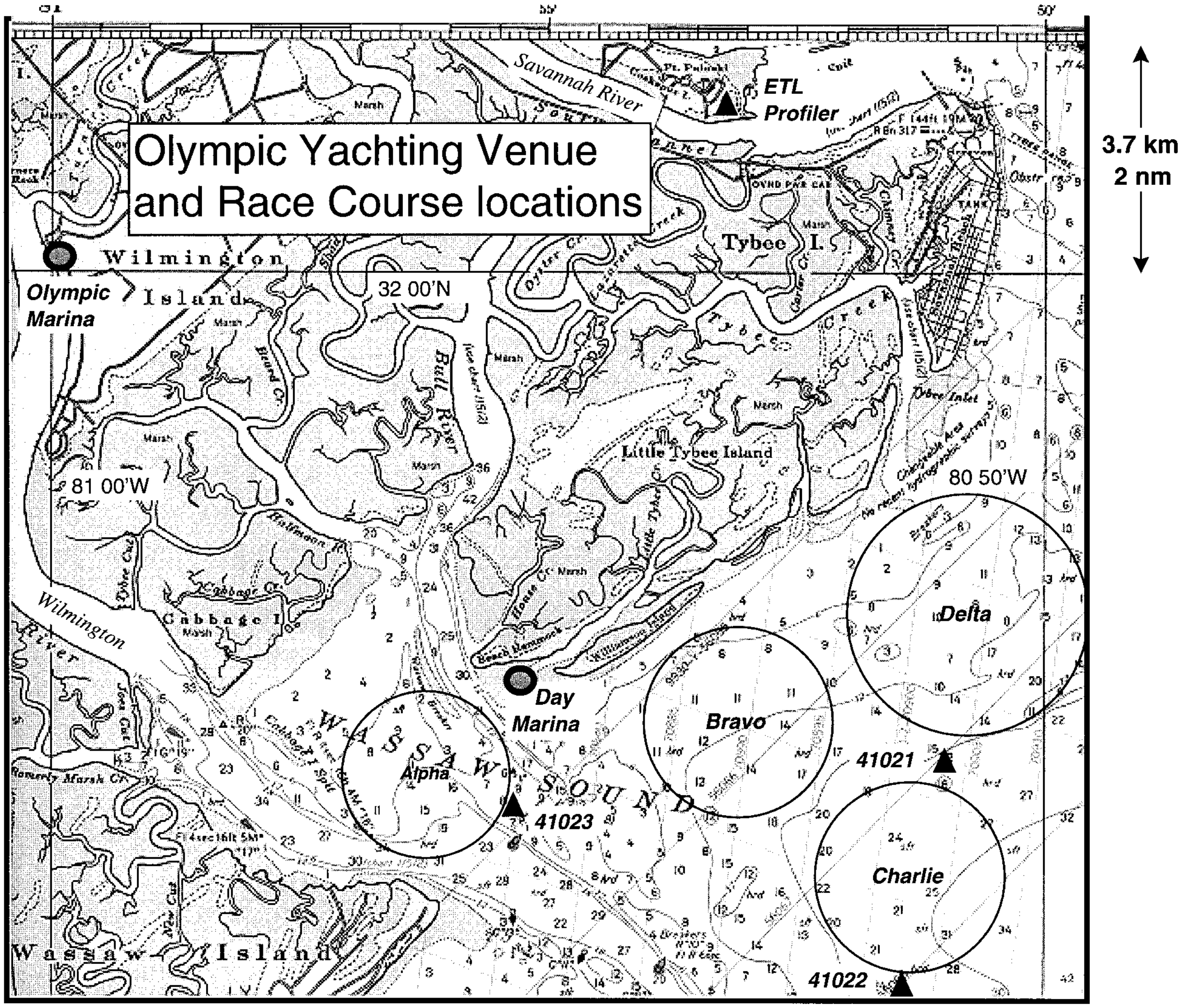

FIG. 5. Map depicting locations of the Olympic marina, day marina, NDBC Olympic buoys, ETL profiler, and the race course areas Alpha–Delta. Adapted from 1977 NOAA navigation chart 11509.

to lightning, a major safety concern was the day marina (Fig. 8), which consisted of an island of many interconnected barges. The day marina was frequently occupied by several hundred athletes, coaches, and volunteers. Unfortunately, the only weather shelters available on the day marina were team tents (with frames welded to the steel barge skin) and mobile homes (containing scoring and communications facilities).

OMWSO staff designed separate wind forecast products for Wassaw Sound and the offshore race courses. Daily wind forecast verification products were also designed using NOAA buoy 41023 for the sound and 41021 for the offshore courses. Buoy 41021's location central to the three offshore course areas made it favorable for verification, while the southern offshore Olympic buoy (41022) was most useful for indication of offshore sea breeze and weather development for the southern course areas. The 0830 LT forecast also included a table of the previous day's hourly winds observed by the Olympic buoys to allow competitors to assess forecast accuracy. To evaluate forecast performance for each of the wind forecast models, verification tables were prepared at the end of each day and made available for forecasters serving the next morning shift. To ensure equal delivery of daily forecast information to all participating countries, the forecast office was closed to team staff and competitors in the morning hours but open at the end of each day. This policy helped minimize the advantage of wealthier teams with meteorologists and oceanographers on their staffs and also allowed the forecasters to work with fewer interruptions.

4. Pregames forecast period

Since the forecast team comprised individuals from several states outside the venue area and included mem-

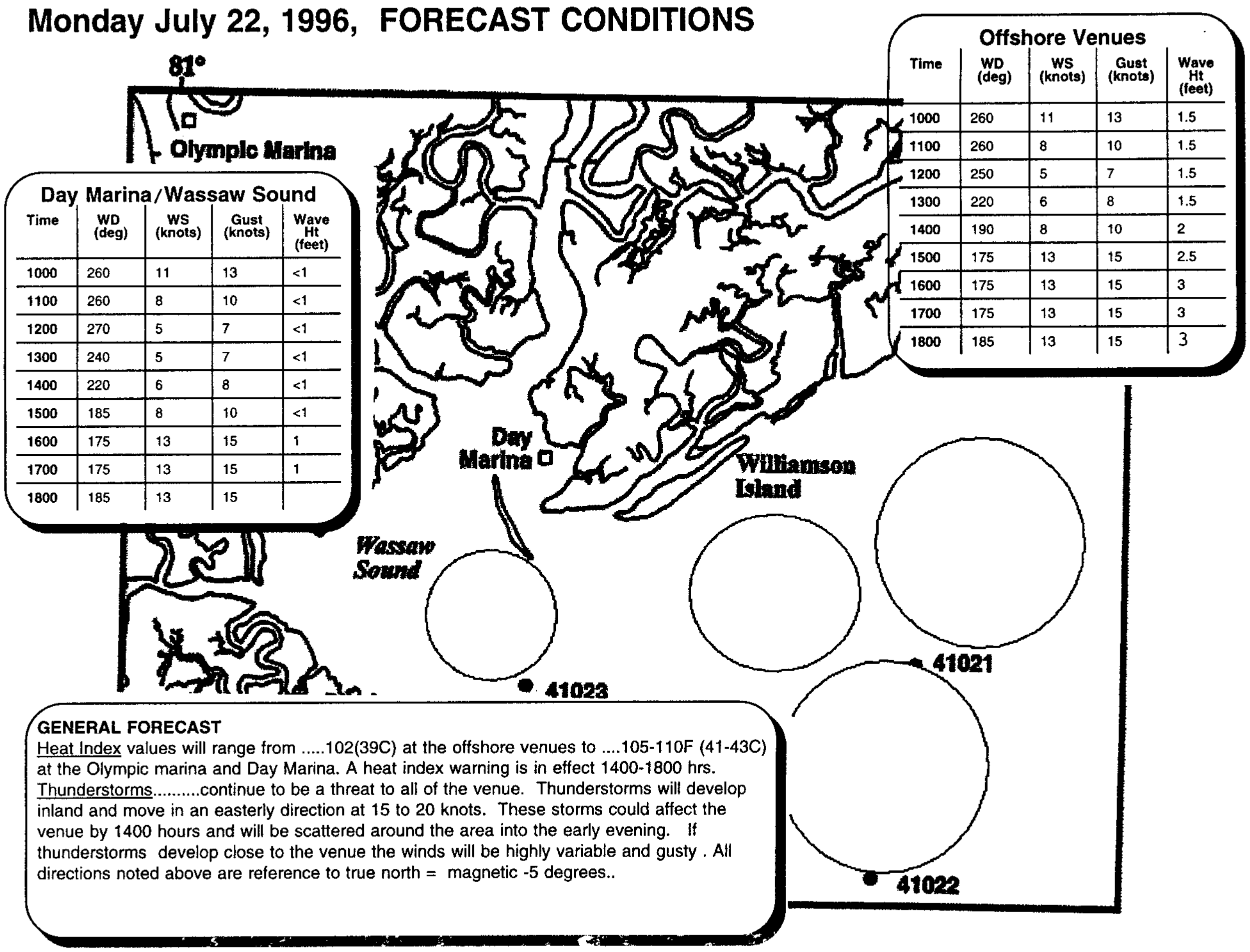

FIG. 6. Second page of the 22 July 1996 Forecast product distributed at the 0830 briefing showing separate wind forecasts for Wassaw Sound and offshore, and a brief summary of the general forecast contained on the first page.

bers from Canada and Australia, it was important that OMWSO team members receive training and familiarization before the Olympics. Some experience was gained during the 1995 pre-Olympic regatta, but that period comprised fair weather southeasterlies associated with the high pressure ridge to the north (Fig. 2a). OMWSO forecasters reported to Savannah nearly a month before the start of competition on 26 June. A dedicated OMWSO technical team transformed an empty mobile home into a fully operational modern weather office one week prior to the report date.

a. Wind and weather conditions

Considering that race management guidelines suggested wind minimums of 3 m s^{-1} for the windsurfing races and 2 m s^{-1} for the other sailing competition classes, race managers were especially sensitive to the seabreeze onset time, direction, and strength, as well as the threat of thunderstorms with associated lightning and variable and gusty winds. During the 26-day pregames period, ''disturbed,'' ''high pressure ridge to the south,'' and ''high pressure centered to the southwest'' synoptic conditions were each present about 25% (six to seven occurrences) of the time with ''high pressure centered to the northwest'' and ''high pressure ridge to the north'' conditions present on five and two occasions, respectively.

1) DISTURBED SYNOPTIC CONDITIONS

Of the seven disturbed category days in the pregames period, stationary fronts or a cold front were present on five days and Hurricane Bertha influenced the weather on two days. Hurricane Bertha posed a threat to the Olympic venues on 11–12 July. OMWSO forecasters participated in hurricane conference calls and assisted Olympic organizers by answering questions associated with forecasts issued by the National Hurricane Center (NHC). The threat of Bertha closed the yachting venue and much of the equipment and boats were evacuated inland. The OMWSO remained open to provide support

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50,E,22,Jul,1996,14:15,
Venue,YCC,
Time,14:15,
Exp Time,15:15,
Urgency Code,0,

ZCZC ATLOWWSAV
TTAA00 KSAV MMDDYY
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National Weather Service
Olympic Marine Weather Support Office
1996 Olympic Yachting Venue
Savannah, Georgia

Weather Warning

Weather Warning for the following venue(s):

Olympic Marina
Wassaw Sound-Day Marina
Off Shore Field of Play

Issuance Time:

This Warning is for:

Lightning
Heavy Rain
Wind > 30 mph

A warning means conditions are already occurring or they are imminent.

This warning is in effect until 15:15.

Discussion: Doppler radar has detected numerous thunderstorms near Savannah moving E at 15 kt (7.5 m/s). Storms will move over the Olympic Marina by 14:40 and the Day Marina by 14:50.

A Strong Wind Watrning is issued when winds > 30 mph (48 kph) are possible in the Warning area.

A Lightning Warning is issued when cloud-to-ground lightning is expected to occur or is occurring near or in the Warning area.

FIG. 7. The initial weather warning for 22 July 1996 distributed by the OMWSO at 1415 LT.

FIG. 8. The day marina was the primary boat launching facility and consisted of several steel barges moored to the bottom by steel columns and covered by all-weather carpet. Athletes were sheltered in tents supported by steel frames.

during this period. In addition, OMWSO advised organizers of any potential tropical systems being examined by NHC and other tropical systems threatening countries participating in the Olympic competition.

Mesoscale models could occasionally forecast the development and movement of thunderstorms, although exact locations and precipitation amounts were only qualitatively useful. The NWSO Charleston WSR-88D, used with the NOAA National Severe Storm Laboratory's WDSS, was invaluable in tracking thunderstorm development, movement, and potential for severe weather. The WDSS also provided indications of lightning potential and interfaced with the national lightning detection network to show the location and polarity of lightning strikes in the vicinity of Olympic venues. Forecasters relied very heavily on the WDSS, issuing specific watches and warnings according to the proximity of activity to the 9-km (5 n mi) circles surrounding the Olympic marina and offshore field of play.

2) SEA-BREEZE CONDITIONS

The pregames period provided valuable experience forecasting thunderstorm development and movement, which was strongly dependent on sea-breeze development. The degree of instability in the atmosphere, coupled with the strength of the low- to midlevel gradient flow and amount of morning cloud cover helped to determine the timing of sea-breeze development and the potential for thunderstorms affecting the venue. With concurrent observations of visible satellite imagery, radar reflectivity, and Olympic buoy observations it was possible to distinguish between the ''sea-breeze front'' (as identified by a prominent cloud line along the convergence line parallel to the coast) and the actual sea-breeze onset (as defined as the time at which the onshore wind speed increases consistently). A revised conceptual model of the Wassaw Sound sea breeze resulted: 1) After clear cool evenings, a morning drainage flow contributed to a relatively strong offshore land breeze. This offshore wind was further enhanced by mixing when flowing over the warm sound and offshore waters resulting in speeds of 7–10 m s^{-1} before decreasing about 1000–1100 LT due to the sea-breeze development influences. Occasionally weak late night and morning showers within the venue and offshore were generated where the land breeze converged with the more southerly gradient flow offshore. 2) As the land heats, the morning offshore flow gradually decreases and backs, with the backing greater farther offshore. 3) A convergence line develops along the coast where the offshore flow meets with the backed flow. 4) The convergence line is visible as a cloud line and sometimes as a fine line (a linear, very low reflectivity feature) on the radar. 5) The actual sea-breeze onset usually occurs a few kilometers offshore from the coastal convergence line although it could also coincide with it or multiple transient convergence lines could develop in response to phantom sea-breeze onsets. 6) After onset the convergence line would propagate inland and the sea-breeze subsidence would be evident as clearing skies offshore. On days with warm, moist, unstable air masses and an offshore gradient flow, the major forecast problem was to determine if sea-breeze onset would occur early enough to push the developing convergence line far enough inland to minimize the thunderstorm threat to the coastal and offshore Olympic venue.

On nondisturbed days, comparison of observations from the Wassaw Sound and offshore buoys indicated peculiar repeatable differences in wind behavior during offshore gradient flow regimes. In particular, the sea breeze was often delayed and on three days never appeared within the sound during periods with offshore gradient flow or relatively strong land breezes. These observations were consistent with mesoscale modeling studies (Tunney 1996) that identified the sensitivity of the sea-breeze front formation to the gradient flow. Comparison of rawinsonde soundings from Charleston and Jacksonville suggested that a threshold velocity for a delayed sea breeze on the sound was a mean low level (sfc–85.0 kPa) offshore flow of about 8 m s^{-1}. The threshold for no sea breeze on the sound was 8–12 m s^{-1}, and the threshold for no sea breeze at either location was an offshore flow in excess of 12 m s^{-1}. ETL wind profiler measurements suggested slightly stronger offshore flow thresholds. Wind profile time cross sections predicted by the Eta and RAMS Models (Snook et al. 1998) were useful for forecasting gradient flow influences on the onset, strength, and direction of the sea breeze.

3) Heat stress

Marine duty forecasters received first-hand experience with the difficulties imposed by midday heat stress. Heat index values at the day marina often exceeded dangerous levels (43°C) and heat stress watches and warnings were issued based on monitoring the temperature and humidity conditions. Heat index values were highest during weak or calm winds prior to sea-breeze onset between the hours of 1100 and 1400 LT.

b. Wind forecast model guidance

Mesoscale model results were made available to forecasters through use of the N-AWIPS NTRANS program to animate forecast fields in the form of surface wind barbs and vertical velocity. Although these fields were useful for identifying sea-breeze front evolution, the fields required increased resolution to determine an hourly forecast. As the pregames period evolved, OMWSO forecasters requested additional mesoscale model wind forecast guidance by designing a wind meteogram for the model gridpoint locations closest to Olympic buoys 41023 and 41021. A text meteogram product was made available each day from the 2-km (half hourly) and 8-km (hourly) versions of the RAMS model (Snook et al. 1998) and the 10-km Eta Model (Dimego 1998, manuscript submitted to *Wea. Forecasting*). The 10-km Eta (run at 0300 UTC), 2-km RAMS (usually run at 0900 UTC), and 8-km RAMS (run at 0600 UTC) were usually available to forecasters in time to be used as guidance for the 0830 LT briefing, while the later 8-km RAMS (usually run at 1300 UTC) was available for guidance in the 1130 LT forecast update.

Based on considerable local experience, a marine forecaster (J. Townsend) developed a vector addition sea-breeze model (JT) that proved quite useful. A pure sea-breeze time series was first created with the speed as a function of time based on weak gradient flow cases and the direction based on a normal to the coastline orientation. The pure sea breeze was then mixed with a percentage of the gradient flow with the percentage based on hourly forecast quantities as a function of time of day and a specified distance over which the sea breeze spread its influence. The quantities determining the degree of mixing included CAPE, percentage cloud cover, and air–sea temperature difference. These three quantities also helped to determine the speed of propagation of the sea breeze, which moved inland at a fraction of the pure sea-breeze component.

c. Currents and waves

Wassaw Sound is formed by the confluence of the Wilmington and Bull Rivers, which, together with 10 primary creeks, drain saltwater from the tidal marsh backwater over an area of 40 km^2 (Gross and Werner 1997). Tides of 1.5-m amplitude over an area with 2–15-m depths help force peak currents in the sound on the order of 1 m s^{-1}. T. Gross of the Skidaway Institute of Oceanography (SKIO), who developed a hydrodynamic model of Wassaw Sound and the offshore vicinity (Gross and Werner 1997), participated on the marine forecast team. The model numerical grid was constructed with updated bathymetry data from a dedicated survey conducted in 1995 by the National Ocean Service. Tidal forcing was predominant within Wassaw Sound but wind forcing also contributed and created noticeable influences in the current distribution offshore. A current vector forecast chart product (Fig. 9) was designed to depict the currents at grid points contained within the race areas as a function of time after low or high tide using input from the time history of the previous day's wind measured by the Olympic buoys. Daily forecasts maps were produced by SKIO and transmitted to the forecast office for distribution at the morning briefing. Forecasts were validated using current measurements at the Olympic buoys. Generic current maps were also included in the climate summary publication distributed to competing teams before the games. The OMWSO

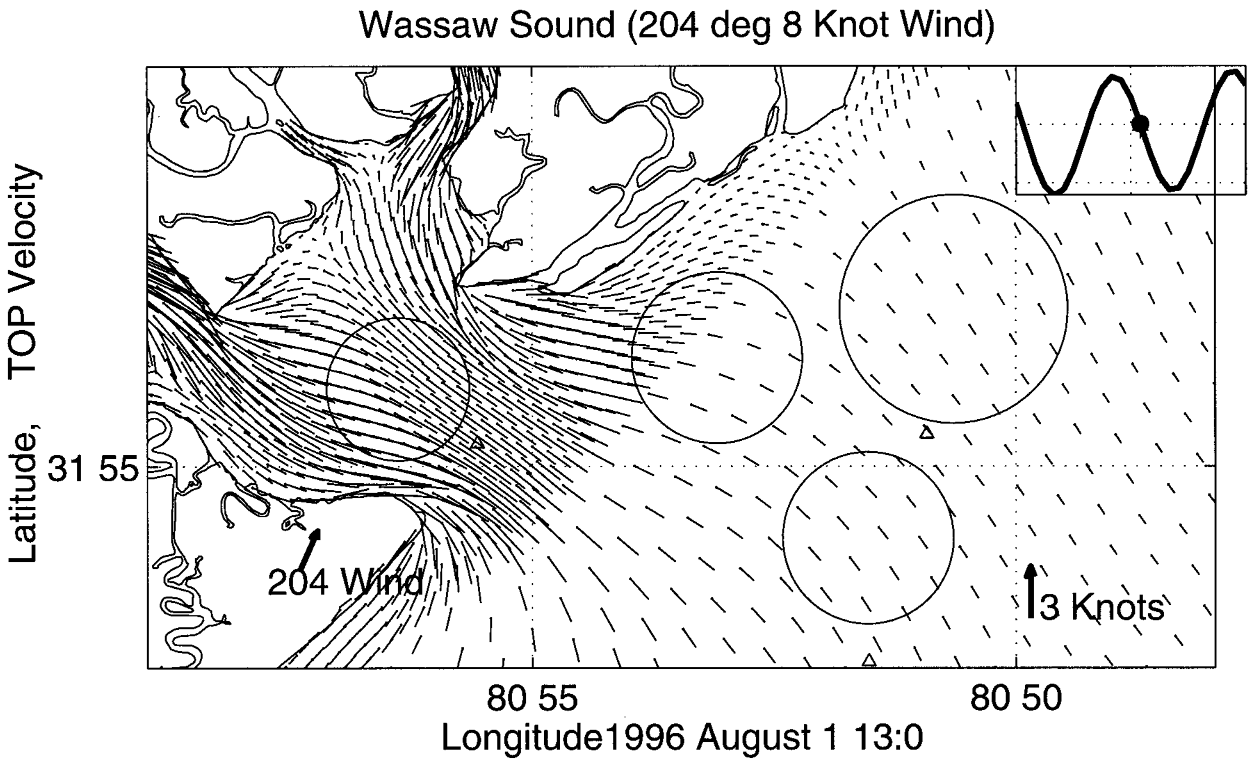

FIG. 9. Current vector forecast valid for 1 August 1996 distributed during the 0830 briefing. The inset shows the phase of the tidal cycle (here in the middle of the ebb tide) and the circles represent race course areas (from Gross and Werner 1997).

also had access to the developmental ocean wave models from NCEP. Due to the proximity of the race areas to shallow water, significant wave heights seldom grew over 2 m and were monitored continuously by the Olympic buoys.

5. Olympic games period

Experiences with weather-benign pre-Olympic regatta weeks in 1994 and 1995 led competition organizers to schedule race start times to take advantage of the relatively dependable sea breeze. Conditions during the pregames period supported this policy, but climatological evidence (Rinard and Powell 1996) suggested that disturbed conditions or thunderstorms developing along the sea-breeze front would be present roughly 40% of the time. The Olympic games period began 22 July and ended on 2 August. A summary of wind and weather conditions experienced, warnings issued, and the effect on competition logistics is summarized in Table 3. Thunderstorms wreaked havoc on the competition schedule on 6 out of the 12 days. Thunderstorms occurred in disturbed conditions associated with low pressure in the area on the first three days and a stalled cold front on the last two days. Thunderstorms also affected the venues on one of four high pressure ridge to the south days. High- and middle-level cloud cover inhibited sea-breeze development on two days resulting in light winds that delayed or postponed sailing.

Warnings were critical for initiating race management decisions but it was difficult to convey the extent and movement of thunderstorm activity. It was very important to include the forecaster on management decisions via venue radio. It is advised for future efforts of this type that the forecast office provide a graphical representation of approaching threatening situations in the form of radar animations. Many times race managers could not associate what they saw on the water with what forecasters referred to in the warnings; often times the features were obscured or out of visual range allowing room for misinterpretation. Competitors in the field of play did not have direct access to warnings (a planned venue management decision) but were under the control of race managers and water rescue staff assigned to each course. In retrospect, the morning hours 0800–1100 LT were the most dependable time period for racing without the threat of thunderstorms; unfortunately the logistical problems associated with the long distances between the marinas and the course areas made it difficult to take advantage of this period until the last few days when most of the competition was completed.

Two days were selected to provide examples of the impact of weather on the Olympic sailing events.

TABLE 3. Effects of weather or warnings on Olympic sailing competition.

Date	Buoy 41021 wind (°at m s^{-1}) at 1400 LLT	Synoptic category	Weather or warnings (times LT)	Effect on competition
22 Jul	170 at 5	Dist	Heat (1400–1800), Tstm (1400–1700), high lightning strike frequency	Eight races postponed, one race abandoned
23 Jul	182 at 7	Dist	Heat (1300–1800), Tstm (1845–1915)	All races completed
24 Jul	188 at 8	Dist	Tstm (1330–1408), Tstm (1445–1545)	Four races postponed, one race abandoned and restarted
25 Jul	175 at 9	HS	Tstm (1500–1837), lightning on course areas	Seven races postponed, one race abandoned
26 Jul	252 at 6	HS	None	All races completed
27 Jul	194 at 3	HNW	Light wind due to extensive cloud deck	Two races postponed
28 Jul	177 at 2	HSW	Light wind due to extensive upper cloud, Tstm (1730–1830)	Long delays, six races postponed
29 Jul	176 at 6	HSW	Heat (1300–1600)	All races completed
30 Jul	190 at 4	HS	None	All races completed
31 Jul	161 at 7	HS	None	All races completed
1 Aug	163 at 5	Dist	Tstm (1330–1800), lightning on course areas	Match race semifinals postponed
2 Aug	157 at 4	Dist	Tstm (1430–1745), lightning on course periphery	Delays but semifinals and finals completed

a. 22 July lightning episode

On 22 July, the first scheduled day of competition, the venue was under the influence of relatively low pressure associated with a low in Virginia. A sea breeze developed as forecast (Fig. 6) about 1745 UTC (1345 LT) offshore allowing all outside course areas to commence races. A relatively strong offshore gradient wind component delayed the sea breeze within Wassaw Sound until 1900 UTC. A thunderstorm warning was issued at 1800 UTC since this same offshore gradient component would allow thunderstorms already developing inland to quickly move eastward out over the race course areas. By 1900 UTC, as depicted in Fig. 10, a few Cbs were developing along the coastal sea-breeze front and a northward-moving outflow boundary was intersecting with scattered areas of convection further inland. By 1930 UTC, the sea-breeze front and inland outflow boundary convection merged to form an east–west-oriented line of intense convection with winds at the Olympic buoys shifting to westerly and gusting over 20 m s^{-1}. From 2000 to 2130 UTC this area slowly moved offshore and continued to grow in extent with a large anvil cloud extending north of the main convection. During this period the WDSS indicated over 200 lightning strikes in the Olympic race course areas. Unfortunately, due to the long distance between the race courses and the Olympic marina, many of the athletes, volunteers, and spectators (including British royalty) were unable to immediately reach shelter and frequent lightning strikes were observed nearby. Many people were able to reach the day marina (Fig. 8) but the metal barge structure with tents was an unsuitable shelter. Eyewitness comments on the lightning included the following ''fireballs exploded on the surface with steam rising as the water boiled'' (Bowman 1996); ''The storm foiled a great race for Tornado sailors John Lovell and Charlie Ogletree. . . . 'We were in third when they called the race, and our main competition was really buried,' said Lovell, who conceded that lightning struck so close to him the hair on his arm stood up.'' (U.S. Sailing 1996). Fortunately no one was hurt. On this day only three races were completed; several races were abandoned before completion and 13 races were postponed.

b. 2 August: Final day of competition

On 2 August, an early start time of 1100 LT was scheduled so Soling class match racing could be completed before the forecast thunderstorms developed. All other racing was completed with the exception of match racing on the offshore course in the Soling class. Race organizers were anxious since both the match race semifinals and finals needed to be completed in one day. Racing began around noon in a weak backing southwesterly flow. A convergence line associated with the sea-breeze front is depicted in the satellite imagery of Fig. 11 at 1702 UTC (1302 LT) and a thunderstorm

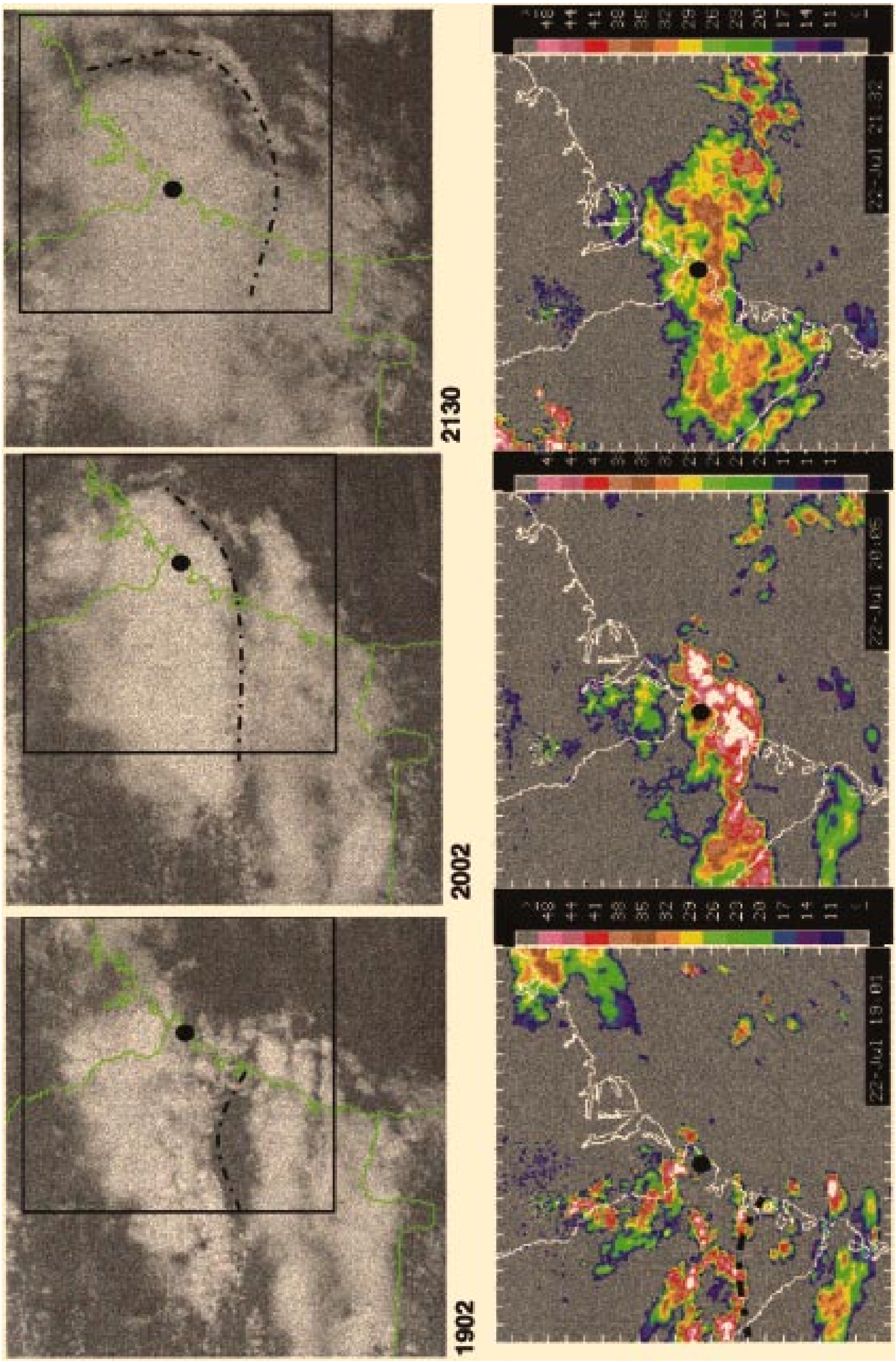

FIG. 10. *GOES-8* visible satellite imagery (top) and WSR-88D radar reflectivity from Charleston (bottom) showing development sequence for the 22 July 1996 lightning episode. The inset box in the satellite images corresponds to the area covered by the radar images. Times refer to UTC.

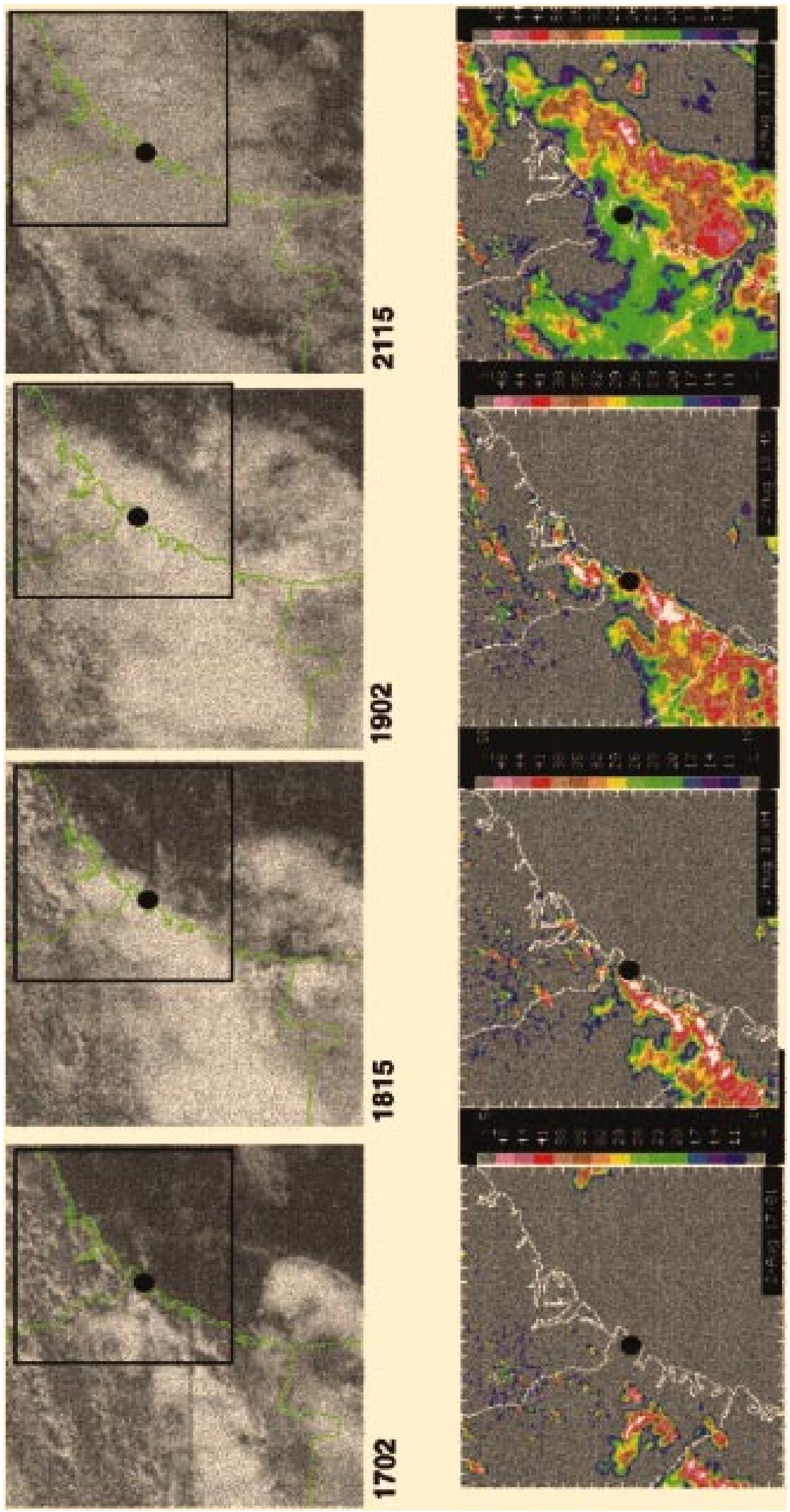

FIG. 11. Same as in Fig. 10 but for 2 August 1996.

TABLE 4. Wassaw Sound verification of marine Olympic wind forecasts (WS: wind speed, and WD: wind direction).

Method	*n* count	WS bias (m s^{-1})	WS rms (m s^{-1})	WD bias (°)	WDrms (°)	MagVectorError (m s^{-1})
Pregames						
OMWSO	179	−0.3	2.9	−6.6	42.0	3.9
Persist	180	0.8	4.4	−2.8	71.6	6.1
Climo	183	−1.1	2.7	−33.9	67.4	5.2
RAMS 0900 UTC	113	−0.3	2.5	−2.8	45.5	3.4
RAMS 1300 UTC	131	−1.0	2.9	−17.5	50.7	4.1
JT	156	−0.2	2.0	−14.8	45.1	3.7
Eta 10	27	−0.9	2.3	8.7	27.7	2.8
Olympics						
OMWSO	108	−0.1	2.0	−1.2	40.2	2.8
Persist	108	0.0	2.8	6.3	51.6	4.1
Climo	108	−0.4	2.0	−23.1	47.1	3.5
RAMS 0900 UTC	83	−0.2	2.2	18.0	49.6	3.1
RAMS 1300 UTC	99	0.3	1.8	7.8	35.4	2.9
JT	108	0.1	2.0	−13.6	40.2	2.9
Eta 10	76	−1.0	2.2	14.5	55.6	3.4

RAMS 1300 UTC: This was not available in time to be used in the daily wind forecast, sometimes the run was made at 1400 UTC.
RAMS 0900 UTC: Sometimes the 2-km RAMS run was made at 1000 or 1100 UTC.
Bias = average of difference: Forecast − Observed
Rms = root-mean-square of differences
MagVectorError = average of the magnitude of the vector error as defined by the square root of the sum of the squares of the north–south and east–west wind components of the differences.

watch was issued at 1710 UTC. The actual southeast sea-breeze onset occurred offshore from the sea-breeze front depicted on radar within a half hour of the forecast and was observed by all the Olympic buoys about 1720 UTC. At 1800 UTC, a thunderstorm warning was issued for the offshore course area. At 1813 UTC, an outflow from the convergence line reached the Wassaw Sound Olympic buoy and at 1830 UTC the outflow produced southwesterly gusts of 13–15 m s^{-1} at the offshore Olympic buoys. The line continued to propagate offshore through 2113 UTC as depicted in Fig. 11. One day earlier (1 August), a widespread thunderstorm area resulted from a similar convergence line and ultimately the wind dropped too low to race. This day, however, after decreasing briefly following the gust front, the breeze built to a 7–9 m s^{-1} southerly beneath light to moderate anvil rain. Apparently this was a rearward outflow while the main convective line pushed offshore. These winds were sufficient to complete the televised semifinals and finals despite the presence of lightning strikes just a few miles offshore.

6. Wind forecast verification

All official OMWSO (0830 LT forecast) and guidance model forecasts (valid for the 10-m level) were verified by comparison to hourly observations (adjusted to 10 m) from the Olympic buoys in Wassaw Sound (41023) and offshore (41021). To assess skill, forecasts were also compared to a climatology (C), based on July 1994 and 1995 data collected offshore at buoy 41021 and to persistence (P), based on the previous day's hourly observations. Verification was divided into two periods: pregames (27 June–21 July 1996) and Olympics (22 July–2 August 1996). During the pregames period, model guidance was not always available and observations were missing for a few hours; the pregames period also included the passage of Hurricane Bertha. Verification summaries are provided in Table 4 (Wassaw Sound) and Table 5 (offshore). The 1300 UTC RAMS model run is listed but not compared to other techniques since the results were not available in time for the 0830 briefing deadline. Verification statistics include average bias and root-mean-square errors for wind speed and wind direction, in addition to the average magnitude of the vector error.

a. Pregames

In Wassaw Sound, all forecasts displayed skill over C and P based on vector errors with the 0900 UTC RAMS and JT models showing the smallest errors. Only a few cases were available for the 10-km Eta Model. The OMWSO performed best in wind direction. For wind speed alone, only the 0900 UTC RAMS and JT models showed skill over C. Offshore, based on vector errors, the JT model, OMWSO, and 0900 UTC RAMS forecasts all showed skill over C and P, with JT displaying the smallest rms errors in wind speed and direction. The 1300 UTC RAMs run also showed skill, but performed slightly worse than the 0900 UTC RAMS. In general, errors were slightly larger in Wassaw Sound, especially for wind direction, probably because of the greater difficulty of forecasting sea-breeze onset during offshore gradient flow.

TABLE 5. Offshore verification of marine Olympic wind forecasts (WS: wind speed, and WD: wind direction).

Method	*n* count	WS bias (m s^{-1})	WS rms (m s^{-1})	WD bias (°)	WDrms (°)	MagVectorError (m s^{-1})
Pregames						
OMWSO	175.0	−0.4	2.5	−3.0	36.9	3.3
Persist	174.0	0.8	4.4	−1.7	63.0	6.1
Climo	177.0	−1.4	3.4	−30.3	61.8	5.2
RAMS 0900 UTC	105.0	−0.5	3.1	6.0	33.1	3.4
RAMS 1300 UTC	113.0	−1.1	3.3	−13.5	43.0	3.9
JT	153.0	−1.0	2.2	−10.4	34.9	3.0
Eta 10	27.0	−0.6	2.3	8.1	16.9	2.2
Olympics						
OMWSO	108.0	−0.1	1.9	−5.8	37.4	2.8
Persist	108.0	0.0	2.7	6.4	48.6	3.8
Climo	108.0	−0.5	2.1	−29.7	47.3	3.7
RAMS 0900 UTC	75.0	−0.1	1.8	15.1	39.8	3.0
RAMS 1300 UTC	99.0	0.2	1.8	4.5	31.7	3.1
JT	108.0	−0.6	1.9	−15.3	37.8	2.7
Eta 10	76.0	−0.7	2.3	13.2	51.9	3.1

RAMS 1300 UTC: This was not available in time to be used in the daily wind forecast, sometimes it was run at 1400 UTC.
RAMS 0900 UTC: Sometimes this was run at 1000 or 1100 UTC.
Bias = average of difference: Forecast − Observed.
Rms = root-mean-square of differences.
MagVectorError = average of the magnitude of the vector error as defined by the square root of the sum of the squares of the north–south and east–west wind components of the differences.

b. Olympics

In general, mean vector errors decreased during the Olympics period and, along with speed errors, were of similar magnitude within Wassaw Sound and offshore; wind direction errors were smaller offshore. This can probably be attributed to the pregames period containing difficult wind forecast cases involving Hurricane Bertha approaching and passing well to the east and a few cases with strong offshore flow that inhibited sea-breeze development. During the Olympics, the main forecasting challenge on several days was the affect of thunderstorms on the winds. There was no way to forecast the affect of thunderstorms on the winds several hours in advance. In Wassaw Sound, all forecasts displayed skill over C and P, with OMWSO and JT showing the smallest vector errors. OMWSO and JT performed equally for wind direction and JT did best on wind speed. The JT method was slightly better than C in wind speed and OMWSO was slightly worse. The 1300 UTC RAMS performed better than the 0900 UTC RAMS during the Olympic period and, although not available in time for the 0830 LT briefing, 0900 UTC RAMS provided useful guidance for updating forecasts. Offshore, all forecasts also improved on C and P with JT showing the lowest mean vector error. OMWSO performed slightly better than JT on wind direction rms error. The 0900 UTC RAMS showed the lowest rms error in wind speed where only the Eta 10-km model lacked skill over C.

7. Summary and recommendations

Marine weather support to the Centennial Olympic Games was a challenging but rewarding experience. The pregames familiarization period was critical for developing and refining forecast products, and allowed the OMWSO staff to gain valuable experience. Forecasters were able to rely on a vast amount of information in near-real time. Satellite and radar imagery, real-time display of wind and current time series plots from all Olympic buoys, live video from the race courses, and duty forecasters on the water ensured continuous weather monitoring. Satellite data were useful for monitoring the sea-breeze convergence line and detecting gust fronts; unfortunately communication bandwidth limitations associated with large graphical numerical weather prediction products needed for N-AWIPS (Snook et al. 1998) often delayed the reception of satellite images at OMWSO by 30–45 min. Possible solutions in hindsight would have been to provide a direct T1 line to NCEP (without having to go through the Atlanta office first), generate graphical workstation products locally, and to run the local-domain mesoscale model in house (also eliminating the need to obtain model data and products elsewhere).

During the Olympics, thunderstorm activity presented a forecast and warning challenge on half of the days. Forecasters provided warnings for activity headed for specific venue locations during rapidly evolving thunderstorm situations. The OMWSO relied heavily on data from the Charleston WSR-88D radar. Lightning strikes at the Charleston WSR-88D caused limited periods without data but the Savannah Weather Service Office WSR-57 RADID display was available to provide backup service. WDSS was invaluable for its ability to track cellular reflectivity features, assess the potential for severe weather in a particular cell, and map lightning strikes. All OMWSO thunderstorm warnings were based on guidance provided from WDSS. Fortunately, two-way radios were provided to facilitate immediate primary communication of warnings. The secondary distribution of warnings via fax to the VCC performed very poorly; often several minutes expired by the time the VCC broadcast or faxed warnings to the venues. Electronic communication via e-mail or World Wide Web intranet would have been a viable alternative. Direct communication with competition managers was essential during warning situations and could be improved by providing managers with access to radar and satellite animations. Lack of suitable lightning shelter put many athletes and volunteers at risk. Lightning experts should have been involved with the design of the venue facilities from the earliest stages.

Marine wind forecasting was conducted on an extremely fine time (1 h) and space (2–10 km) scale for the first time in the Olympics. The OMWSO forecasts, a simple vector addition sea-breeze model, and sophisticated mesoscale forecast models all performed with skill over climatology and persistence as defined by mean vector errors and wind direction rms errors; however, climatology proved best able to forecast wind speed. In past Olympics, some teams gained an advantage by forming their own staff of meteorologists and oceanographers. For the centennial games, forecasting expertise on a level equivalent to dedicated America's Cup weather teams was made equally available to all countries competing in the Olympics. OMWSO forecasts helped to level the playing field for teams that could not afford their own forecast staff. Perhaps this is one reason why a record number of countries (22) shared the 30 Olympic sailing medals. A questionaire distributed after the event suggested athletes, coaches, and team meteorologists appreciated the quality of the information in the forecasts and weather briefings. Several team meteorologists commented that OMWSO effort surpassed previous marine weather support at international sailing events. Many simply used the OMWSO forecast as a baseline and attempted to add value or further interpretation. Sailing is such a weather-dependent sport, it would be advantageous for future marine Olympic weather offices to provide display terminals at venue locations congregated by athletes for display of wind and current time series, forecasts, and radar and satellite animations.

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