Journal of Coastal Research	19	3	503–513	West Palm Beach, Florida	Summer 2003

Surface Wind Fields for Florida Bay Hurricanes

Samuel H. Houston* **and Mark D. Powell**

Hurricane Research Division
AOML/NOAA
Miami, FL 33149, U.S.A.
sam.houston@NOAA.gov

ABSTRACT

HOUSTON, S.H. and POWELL, M.D., 2003. Surface wind fields for Florida Bay hurricanes. *Journal of Coastal Research,* 19(3), 503–513. West Palm Beach (Florida), ISSN 0749-0208.

The surface wind fields of several tropical cyclones which impacted Florida Bay and the surrounding coastal areas were reconstructed by the Hurricane Research Division (HRD) of the National Oceanographic and Atmospheric Administration. These cyclones provided the forcing for significant changes in water-levels, waves, and currents, resulting in sediment transport, deposition, and other physical processes affecting the bay. In addition, tropical cyclones had direct and indirect effects on plant and animal life in the bay and the surrounding coastal areas, such as the Florida Keys and Everglades. The HRD wind fields are being made available in gridded form for use in hindcasts, which may help researchers to estimate the potential impacts of future tropical cyclones on the south Florida ecosystem, especially in relation to Florida Bay.

The tropical cyclones investigated represent vastly different scenarios for the type of events that might be expected over extreme south Florida. The reconstructed storms range in intensity from Tropical Storm Gordon of 1994 to the Labor Day Hurricane of 1935 (the United States' most intense hurricane at landfall).

This paper summarizes the methods used to reconstruct tropical cyclone surface wind fields and provides examples of their circulation features and wind swaths. Comparisons of winds to observed damage are also presented for three major hurricanes. The wind fields for all of these tropical cyclones are being made available to researchers as graphical products and gridded data sets on a Web site maintained by HRD (www.aoml.noaa.gov/hrd).

ADDITIONAL INDEX WORDS: *Hydrographic modeling, ecological impacts, sediment transport, gridded fields, disaster studies, mangroves, forests, palms, damage assessment.*

INTRODUCTION

Tropical cyclones are believed to exert considerable influence on the ecological health of Florida Bay. The effects of these episodic events are manifested by significant changes in physical processes, such as water-levels, waves, currents, and sediment transport. Hurricane conditions, which were relatively rare in the vicinity of Florida Bay during the 1970's and 1980's (JARRELL *et al.,* 1992), have frequently impacted the region (Figure 1). The winds associated with hurricanes generate surface stresses and associated responses in the bay's circulation patterns and sediment transport. High mortality rates of plants and animals occur in association with damaging hurricane winds, which also produce storm surges and waves. The post-storm decay of organic material may contribute to poor water quality, algal blooms, and additional damage to plant and animal life in and around the bay by upsetting the salinity balance (SMITH *et al.,* 1994). Heavy rainfall associated with very wet, slow moving tropical cyclones can also cause extensive freshwater flooding over mainland Florida and the keys. Freshwater discharges into the bay can have short lived and sometimes long-term consequences on the vitality of the bay's ecosystem. Other researchers have found that hurricanes may be directly or indirectly beneficial to the vitality of the bay. For example, SWART *et al.* (1996) believe that hurricanes promote resuspension and flushing of organic carbon, which would likely lead to improved environmental conditions. Therefore, changes in the frequency of major hurricanes is a potential controlling mechanism for carbon storage and removal from Florida Bay (NELSEN *et al.,* 2001). In order to assess the response of Florida Bay to episodic wind events, circulation and ecological modelers can benefit from the use of reconstructed surface wind fields in hurricanes.

The Hurricane Research Division (HRD) of the National Oceanic and Atmospheric Administration (NOAA) has been providing real-time tropical cyclone surface wind fields on an experimental basis to forecasters at the National Hurricane Center (NHC) of the Tropical Prediction Center since 1993 (POWELL and HOUSTON, 1998). The forecasters use the HRD wind fields as guidance for their advisories and forecasts of wind radii (*i.e.,* the extent of 17.5, 25.0, and 33.0 m s^{-1} winds from the tropical cyclone's center in all quadrants). This information is useful for marine interests and for emergency managers if warnings are issued. The HRD real-time surface wind fields are generated by analyzing all available quality controlled data. These data are adjusted to a common framework accounting for height and averaging time. Examples of recent real-time surface wind fields include Hurricanes Georges (1998) in Figure 2a, which primarily impacted the

00082 received and accepted in revision 20 June 2000.
* Corresponding author's address: Sam Houston, HRD/AOML/NOAA, 4301 Rickenbacker Causeway, Miami, FL 33149, e-mail: houston@aoml.noaa.gov.

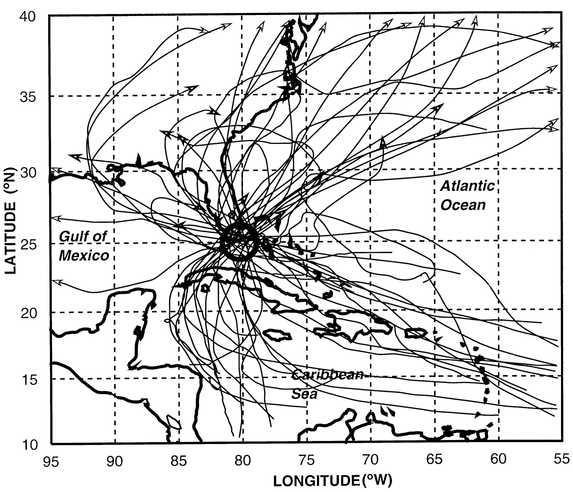

Figure 1. Tracks of all hurricanes passing within 140 km of Florida Bay (large circle) during 1886–1995.

lower Florida Keys and western Florida Bay as a category 2 hurricane on the SAFFIR and SIMPSON (1974) scale, and Hurricane Irene (1999) in Fig. 2b, which was a category 1 hurricane that moved across the middle Florida Keys and Florida Bay.

The reconstructed, gridded surface wind fields for Florida Bay tropical cyclones were developed using techniques similar to those employed to produce HRD's real-time surface winds for NHC. If there were not enough surface wind observations available for some of the early Florida Bay hurricanes (*e.g.,* the Labor Day Hurricane of 1935), a parametric model was used to compute a background wind field.

Tropical cyclones that impacted Florida Bay with a broad range of intensities over the past century were included in this study (Figure 3). The reference for the storm history of each tropical cyclone is listed in Table 1. The reconstructed storms range in intensity from Tropical Storm Gordon of 1994 to the Labor Day Hurricane of 1935 (the United States' most intense hurricane at landfall). Hurricane Andrew's (1992) surface wind fields over south Florida (POWELL and HOUSTON, 1996) were also included in this study.

In the following sections, the methods used to reconstruct the Florida Bay tropical cyclone wind fields are described. Two examples of reconstructed hurricane wind fields are presented (Donna of 1960 and the Labor Day Hurricane of 1935), and some of the ecological impacts of these two intense hurricanes and Hurricane Andrew on the environment of the bay and surrounding areas are reviewed. Conclusions are provided in the last section.

METHODOLOGY

All available surface wind observations in each Florida Bay tropical cyclone examined in this study were processed to achieve a consistent framework in terms of averaging time, height and exposure using the methods of POWELL *et al.* (1996). A major assumption of these procedures was that each hurricane was in nearly steady state during the time the data are composited (~6 h). Most of the data available in the core of the hurricanes examined during the era of aircraft reconnaissance flights were based on flight-level observations adjusted to the surface. All data used were adjusted to maximum 1-min sustained winds at a height of 10 m for marine exposure. Some past hurricanes had limited surface data available. In these latter cases, a planetary boundary layer model developed by SHAPIRO (1983) and implemented by VICKERY and TWISDALE (1995) was adapted to construct a background field of surface winds.

Analyses of Hurricane Wind Data

Data for hurricanes such as Donna were available from a number of platforms. Most of these observations were found in HRD's microfilm archives. The most important data obtained in the core of Donna were the flight-level observations from two National Hurricane Research Project (NHRP; predecessor organization of HRD) flights into Donna's inner core around 1800 UTC 9 September 1960. Examples of observations that were available from the NHRP aircraft and surface wind observations (*e.g.,* from manned lighthouses, airports, ships, amateur weather hobbyists, *etc.*) in the Florida Keys and surrounding areas are shown in Figures 4a and b. The observations from the manned lighthouses in the Florida Keys, some made in dangerous conditions within Donna's eyewall, were essential for describing the surface wind field.[1]

The surface wind data were objectively analyzed using the Spectral Application of Finite-Element Representation (SAFER) method (OOYAMA, 1987; FRANKLIN *et al.,* 1993). As described in POWELL *et al.* (1996), the method uses cubic B-splines to minimize the difference between the input observations and the analysis. Each analysis produces fields of mesoscale winds (V_{MESO}). The scale of each analysis is controlled by the analyst and is dependent on the features that need to be resolved. An advantage of this analysis system is that multiple nests are used, which allows the inner most features near the storm center (*e.g.,* the eye, eyewall, inner rainbands, etc.) to be resolved. Nested meshes also allow the winds in the outer portion of the domain to be smoothed more due to sparser data coverage. Fields of maximum 10-min mean surface winds valid for marine exposure (V_{M10}) were considered best for examining oceanic responses to surface stress (HOUSTON *et al.,* 1999). These V_{M10} may be converted to NHC's standard maximum 1-min sustained wind speed by multiplying with a factor of 1.11. The V_{M10} were computed from the V_{MESO} winds using a gust factor relationship described by POWELL and HOUSTON (1996) and HOUSTON *et al.* (1999).

Modeling of Hurricane Winds

The basis for the model used to create parametric wind fields for some of the early Florida Bay hurricanes without sufficient data (*e.g.,* the Labor Day Hurricane of 1935 and

[1] It was determined that observations in 1960 from Florida surface stations, such as these lighthouses, were reported in Eastern Standard Time (J. Dunion, HRD, personal communication, 2000).

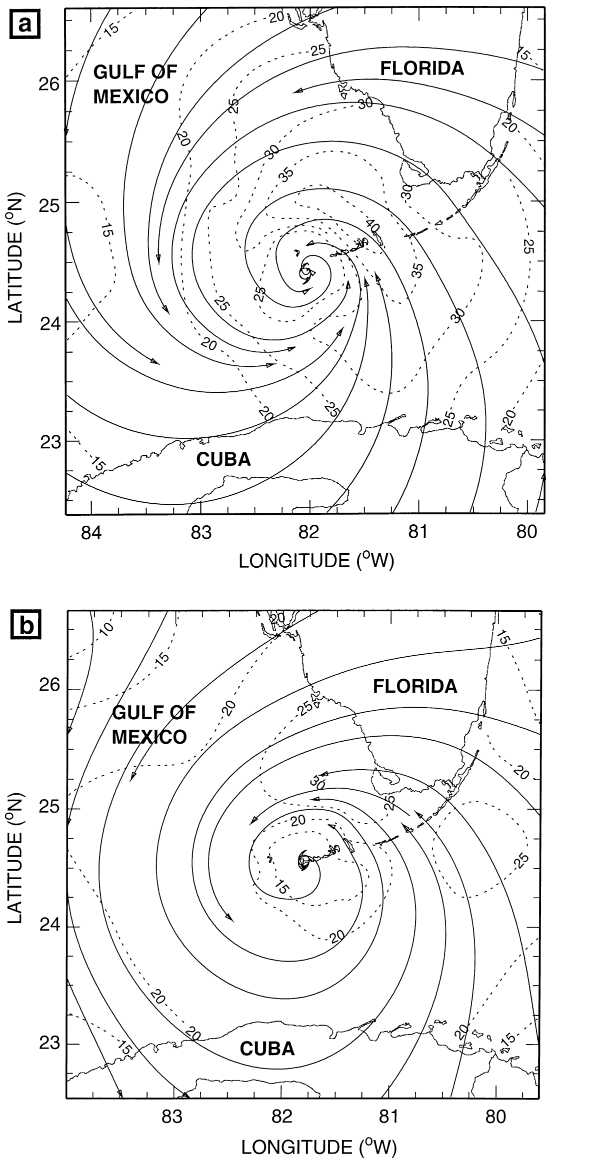

Figure 2. Examples of surface wind fields provided to the forecasters at NHC in real-time. The wind field is represented as isotachs (units = m s^{-1}) and streamlines. These winds are maximum 1-min sustained speeds valid only for marine exposure at 10 m where a) is Hurricane Georges at 1630 UTC on 25 September 1998 and b) is Hurricane Irene at 1330 UTC 15 October 1999.

Betsy of 1965) was a simple slab boundary layer model which SHAPIRO (1983) developed to examine the steady boundary layer flow under a translating symmetric hurricane vortex. His model was used to examine the effect of surface friction on the asymmetries in the hurricane's boundary layer wind. The SHAPIRO (1983) model solves the momentum equations for a slab boundary layer having constant depth under an imposed symmetric pressure distribution. The model uses a storm-relative coordinate system in which there is gradient balance between the boundary layer winds and the pressure field above the boundary layer.

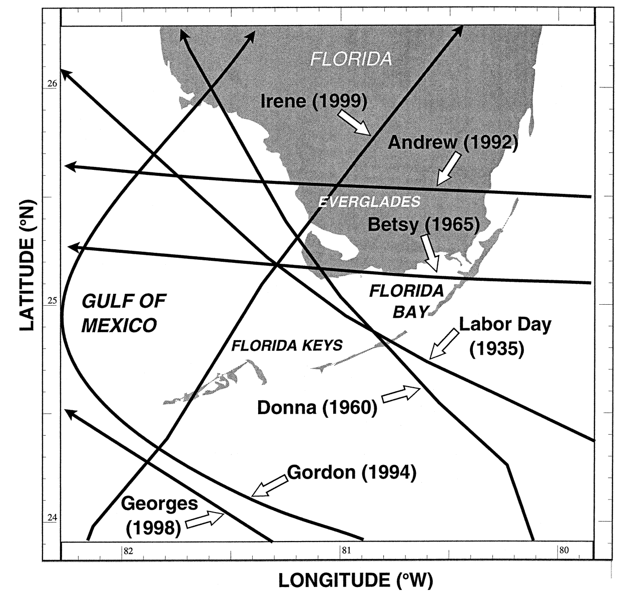

Figure 3. Tracks of Florida Bay tropical cyclones examined in the study.

VICKERY and TWISDALE (1995) used the output from the SHAPIRO (1983) model to derive equivalent 10 m surface winds. Their work required a drag coefficient that related the vertically integrated wind speed computed by SHAPIRO to the wind speed at 10 m height. SHAPIRO (1983) used a drag coefficient, which increased linearly with velocity. VICKERY and TWISDALE (1995) applied a reduction of 50% to the drag coefficient assigned to the upper level winds before they were adjusted to 10 m height over the ocean.

The wind speeds, *V*, produced by the numerical model are vertically averaged values defined as:

$$V = \left(\frac{1}{h}\right) \int_0^h V(z)\, dz,$$

in which the boundary layer depth, *h*, is assumed to be 1 km and *z* is the incremental depth of the boundary layer. The vertically averaged wind speed is assumed to be equivalent to the SHAPIRO (1983) wind speed at 500 m (VICKERY and TWISDALE, 1995). The 500 m winds are adjusted to 10 m height assuming marine exposure by implementing a varying percentage reduction according to radius, r, from the storm center. The value of r is related to the radius of maximum winds, R_{max}. Based on comparisons of the model output with the Hurricane Andrew surface wind field at landfall in south

Table 1. *Reference for the storm history of each tropical cyclone used in the study.*

Tropical Cyclone	Storm History
Labor Day (1935)	MCDONALD (1935)
Donna (1960)	DUNN (1961)
Betsy (1965)	SUGG (1966)
Andrew (1992)	MAYFIELD *et al.* (1994)
Gordon (1994)	AVILA and RAPPAPORT (1996)

Florida (Powell and Houston, 1996), the percentage reduction for $r < 1.5\ R_{max}$ was 10% and for $r > 5\ R_{max}$ was 20%. The reduction of wind speeds for $1.5\ R_{max} < r < 5\ R_{max}$ was based on a smooth transition function having 10–20% reductions. The averaging time was assumed to be 1 h, so the wind speeds were adjusted to V_{M10} values (Powell *et al.,* 1996; Houston *et al.,* 1999). For consistency with the gridding of the wind fields based on analyzed data and to produce wind swaths, the model outputs were also objectively analyzed.

TWO INTENSE FLORIDA BAY HURRICANES

One example of an intense hurricane that passed through Florida Bay was Hurricane Donna, which was a category 4 hurricane when it made landfall in the central Florida Keys early on 10 September 1960. The number of surface wind observations available in the Florida Keys was unusually large for this storm. Another intense hurricane which occurred 25 years earlier and moved across the same area of the Florida Keys was the very intense Labor Day Hurricane (1935). The 1935 hurricane caused considerable loss of life to residents and railroad workers in the area of the highest winds, storm surge, and wind driven waves in the vicinity of landfall (McDonald, 1935a). Man made structures and the natural habitat suffered complete destruction in the region of the central Florida Keys where the relatively small Labor Day Hurricane's eyewall crossed. Only a few observations were available where this hurricane made landfall, so modeled surface winds were required to produce the background wind field.

Hurricane Donna (1960)

In his pioneering research using boundary layer observations from Hurricane Donna, Miller (1963, 1964) provided wind trajectories and wind analyses based on the relatively large amount of data that were available. He apparently did not adjust the observed wind data into a common framework for averaging time, height, and exposure. The methods of Powell *et al.* (1996) were used to adjust all of the wind data that were available for Donna. The time windows for acceptance of data into each analysis time are shown in Table 2.

Donna's track as it approached the keys was available from two sources: Navy aircraft reconnaissance and ground-based radar (Senn and Hiser, 1962; Conover, 1962). Conover (1962) found that the reconnaissance aircraft fixes had large deviations from known positions as Donna approached and made landfall in Florida. There were also uncertainties in the available ground-based radar center fixes (Senn and Hiser, 1962; Conover, 1962). The final track used was based on a blend of these radar data and nearby surface observations.

Based on the 0000 UTC 10 September surface wind analysis (Figure 5a), V_{M10} winds of 25–30 m s^{-1} from the northeast were occurring over the northeastern portion of Florida Bay 140 km from Donna's eye. The 0600 UTC analysis (Figure 5b) shows the surface wind field shortly before the center of Donna made landfall near Conch Key, Florida. The highest winds ($V_{M10} > 55$ m s^{-1}) were located in an 11×18 km^2 area centered ~35 km north-northeast of the eye over Florida Bay. These strong northeast winds resulted in a substantial drop

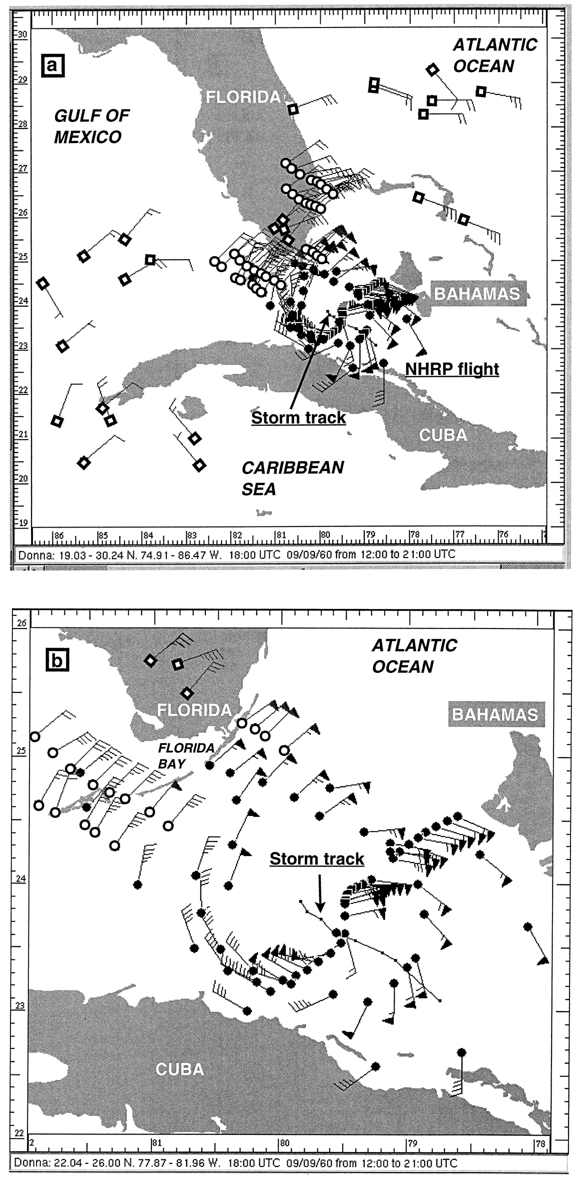

Figure 4. Example of the coverage of wind data recorded at lighthouses (open circles), ships (squares), and NHRP research aircraft data adjusted to the surface (filled circles) from 1200 to 2100 UTC 9 September 1960 in storm-relative coordinates for Hurricane Donna centered at 1800 UTC. The observations are shown as wind barbs where each whole barb = 5 m s^{-1}, each half barb is 2.5 m s^{-1}, and each flag is 25 m s^{-1}. The area shown in a) is over 1600 km^2 and b) ~440 km^2 and shows the data coverage of the NHRP flight-level data adjusted to the surface.

in water-levels over portions of Florida Bay as water was pushed southwest toward the Gulf of Mexico (Ball *et al.,* 1967). At the same time, significantly increased water-levels (> 1 m above normal) and large breaking waves (likely ranging 3.0–4.5 m on the outer reefs) were causing considerable problems along the Atlantic side of the northern keys (Ball *et al.,* 1967) where southeasterly $V_{M10} > 45$ m s^{-1} were occurring to the right of Donna's circulation. Ball *et al.* (1967)

Table 2. *Time window of data used for each analysis in Donna (the day of the month in September 1960 is shown in parentheses).*

Analysis time [UTC]	Data time window [UTC]
1800 (9)	1200–2100
0000 (10)	2100 (9)–0100 (10)
0600 (10)	0100–0700
1200 (10)	0700–1200
1800 (10)	1200–2000

also indicated that channels between the keys connecting the Atlantic Ocean to Florida Bay were flooded and contained high-velocity currents flowing primarily toward the bay to the right of Donna. After Donna's eye passed north of the keys and Cape Sable, southerly (and later southwesterly) V_{M10} in excess of 30 m s^{-1} covered most of northern Florida Bay (Figure 5c). These southerly and southwesterly V_{M10} winds over the bay were slightly weaker for most areas than the northeasterly winds which preceded the storm's eye passage a few hours earlier. The storm tide on the southeast facing portion of the keys began to subside, while a rapid increase in water-levels over Florida Bay occurred. BALL *et al.* (1967) noted that data from a U.S. Geological Survey tide gage in western Florida Bay measured a tide of 0.5 m *below* mean low water (MLW) at 0545 UTC 10 September, while a peak high tide of 3.7 m above MLW was measured at 1200 UTC 10 September. As the winds over Florida Bay shifted to a more westerly direction, the storm tide continued to increase over the eastern portion of the bay, while it continued

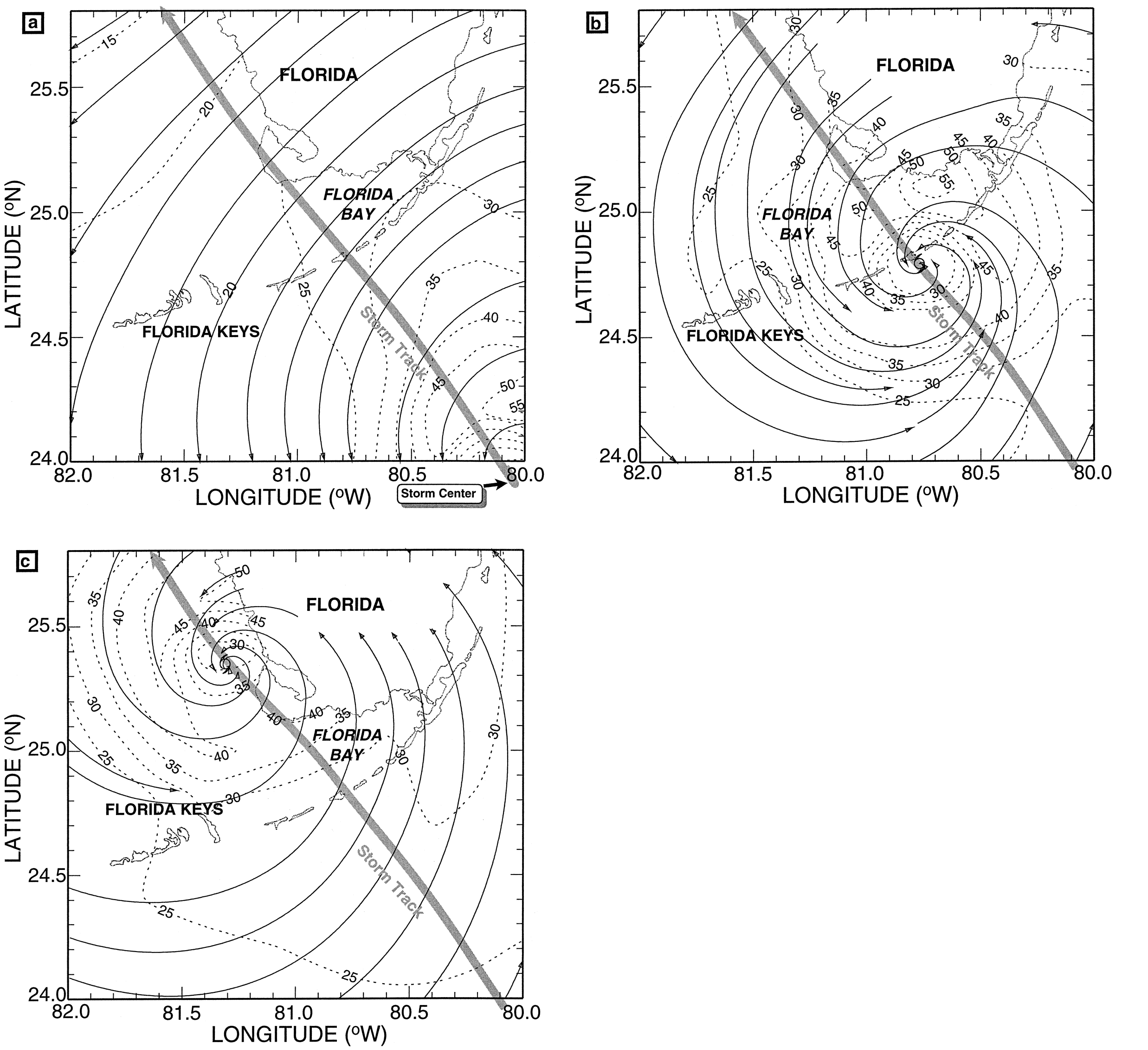

Figure 5. "Snapshot" of Hurricane Donna's V_{M10} field on 10 September 1960 displayed over water as streamlines (solid lines with arrows) and isotachs (dashed lines; units = m s^{-1}) at a) 0000 UTC (the storm center is just outside of the domain at this time), b) 0600 UTC, and c) 1200 UTC.

to decrease on the southeastern side of the keys. The difference in water levels between the bay and the Atlantic Ocean, was compounded by the wind forcing, which pushed "rivers of mud-charged water" through channels between the keys (BALL *et al.,* 1967). These "muddy waters" would have flowed out over the reef tract, resulting in considerable sediment deposition. Wind damage to the flora and fauna of the southern and southwestern Everglades would likely have been the most severe between 0600 UTC and 1800 UTC on 10 September. BALL *et al.* (1967) also indicated that there was likely a significant mortality rate for marine life exposed to strong offshore winds when water in Florida Bay was nearly emptied along the shoreline of the mainland prior to 0600 UTC. By 1800 UTC (not shown), the winds over Florida Bay had decreased significantly and many of the most severe direct effects of Donna's winds likely began to diminish.

Labor Day Hurricane (1935)

The Labor Day Hurricane was of category 5 intensity when it made landfall in the central keys at 0300 UTC 3 September 1935. The minimum pressure of 89.2 kPa was the lowest ever observed in a landfalling hurricane in the United States (MCDONALD, 1935b; HEBERT *et al.,* 1993). The winds associated with this hurricane resulted in "phenomenal violence" according to MCDONALD (1935a). Extreme winds were reported nearly three hours prior to the arrival of the eye, and some observers indicated that the winds may have been even stronger after the eye passed. The lenses and 0.9 cm (3/8″) thick protective glass of Alligator Reef Lighthouse, located at 41 m height, were reported by MCDONALD (1935a) to have been completely destroyed by the storm. At this altitude, and with winds blowing over the open ocean, it is unlikely that flying debris caused these damages. Over a distance of 48 km, from Tavernier to Vaca Keys, the destruction of buildings, roads, viaducts, and bridges was nearly complete. This damage was primarily the result of storm surges and wind driven waves. An 11 car rescue train was washed completely off its tracks on Lower Matecumbe Key, killing many World War I veterans who were working on roadway projects in the area (U.S. HOUSE OF REPRESENTATIVES, 1936). Only the locomotive remained on the tracks after the hurricane's winds and flooding subsided. MCDONALD (1935a) also indicates that the "disposition of the debris and nature of the erosion of railroad embankments clearly indicate that the destructive tide flowed from southeast to northwest, in the direction of advance of the storm center". A section of railroad tracks and cross-ties over 9 m above sea-level were washed off of a viaduct.

A few valuable observations were provided by MCDONALD (1935a). J. E. Duane, a cooperative observer for the U.S. Weather Bureau (predecessor organization of today's National Weather Service), was located at a fishing camp on Long Key near mile marker 68. Duane's observations, though understandably cryptic in some cases, provide the best clues for the wind profile and timing of the eye crossing in the central Florida Keys. This information was invaluable for determining the approximate time and location of landfall. The parameters provided in the "best track" data set (JARVINEN *et al.,*

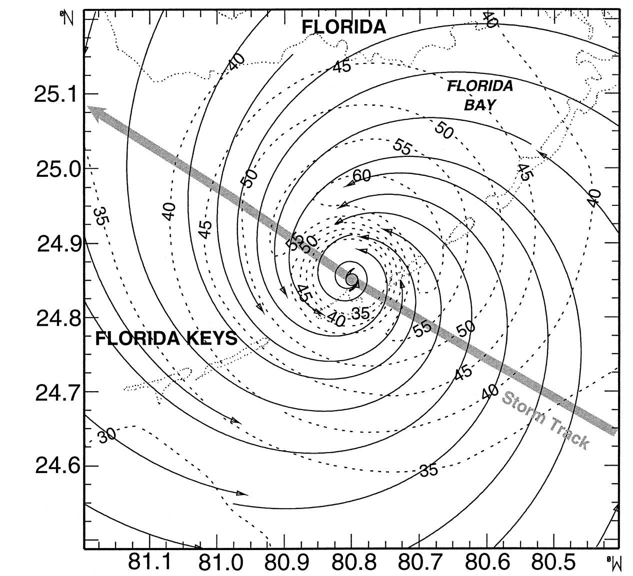

Figure 6. "Snapshot" of the Labor Day Hurricane (1935) V_{M10} field displayed over water as streamlines (solid lines with arrows) and isotachs (dashed lines; units = m s^{-1}) at 0300 UTC 3 September.

1988) indicated that landfall was 3 h later and slightly to the right of the location based on Duane's observations. Therefore, a landfall time near 0300 UTC was used for the model run to compute the Labor Day Hurricane's wind field over the keys and Florida Bay. Based on the size of the eye reported by MCDONALD (1935a), it was assumed that the storm's forward translation speed was 5 m s^{-1}. The direction of motion was toward 305° based on "best track." The R_{max} used in the model was 11 km following HO *et al.* (1987).

Using the minimum central pressure and the available wind observations to determine the model parameters, the V_{M10} field (Figure 6) was computed using the model based on SHAPIRO (1983) and VICKERY and TWISDALE (1995). The highest computed V_{M10} winds were slightly over 64 m s^{-1} across a portion of the central Florida Keys to the right of the hurricane's landfall.

ECOLOGICAL IMPACTS OF THESE TWO HURRICANES

Literature regarding the ecological impact of the Labor Day (1935) Hurricane on Florida Bay was sparse, but several researchers included references to the damage in their findings concerning damage from Hurricane Donna to the bay and surrounding areas. For example, CRAIGHEAD and GILBERT (1962) and CRAIGHEAD (1971) reported on a study of the impact of Donna on the Everglades National Park. Their research indicated that in some cases the damage produced in 1935 was still evident after Donna. In other cases, Donna destroyed flora which had survived the 1935 catastrophe. In other areas, which had been severely damaged by the 1935 hurricane, Donna adversely impacted the growth of the new vegetation.

The "mangrove belt" surrounding Florida Bay was severely impacted by the Labor Day Hurricane according to CRAIGHEAD and GILBERT (1962). Trunks of many of the trees killed by the 1935 hurricane were still standing in a forest near Flamingo when Donna struck the same area in 1960. Some trees that had survived the 1935 event rose conspicuously above the recovering forest in September 1960. Donna killed most of these survivors of the earlier hurricane, since nearly all trees with trunks larger than 5 cm in diameter were sheared 2–3 m above the ground in many areas between Flamingo and West Lake. The most severe damage observed by CRAIGHEAD and GILBERT (1962) in Donna was from Madeira Bay west to the Shark River. North of the Shark River to Lostman's River, 50 to 75% of the mature mangroves (up to 24 m high and 0.6 m in diameter) were killed. Between Lostman's River and Everglades City, the losses were generally 10 to 25%.

CRAIGHEAD and GILBERT (1962) also described losses of palm trees in some of the Florida Bay Keys. For example, on Palm Key there were fifty large cabbage palms that had survived the 1935 hurricane that were estimated to be over 100 years old. All but three of these trees were destroyed by Donna 25 years later. On Clive Key, many thatch palms in the vicinity of Fan Palm Hammock were destroyed by the 1935 hurricane, though a number survived. On the same island, only seven of twenty coconut palms survived Donna. Other observations by CRAIGHEAD and GILBERT (1962) indicated that the mangrove fringes on many of the keys were completely destroyed by the 1935 hurricane. Donna also severely damaged these mangrove rims, especially on the south and east sides of the keys. The broken trees were generally transported to the opposite sides of the islands by wind and wave action, and ended up in piles there. All remaining trees were defoliated, except low shrubs and occasional clumps of mangroves.

Cape Sable was severely affected by the storm surge that was over 2 m, based on the observed debris lines (CRAIGHEAD and GILBERT, 1962). Damage in the 10,000 Islands was much less than in the vicinity of Flamingo. Most of the damage was on the west side facing the Gulf of Mexico, where the strongest winds and storm surge from Donna would have likely occurred at this location after the eye moved north of the area.

One method for comparing the surface winds and the damage in a hurricane was to produce swaths of maximum values, the duration of greater than 50 m s^{-1}, and steadiness[2] of the V_{M10} (POWELL *et al.,* 1995; POWELL and HOUSTON, 1996, 1998). Figure 7a shows the swath of peak V_{M10} winds across the Florida Keys for the Labor Day Hurricane of 1935 assuming a forward storm motion of 5 m s^{-1} based on MCDONALD's (1935a) account. The zone of nearly complete destruction of buildings, roads, viaducts, and bridges is roughly bound by the 50 m s^{-1} contours. This wind speed contour generally delineated the greatest damage in Hurricane Andrew (POWELL *et al.,* 1995). In addition, very low values of steadiness in the vicinity of Andrew's track were also found to accompany severe destruction. Figure 7b shows the duration of 50 m s^{-1} winds was over 2.5 h in the hardest hit areas and was at least 0.5 h over most of the severely damaged keys. The contours of steadiness across the keys and Florida Bay (Figure 7c) were in a very narrow band (4.5 km width) of values < 0.1 along the track. The steadiness contours of 0.3 encompassed much of the central Florida Keys.

Figure 8a shows duration of greater than 50 m s^{-1} V_{M10} winds over portions of the keys and Florida Bay was > 2 h. The swath of steadiness values < 0.1 for Donna (Figure 8b) was along a 8.5 km band surrounding the track, which was almost twice the size found in the 1935 hurricane.

The strongest V_{M10} winds (> 57 m s^{-1}) were in a narrow band centered $\sim$30 km to the right of Donna's track. This band of intense winds extended over the north central keys, Florida Bay, and into the southwest Everglades (Figure 9). The maximum V_{M10} swath in Donna is shown overlaying some of the damage described by CRAIGHEAD and GILBERT in Figure 9. The region with wind speeds greater than 50 m s^{-1} corresponds closely to locations with severe damage to vegetation. The swath of highest V_{M10} was slightly east of Flamingo where some of the greatest disruption of the mainland ecosystems occurred. It is plausible that the R_{max} here was slightly larger than observed. However, damage to vegetation and structures also depends on other features of a hurricane's wind field. For example, the duration of high winds and changes in wind direction (*i.e.,* steadiness) are other important factors that could account for some of the most severe damage occurring within the R_{max} (POWELL *et al.,* 1995). The variation in steadiness values for the 1935 hurricane and Donna may have been responsible for cases where surviving trees of the former storm were felled by slightly weaker winds in the later storm. This was especially true on Clive and Palm Keys where the steadiness was larger in the 1935 case ($\geq$0.3) in Figure 7c, than in 1960 ($<$0.3) in Figure 8b.

Another important element in the variation of damage, especially for the Florida Bay Keys and the coastline north of Florida Bay, would have been the storm surge. A deposit of silt varying from a trace to 13 cm in depth was carried over many areas by the storm surge in Donna according to CRAIGHEAD and GILBERT (1962). Sediment transport by storms, including hurricanes, affecting southwest Florida was described by PERLMUTTER (1982). He indicated that hurricanes approaching this area normally produce strong offshore winds during the initial stages (*e.g.,* Figures 5a and b). The decrease in water levels associated with these winds can expose sediments which are normally submerged in the nearshore region. Strong onshore winds, which would be expected subsequent to the passage of the eye (*e.g.,* Figure 5c), cause the water to rush in and resubmerge the nearshore region, and a portion of the coastal area with water at depths of up to several meters above MLW. This storm surge ebbs slowly as the onshore winds subside. The rapid rise of the storm surge is accompanied by strong, turbulent currents (BALL *et al.,* 1967). PERLMUTTER's (1982) calculations indicated a hur-

[2] Steadiness is defined for some time period as the ratio of the magnitude of the mean wind vector to the average speed of the wind without regard to direction (HUSCHKE, 1959). Therefore, in a translating hurricane, steadiness is usually a minimum along the track of the circulation center.

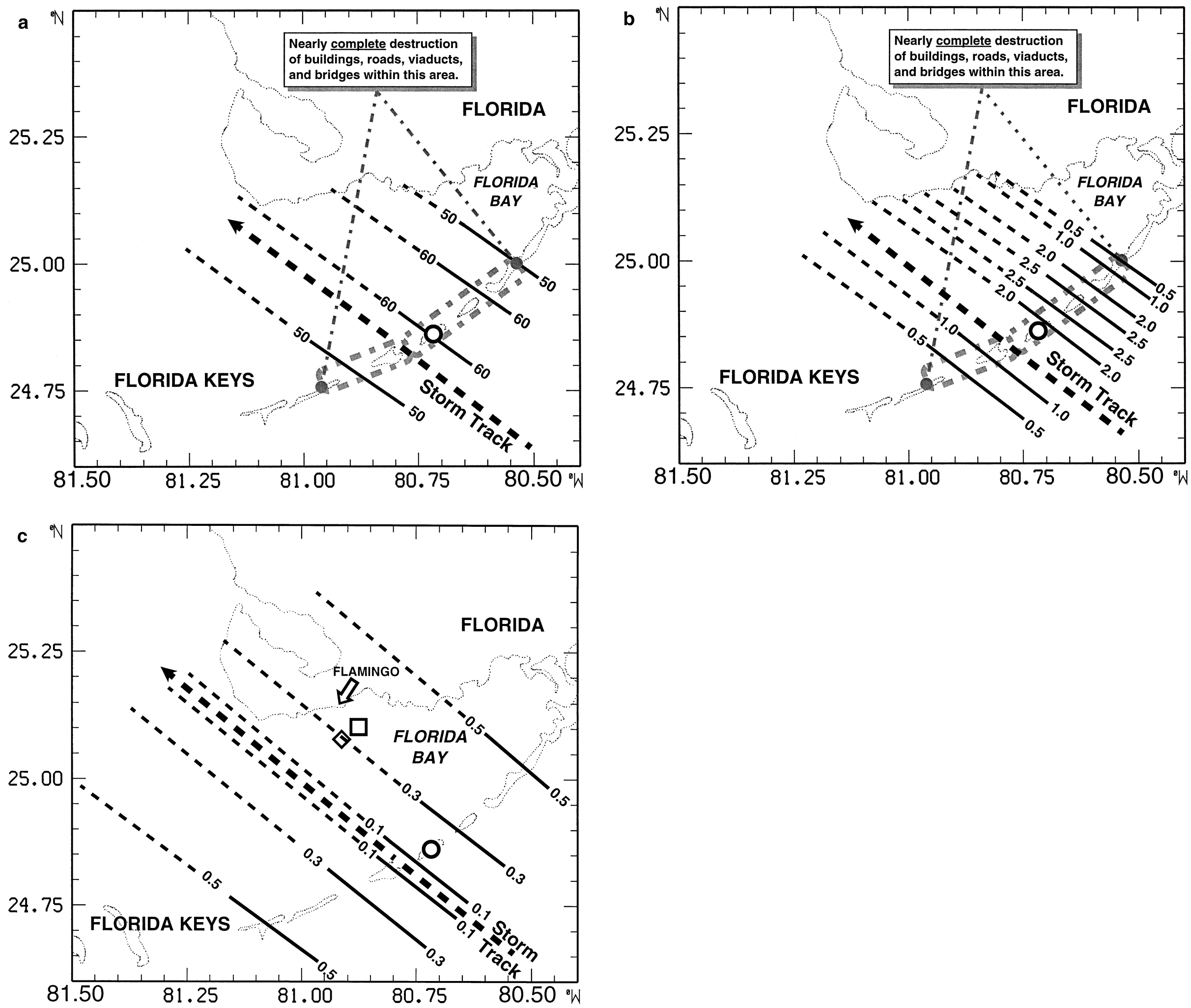

Figure 7. Swath of the 1935 Labor Day hurricane's a) 50 and 60 m s^{-1} V_{M10} and b) duration (h) of V_{M10} winds over 50 m s^{-1}, and c) steadiness (0.1, 0.3, and 0.5) across the Florida Keys (solid) and extrapolated across Florida Bay (dashed). The area of nearly complete destruction of manmade structures is shown as rectangular sections between the two gray filled circles. The location of the 11 car rescue train that was washed off of its tracks at Lower Matecumbe Key (shown as an open black circle). In c) the approximate locations of Clive and Palm Keys are represented by a diamond and a square, respectively.

ricane may produce seven times the suspended sediment load than might be experienced in a winter storm affecting southwest Florida. He found that the coarsest sediments were deposited in inlets opening into lagoons. In Florida Bay, lime mud deposits in lagoonal basins due to Donna were described by BALL *et al.* (1967). PERLMUTTER (1982) concluded that background processes and winter storms primarily rework existing sediment in southwest Florida and Florida Bay, but hurricanes are responsible for the introduction and removal of significant quantities of sediment.

For comparison purposes, the swath of maximum 1 min sustained winds for Hurricane Andrew from POWELL and HOUSTON's (1996) research is shown in Figure 10a. The wind swath is superimposed on some examples of damaged areas in the region. For example, SMITH *et al.* (1994) found the most severe damage to mangroves was on Elliott and Old Rhodes Keys and along the western shore of Biscayne Bay from Matheson Hammock to Mangrove Point. On the southwest coast of Florida, damaged mangroves were found from the Chatham River to the Shark River according to SMITH *et al.* (1994). They also found the remains of some mangrove tree trunks killed by Donna (Figure 9) during their surveys immediately after Andrew.

The approximate area of major damage to buildings and vegetation in the suburban areas of southeast Florida is also shown in Figure 10. An example of Andrew's impact on some of the "uplands" in the Florida Everglades was at Long Pine Key (LOOPE *et al.,* 1994) shown in Figure 10. Here the storm's wind downed nearly one-third of the trees in the pine forest. The trees that snapped did so at heights of 1–6 m and approximately 2–3 times as many were snapped as were uprooted. LOOPE *et al.* (1994) also noted that the wind appeared to have had little impact on the pineland understory at this location, since most of the leaves were undamaged on shrubs here.

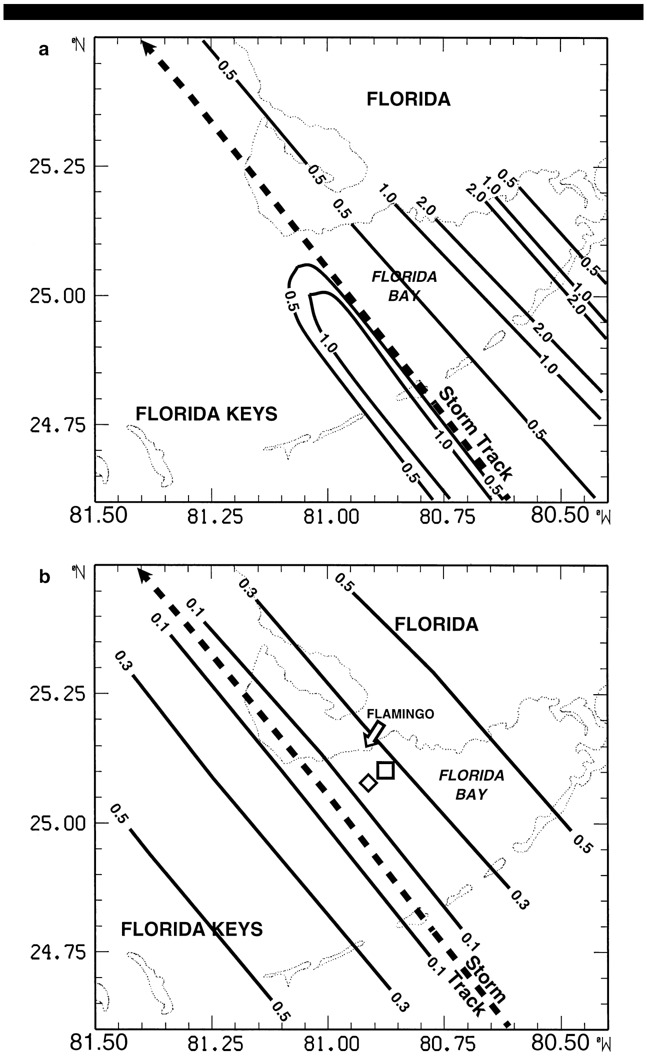

Figure 8. Swath of Hurricane Donna's a) duration (h) of V_{M10} winds over 50 m s^{-1} shown as contours and b) steadiness (0.1, 0.3, and 0.5) with the approximate locations of Clive and Palm Keys represented by a diamond and square, respectively.

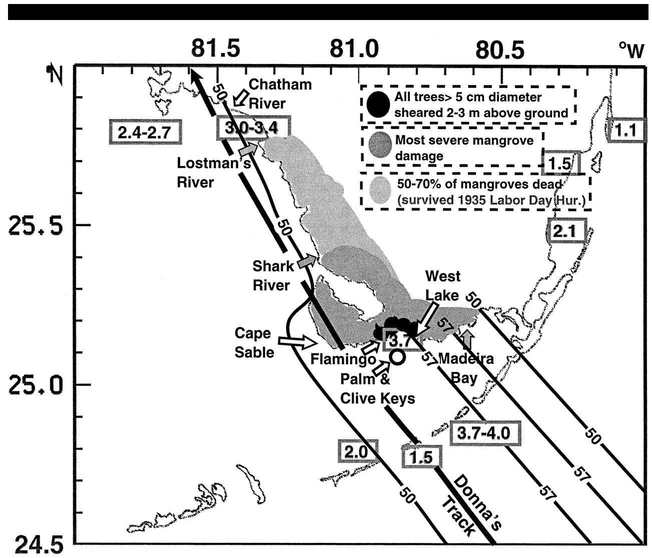

Figure 9. Swath of Hurricane Donna's 50 and 57 m s^{-1} V_{M10} drawn as contours and peak storm surge (m) shown in boxes. These values are superimposed on the environmental damage to the areas surrounding Florida Bay (CRAIGHEAD and GILBERT, 1962); areas of damaged vegetation are shaded.

These damaged areas were mostly within the 50 m s^{-1} region of the Andrew wind swath, but some were in the > 40 m s^{-1} winds, especially south of Andrew's track on the Florida west coast. During Andrew's transit across the area, strong onshore winds on the west coast enhanced storm surge flooding from the Gulf of Mexico.

The contours of steadiness for Andrew as it crossed south Florida are shown in Figure 10b. As was shown for the 1935 hurricane (Figure 7c) and in Donna (Figure 8b), the lowest values of steadiness were associated with most of the wind damage caused by Andrew. The area with values below 0.5 and 0.3 are coincident with damage to buildings on the urban east coast and mangroves on both coasts. It is evident from Figures 10a and b that Florida Bay was not exposed to the damaging eyewall core of Andrew as it passed north of the area. In fact, Andrew's wind field appears to be similar to the small, but intense 1935 Labor Day Hurricane in that both storms confined their damage streaks to relatively narrow areas under their respective eyewalls.

CONCLUSIONS

Surface wind (maximum 10 min sustained values valid for marine exposure or V_{M10}) fields were reconstructed for several hurricanes that affected Florida Bay. The wind fields and some impacts on the bay were shown for two of the most intense hurricanes to impact Florida Bay during the twentieth century: The Labor Day Hurricane of 1935 and Hurricane Donna of 1960. The structure and surface wind fields of each hurricane were very different. However, based on some of the evidence from damage to vegetation, these hurricanes produced similar swaths of damage. There were some instances however, where Donna destroyed trees which had survived the more intense 1935 hurricane (*e.g.,* on Clive and Palm Keys). This appears to be a function of the smaller size of the Labor Day Hurricane's core, in much the same way that the slightly less intense Hurricane Andrew destroyed vegetation in a very narrow band across the extreme south Florida peninsula and left the Florida Keys nearly unscathed. This variation in size of the hurricane's core region appears to be most important in differences in wind direction changes or steadiness between storms. Variations in the storm surges across the keys and the coastlines of northern Florida Bay may have also contributed to differences in the extent of damage here.

Hydrographic modeling of these two vastly different scenarios for Florida Bay might provide some very interesting results. For example, current and sediment transport models might be developed for near real-time impacts on the bay and surrounding areas for future tropical cyclone events in this region. These and other modeling efforts could be extremely useful for studies of where to focus post-storm recovery ob-

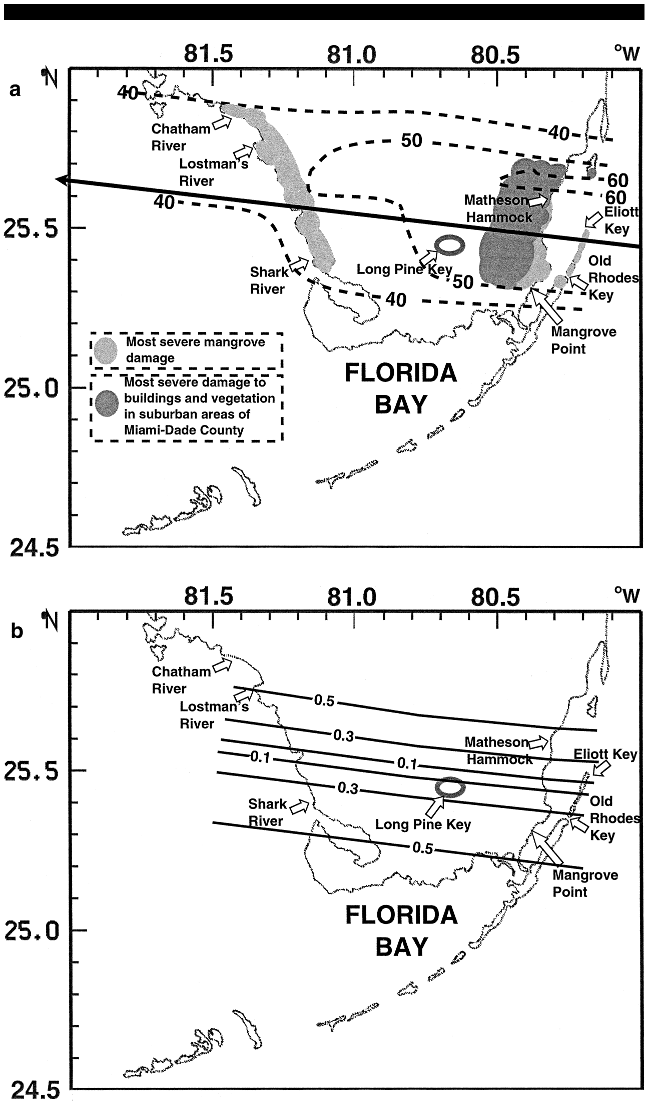

Figure 10. Swath of Hurricane Andrew's maximum 1-min sustained wind speeds (m s^{-1}) drawn as contours based on POWELL and HOUSTON (1996). Wind speeds over water are for marine exposure and those over water are for open terrain, over land exposure. These values are superimposed on some examples of damage to the environment and urban areas of south Florida. b) Swath of Hurricane Andrew's steadiness (0.1, 0.3, and 0.5). Note that in most cases, the damage to areas immediately adjacent to Florida Bay was not very severe.

servation efforts that might be launched as part of the restoration efforts currently being funded for Florida Bay.

Recently, VALIELA *et al.* (1998) described the recovery that had taken place in the natural system in New England after the landfall of Hurricane Bob (1991). They found that although this hurricane caused intense changes to the environment, the thorough hydrographic initial mixing largely disappeared within two days. Extreme effects on phytoplankton and macroalgae were no longer evident after a few days. However, some effects were observed over much longer timescales (from one to several years). One important difference they found in recovery times for terrestrial and aquatic components of the environment was in the observed recovery time. For aquatic systems, the recovery times were mostly hours to days, while recovery from disturbances to the terrestrial regions was from months to decades long. These differences in recovery time may also be important in regions such as Florida Bay where tropical cyclones may provide direct long-term benefits to the bay itself. However, the surrounding land areas might have longer recovery times, which could adversely affect the health of the bay for several years. For example, the availability of organic material and storm damaged flora and fauna entering the bay from the surrounding Florida Everglades or Keys may be enhanced.

Florida Bay tropical cyclone surface wind field images are now archived on HRD's Web site (www.aoml.noaa.gov/hrd). Work continues to make gridded surface wind fields available for import to models and geographical information systems (GIS) to be used in correlation studies with other geo-referenced fields, such as mangroves, reefs, and turbidity plumes.

ACKNOWLEDGMENTS

This work was partially funded by NOAA's Coastal Ocean Program. Many people were responsible for helping to gather the data that were used to generate the Hurricane Donna wind fields. These included P. Black, S. Murillo, J. Berkeley, J. Kaplan, and J. Dunion (HRD), and S. Fox (Coral Gables High School). P. Dodge (HRD) assisted with examining the radar data from Donna. B. Kohler, C. Baker, and L. Amat (HRD) assisted with the display and quality control of the data. G. Soukup (HRD) developed software to produce wind swaths. N. Dorst and S. Spisak (HRD) put these wind fields on HRD's web site. P. Vickery provided his code for the Shapiro model and the Vickery and Twisdale software. T. Ross of the National Climatic Data Center provided much of the wind data available for Florida during Hurricane Donna. T. Nelsen (OCD/AOML) assisted with the study of the effects on these hurricanes on natural habitats around Florida Bay. W. Drye provided additional historical documentation for the Labor Day Hurricane. L. Pikula, M. Bello, and R. Britter of the AOML and NHC libraries were particularly helpful in locating many of the historical documents in Miami and elsewhere that were required to study past hurricanes. Reviews of earlier drafts of this manuscript by C. Landsea, J. Kaplan, and J. Dunion of HRD were very helpful.

LITERATURE CITED

AVILA, L.A. and RAPPAPORT, E.N., 1996. Atlantic hurricane season of 1994. *Monthly Weather Review,* 124, 1558–1578.

BALL, M.M.; SHINN, E.A., and STOCKMAN, K.W., 1967. The geologic effects of Hurricane Donna. *Journal of Geology,* 75, 583–597.

CONOVER, L.F., 1962. Evaluation of eye fixes obtained by radar for Hurricane Donna. September 1960. Miami, Florida: National Hurricane Research Project Report No. 50, *Proceedings of the Second Technical Conference on Hurricanes,* 27–30 June 1961, Miami Beach, Florida, pp 85–100.

CRAIGHEAD, F.C. and GILBERT, V.C., 1962. The effects of Hurricane Donna on the vegetation of southern Florida. *Quarterly Journal of the Florida Academy of Sciences,* 25, 1–28.

CRAIGHEAD, F.C., SR., 1971. *The Trees of South Florida. Vol. 1 The Natural Environments and their Succession.* Coral Gables, Florida: University of Miami Press, 212p.

DUNN, G.E., 1961. The hurricane season of 1960. *Monthly Weather Review,* 89, 99–108.

FRANKLIN, J.L.; LORD, S.J.; FEUER, S.E., and MARKS, F.L., JR., 1993. The kinematic structure of Hurricane Gloria (1985) determined from nested analyses of dropwindsonde and Doppler data. *Monthly Weather Review,* 121, 2433–2451.

HEBERT, P.J.; JARRELL, J.D., and MAYFIELD, M., 1997. *The deadliest, costliest, and most intense United States hurricanes of this century (and other frequently requested hurricane facts).* Miami, Florida: Tropical Prediction Center, NOAA Technical Memorandum, NWS-TPC-1, 30p.

HO, F.P.; SU, J.C.; HANEVICH, K.L.; SMITH, R.J., and RICHARDS, F.P., 1987. *Hurricane climatology for the Atlantic and Gulf Coasts of the United States.* Silver Spring, Maryland: NOAA Technical Report, NWS-38, 195p.

HOUSTON, S.H.; SHAFFER, W.A.; POWELL, M.D., and CHEN, J., 1999. Comparisons of HRD and SLOSH surface wind fields in hurricanes: Implications for storm surge modeling. *Weather and Forecasting,* 14, 671–686.

HUSCHKE, R.E., 1959. *Glossary of Meteorology.* Boston, Massachusetts: American Meteorological Society, 638p.

JARRELL, J.D.; HEBERT, P.J., and MAYFIELD, M., 1992. *Hurricane experience levels of coastal county populations from Texas to Maine.* Miami, Florida: Tropical Prediction Center, NOAA Technical Memorandum, NWS-NHC-46, 152p.

JARVINEN, B.R.; NEUMANN, C.J., and DAVIS, M.A.S., 1988. *A tropical cyclone data tape for the North Atlantic Basin, 1886–1983: Contents, limitations, and uses.* Miami, Florida: Tropical Prediction Center, NOAA Technical Memorandum, NWS-NHC-22, 21p.

LOOPE, L.; DUEVER, M.; HERNDON, A.; SNYDER, J., and JANSEN, D., 1994. Hurricane impact on uplands and freshwater swamp forest. *Bioscience,* 44, 238–246.

MAYFIELD, M.; AVILA, L.A., and RAPPAPORT, E.N., 1994. Atlantic hurricane season of 1992. *Monthly Weather Review,* 122, 517–538.

MCDONALD, W.F., 1935a. The hurricane of August 31 to September 6, 1935. *Monthly Weather Review,* 63, 269–271.

MCDONALD, W.F., 1935b. Lowest barometer reading in the Florida Keys storm of September 2, 1935. *Monthly Weather Review,* 63, 295.

MILLER, B.I., 1963. *On the filling of tropical cyclones over land.* Miami, Florida: National Hurricane Research Project Report No. 66, 82p.

MILLER, B.I., 1964. A study of the filling of Hurricane Donna (1960) over land. *Monthly Weather Review,* 92, 389–406.

NELSEN, T.A.; WANLESS, H.; TREFRY, J.; ALVAREZ-ZAIKIAN, C.; HOOD, T.; BLECKWELDER, P.; SWART, P.; TEDESCO, L.; KANG, W.-J.; METZ, S.; GARTE, G.; FEATHERSTONE, C.; SOUCH, C.; PACHUT, J.F.; O'NEAL, M., and ELLIS, G., 2000. Linkages between the South Florida peninsula and coastal zone: A sediment-based history of natural and anthropogenic influences. Invited chapter in: *Linkages Between Ecosystems in the South Florida Hydroscape: The River of Grass Continues. In:* PORTER, K. and PORTER, J. (Eds.), Boca Raton, Florida: CRC Press, pp. 415–449.

OOYAMA, K.V., 1987. Scale controlled objective analysis. *Monthly Weather Review,* 115, 2479–2506.

PERLMUTTER, M.A., 1982. The recognition of storm sedimentation in the nearshore, southwest Florida. PhD. Dissertation, Coral Cables, Florida: University of Miami, 223p.

POWELL, M.D.; HOUSTON, S.H., and ARES, I., 1995. Real-time damage assessment in hurricanes. *AMS 21st Conference on Hurricanes and Tropical Meteorology,* Miami, Florida, April 24–28, 1995, pp. 500–502.

POWELL, M.D.; HOUSTON, S.H., and REINHOLD, T.A., 1996. Hurricane Andrew's landfall in south Florida. Part I: Standardizing measurements for documentation of surface wind fields. *Weather and Forecasting,* 11, 304–328.

POWELL, M.D. and HOUSTON, S.H., 1996. Hurricane Andrew's landfall in south Florida. Part II: Surface wind fields and potential real-time applications. *Weather and Forecasting,* 11, 329–349.

POWELL, M.D. and HOUSTON, S.H., 1998. Surface wind fields of 1995 Hurricanes Erin, Opal, Luis, Marilyn, and Roxanne at landfall. *Monthly Weather Review,* 126, 1259–1273.

SAFFIR, H. and SIMPSON, R., 1974. The hurricane disaster potential scale. *Weatherwise,* 27, 169, 186.

SENN, H.V. and HISER, H.W., 1962. Effectiveness of various radars in tracking hurricanes. Miami, Florida: National Hurricane Research Project Report No. 50, *Proceedings of the Second Technical Conference on Hurricanes,* 27–30 June 1961, Miami Beach, Florida, pp 101–114.

SHAPIRO, L.J., 1983. The asymmetric boundary layer flow under a translating hurricane. *Journal of Atmospheric Science,* 40, 1984–1998.

SMITH, T.J., III; ROBBLEE, M.B.; WANLESS, H.R., and DOYLE, T.W., 1994. Mangroves, hurricanes, and lightening strikes. *Bioscience,* 44, 256–262.

SUGG, A.L., 1966. The hurricane season of 1965. *Monthly Weather Review,* 94, 183–191.

SWART, P.K.; HEALY, G.; DODGE, R.E.; KRAMER, P.; HUDSON, J.; HALLEY, R., and ROBBLEE, M., 1996. The stable oxygen and carbon isotopic record from a coral growing in Florida Bay: A 160 year record of climatic and anthropogenic influence. *Palaeo,* 123–219.

U.S. HOUSE OF REPRESENTATIVES, 1936. *Florida Hurricane Disaster. Hearings: Committee on World War Veteran's Legislation.* Washington, District of Columbia: H.R. 9486, The 75th Congress, 2nd Session. 592p.

VALIELA, I.; PECKOL, P.; D'AVANZO, C.; KREMER, J.; HERSH, D.; FOREMAN, K.; LAJTHA, K.; SEELY, B.; GEYER, W.R.; ISAJI, T., and CRAWFORD, R., 1998. Ecological effects of major storms on coastal watersheds and coastal waters: Hurricane Bob on Cape Cod. *Journal of Coastal Research,* 14, 218–238.

VICKERY, P.J. and TWISDALE, L.A., 1995. Wind field and filling models for hurricane wind speed predictions. *Journal of Structural Engineering,* American Society of Civil Engineering, 121, 1700–1709.