Hurricane *Andrew*

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During the pre-dawn hours of 24 August 1992, Hurricane *Andrew* slammed into the south-east coast of Florida with maximum sustained winds near 125 kn, gusts measured in excess of 150 kn and a storm surge of about 4.5 m. In a period of less than four hours *Andrew* became the most expensive natural disaster in US history. The cost of the damage in southern Dade County, Florida, alone, could surpass US$25 billion. The force of the hurricane also killed 15 people in Florida, 8 in Louisiana and 3 in the Bahamas. At least 39 more lives were lost from the indirect effects of *Andrew* and about 250000 people were left temporarily homeless. The recovery process will take years to complete.

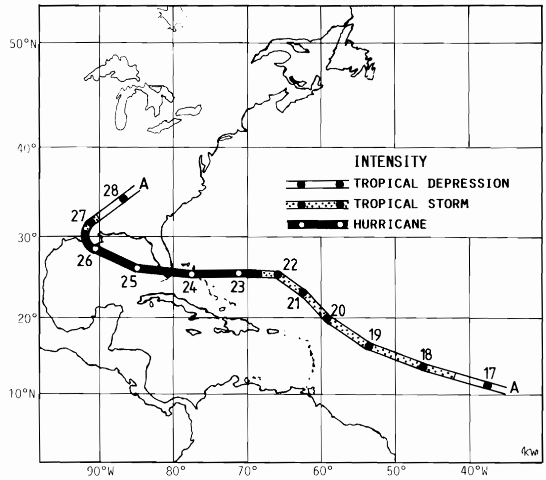

Fig. 1 Andrew'*s track from 17 to 28 August 1992. Dates placed alongside indicate 0000 GMT position of tropical cyclone centre.*

Andrew's evolution

Formation

Satellite pictures and rawinsonde data indicate that *Andrew* developed from one of about 60 tropical waves that move westward at low latitudes across the North Atlantic Ocean each hurricane season (1 June to 30 November). Whereas clusters of showers and squalls often accompany tropical waves, only about one in five waves undergoes the transformation to tropical depression, wherein a low-level, closed cyclonic circulation develops in association with the deep convection. Analysis of satellite images using the Dvorak (1984) technique suggests that *Andrew* reached that stage of development about 3000 km to the east of the Lesser Antilles Islands on 16 August.

The depression formed in an environment of easterly vertical wind shear. Nevertheless, narrow, spiral-shaped bands of deep convection strengthened near the circulation centre on 17 August. On that date, the National Hurricane Center (NHC) of the US National Oceanic and Atmospheric Administration (NOAA) upgraded the system to Tropical Storm *Andrew* when estimated sustained surface winds (1-minute average at 10 m elevation) reached 34 kn.

Crossroads

Andrew nearly failed to reach hurricane strength. Between the 17th and 19th, the flow around the south-western periphery of a high pressure area centred over the eastern North Atlantic steered the tropical storm westward and then north-westward (Fig. 1). The turn toward the north-west spared the Lesser Antilles and carried *Andrew* to the vicinity of a strong upper-level low pressure system centred about 800 km to the east-south-east of Bermuda and to a trough that extended southward from the low for several hundred kilometres. These features created an environment of strong south-westerly vertical wind shear which stripped away deep convection from *Andrew*'s low-level circulation. *Andrew's* central pressure rose to an unusually high value for a tropical cyclone, 1015 mbar (Fig. 2).

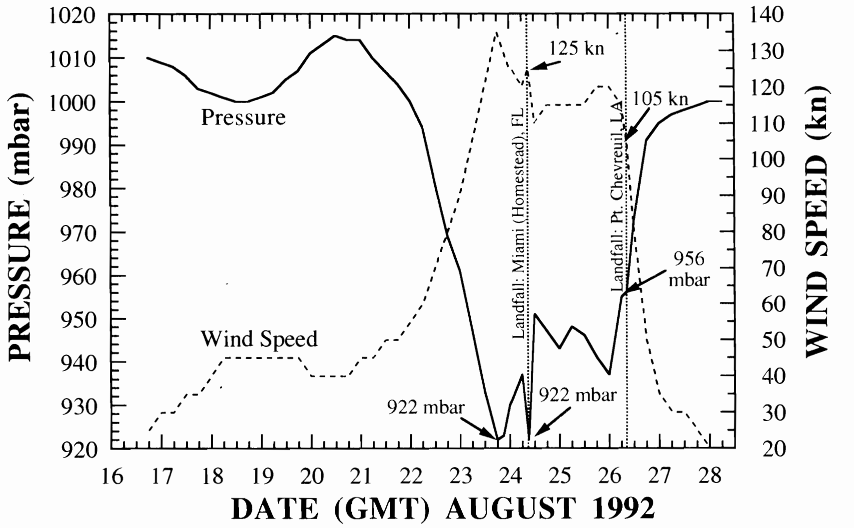

Fig. 2 Andrew*'s minimum central pressure and maximum sustained wind speed. Dates labelled at 0000* GMT.

A reconnaissance aircraft from the US Air Force Reserves investigated *Andrew* on the 20th and found that, although 70kn winds persisted at an altitude of 0.5km, the cyclone had degenerated to the extent that only a diffuse circulation centre remained at low levels. Furthermore, some computer simulations then suggested that, even if the tropical cyclone survived, forecast steering currents might carry *Andrew* northward into the open waters of the central North Atlantic.

Significant changes in the large-scale environment near and downstream from *Andrew* began by 21 August. Animation of satellite images in a water vapour channel showed that the low aloft to the east-south-east of Bermuda weakened and split. The bulk of the low opened into a trough which retreated northward. That evolution decreased the vertical wind shear over *Andrew.* The remainder of the low dropped southward to a position just south-west of *Andrew* where its circulation enhanced the upper-level outflow over the tropical storm.

At the same time, a strong and deep high pressure cell formed near the US south-east coast. A ridge built eastward from the high into the south-western North Atlantic. The axis of the ridge lay just north of *Andrew.* The associated steering flow over the tropical storm became easterly. *Andrew* turned toward the west, accelerated to near 16kn, and intensified into a small and powerful tropical cyclone.

Rapid intensification

Andrew reached hurricane strength on 22 August. An eye formed that morning and the rate of strengthening became rapid (Holliday and Thompson 1979). From 0000 GMT on the 21st (when *Andrew* had a barely perceptible low-level centre) to 1800 GMT on the 23rd the central pressure fell 92mbar, down to 922mbar. In fact, in a period of just 36 hours, *Andrew* had intensified from a tropical storm to the threshold of a Category 5 hurricane on the Saffir/Simpson Hurricane Scale (SSHS; see Table 1).

About noon on 23 August, a reconnaissance aircraft at an altitude of about 2.5km encountered 170kn winds in *Andrew*'s eyewall. *Andrew* then had estimated sustained surface winds near 135kn and was centred about 100km east of the north-west Bahamas.

Landfall in the Bahamas and Florida

Andrew came ashore in the north-west Bahamas and then south-east Florida (Fig. 3, see front cover) on the night of 23/24 August

Table 1 The Saffir/Simpson Hurricane Scale

Category 1
Winds 64 to 82 kn. Damage primarily to shrubbery, trees, poorly constructed signs, and unanchored mobile homes. No significant damage to other structures.

Storm surge 1 to 1.5 m above normal tide. Low-lying coastal roads inundated, minor pier damage, some small craft in exposed anchorages torn from moorings.

Category 2
Winds 83 to 95 kn. Considerable damage to shrubbery and tree foliage; some trees blown down. Extensive damage to poorly constructed signs. Major damage to exposed mobile homes. Some damage to roofing materials of buildings; some wind and door damage. No major damage to buildings.

Storm surge 2 to 2.5 m above normal tide. Coastal roads and low-lying escape routes made impassable by rising water 2 to 4 hours before arrival of hurricane centre. Considerable damage to piers. Marinas flooded. Small craft in unprotected anchorages torn from moorings. Evacuation of some shoreline residences and low-lying island areas required.

Category 3
Winds 96 to 113 kn. Foliage torn from trees; large trees blown down. Practically all poorly constructed signs blown down. Some damage to roofing materials of buildings; some window and door damage. Some structural damage to small buildings. Mobile homes destroyed.

Storm surge 2.5 to 3.5 m above normal tide. Serious flooding at coast and many small structures near coast destroyed; large structures near coast damaged by battering waves and floating debris. Low-lying escape routes made impassable by rising water 3 to 5 hours before hurricane centre arrives. Flat terrain 1.5 m or less above sea-level flooded inland 13 km or more. Evacuation of low-lying residences within several blocks of shoreline possibly required.

Category 4
Winds 114 to 135 kn. Shrubs and trees blown down; all signs down. Extensive damage to roofing materials, windows and doors. Complete failure of roofs on many small residences. Complete destruction of mobile homes.

Storm surge 4 to 5.5 m above normal tide. Flat terrain 3 m or less above sea-level flooded inland as far as 11 km. Major damage to lower floors of structures near shore due to flooding and battering by waves and floating debris. Low-lying escape routes made impassable by rising waters 3 to 5 hours before hurricane centre arrives. Major erosion of beaches. Massive evacuation of all residences within 500 m of shore possibly required, and of single-storey residences on low ground within 3 km of shore.

Category 5
Winds greater than 135 kn. Shrubs and trees blown down; considerable damage to roofs of buildings; all signs down. Very severe and extensive damage to windows and doors with extensive shattering of glass components. Complete failure of roofs on many residences and industrial buildings. Some complete building failures. Small buildings overturned or blown away. Complete destruction of mobile homes.

Storm surge greater than 5.5 m above normal tide. Major damage to lower floors of all structures less than 4.5 m above sea-level within 500 m of shore. Low-lying escape routes made impassable by rising water 3 to 5 hours before hurricane center arrives. Massive evacuation of residential areas on low ground within 8 to 16 km of shore possibly required.

accompanied by a 50 km wide zone of destructive winds and, near the coastline, decimating storm surges characteristic of a Category 4 hurricane on the SSHS. In the Bahamas, the wind speed indicator on the Harbour Island anemometer reached the top end of the scale, 120 kn, and then stuck there, malfunctioning. A combination of waves and storm surge reached 7 m at the town of The Current.

In Florida, wind gusts exceeded 150 kn (details below). The 5 m storm tide (sum of the storm surge and astronomical tide) that headed inland from Biscayne Bay is a record maximum for the south-east part of the Florida peninsula (Fig. 4).

Andrew moved nearly due west when over land and crossed the extreme southern portion of the Florida peninsula in about four hours. The hurricane weakened about one category on the SSHS during its transit over land.

Final landfall

The track of the hurricane gradually turned

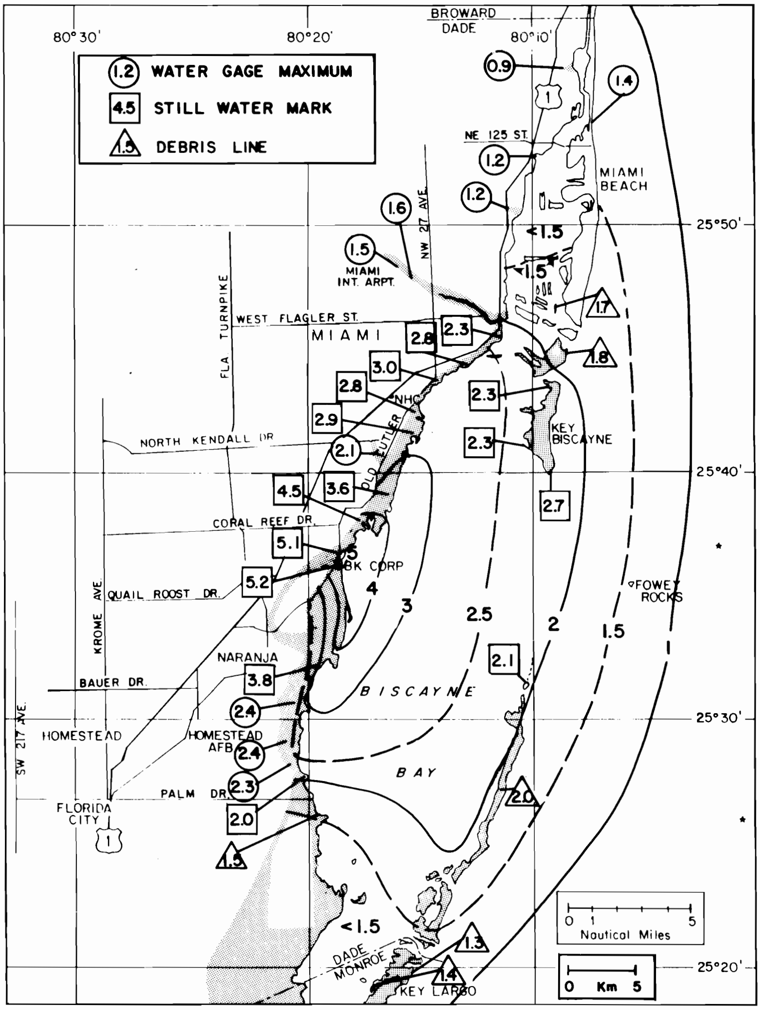

Fig. 4 Analysis and representative observations of the maximum storm tide during Hurricane Andrew*'s landfall in Florida, labelled in metres above 1929 mean sea-level. Shading indicates inland inundation.*

toward the west-north-west and *Andrew* underwent the first of two cycles of modest strengthening when the cyclone reached the Gulf of Mexico. The high pressure system to the north-east of the hurricane then weakened and a strong mid-latitude trough approached the area from the north-west. The associated steering currents weakened temporarily. *Andrew* turned toward the north and its forward speed decreased to about 10 kn.

The hurricane struck a sparsely populated section of the south-central Louisiana coast on the morning of 26 August with sustained winds near 105 kn and a central pressure of about 956 mbar. *Andrew* weakened rapidly after landfall, to tropical storm strength in about 10 hours and to tropical depression status 12 hours later. During this weakening phase, the cyclone moved northward and then accelerated north-eastward. By midday on the 28th, *Andrew* had begun to merge with a frontal system over the US mid-Atlantic states.

Andrew, and later its remnants, produced isolated severe weather over a large part of the south-eastern USA. Tornadoes occurred in several states and killed two people in Louisiana. The cyclone also dropped enough rain to cause local floods. Hammond,

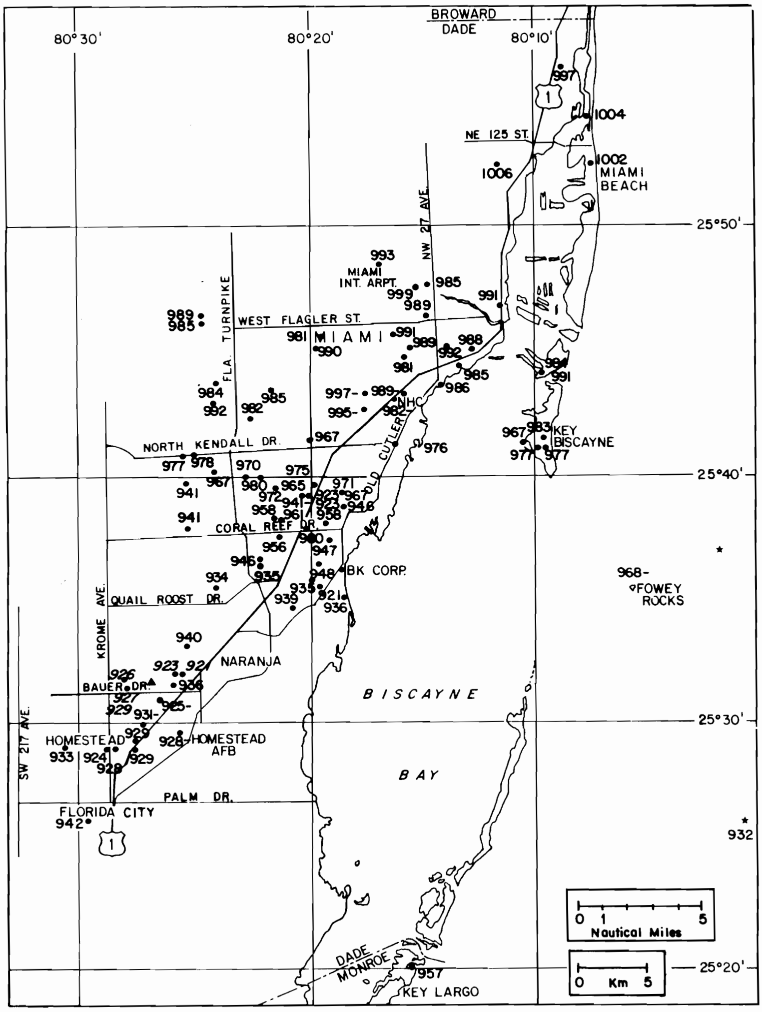

Fig. 5(a) Minimum pressure observations (mbar) during Hurricane Andrew*'s landfall in Florida. Minus signs indicate that a lower pressure may have occurred. The five italicised labels (near Bauer Dr.) show readings recalibrated and considered reliable in pressure-chamber tests. Nearby small triangle denotes approximate position of warmest spot (darkest area) within* Andrew*'s eye seen in Fig. 7. Offshore reading of 932 mbar reported from reconnaissance aircraft on its final pass through* Andrew *before landfall over Florida.*

Louisiana, reported the largest rainfall, 303 mm.

***Andrew*'s intensity at landfall in Florida**

Neither of the two conventional measures of hurricane intensity, central barometric pressure and maximum sustained wind speed, were observed at official surface weather stations in close proximity to *Andrew* at landfall. Homestead Air Force Base and Tamiami Airport discontinued routine meteorological observations prior to receiving direct hits from the hurricane. Miami International Airport was the next closest station, but it was outside of the eyewall by about 10 km when *Andrew*'s centre passed to the south of that airport.

To supplement the official information, requests for data were made to the public through the local media. Remarkably, more than 100 quantitative observations have been received so far (see Figs. 5(a) and 6). Many of

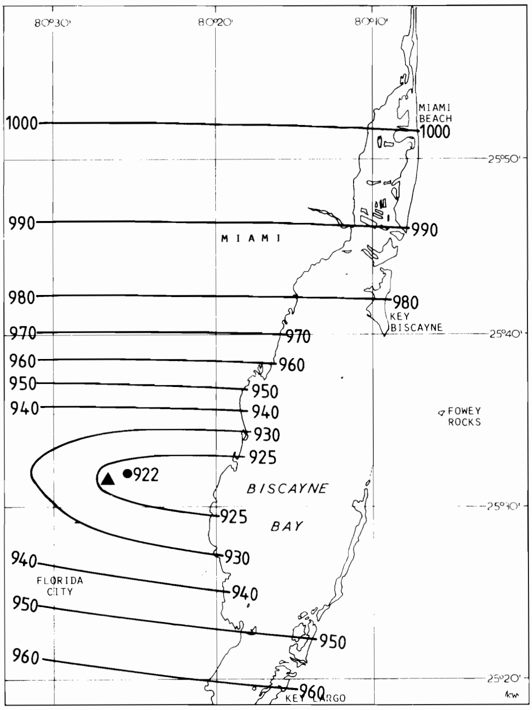

Fig. 5(b) Smoothed analysis of minimum pressure observations (mbar) shown in Fig. 5(a). Small dot indicates neighbourhood of lowest analysed pressure (922 mbar). Nearby small triangle denotes approximate position of warmest spot (darkest area) within Hurricane Andrew*'s eye seen in Fig. 7.*

the reports came from observers who vigilantly took readings through frightening conditions including, in several instances, the moment when their instruments and even their homes were destroyed.

Some of the unofficial observations were dismissed as unrealistic. Others were rendered suspect or eliminated during follow-up inquiries or analyses. The remainder, however, revealed a physically consistent and reasonable pattern. They also provided a few surprises.

Barometric pressure

Andrew weakened when it passed over the western portion of the Great Bahama Bank and, based on reconnaissance aircraft reports, its central pressure was 941 mbar at 0410 GMT on the 24th. The hurricane rapidly reintensified, however, when it moved westward over the Straits of Florida. Radar, aircraft and satellite data showed a decreasing eye diameter and strengthening eyewall convection. At 0546 GMT, the pressure was down to 936 mbar.

The final offshore 'fix' by the reconnaissance aircraft came at 0804 GMT and placed the centre of the hurricane only 30 km, or about one hour of travel time, from the mainland. A dropsonde indicated a pressure of 932 mbar at that time. The pressure had been falling at the rate of about 2 mbar per hour, but the increasing interaction with land was expected to at least partially offset, if not reverse, that trend. Hence, a landfall pressure within a couple of millibars of 932 mbar seemed reasonable.

The public observations indicate otherwise (Fig. 5(a)). Shortly after *Andrew*'s passage, reports of minimum pressures slightly below 930 mbar were received from the vicinity of Homestead, Florida. Several of the barometers displaying the lowest pressures were subsequently tested in a pressure chamber and calibrated by the Aircraft Operations Center (AOC) of NOAA. The lowest accepted pressure in these AOC tests came from an instrument that also proved to be the most reliable, a spare barometer from Homestead Air Force Base that was in the custody of an off-base observer during the hurricane. A corrected reading of 926 mbar from that instrument became an initial (and conservative) estimate of the minimum pressure at landfall.

The NHC received two additional important observations about one month later. The reports came from a Mrs Hall and Mr Martens, sister and brother. They rode out the storm in residences about 0.5 km apart and located about 4 km due east of the 926 mbar observation (see Fig. 5(a)). Mrs Hall's home was built by her father and grandfather in 1945 to be hurricane-proof. Although some of the windows broke, the 56 cm thick concrete and coral rock walls held steady, allowing her to observe her barometer in relative safety. Her barometer performed well in AOC tests and was adjusted to 921 mbar. The barometer at her brother's home was judged a little more reliable and the corrected reading there was 923 mbar. A minimum pressure of 922 mbar has been assigned to Mrs Hall's and Mr Martens' neighbourhood (Fig. 5(b)).

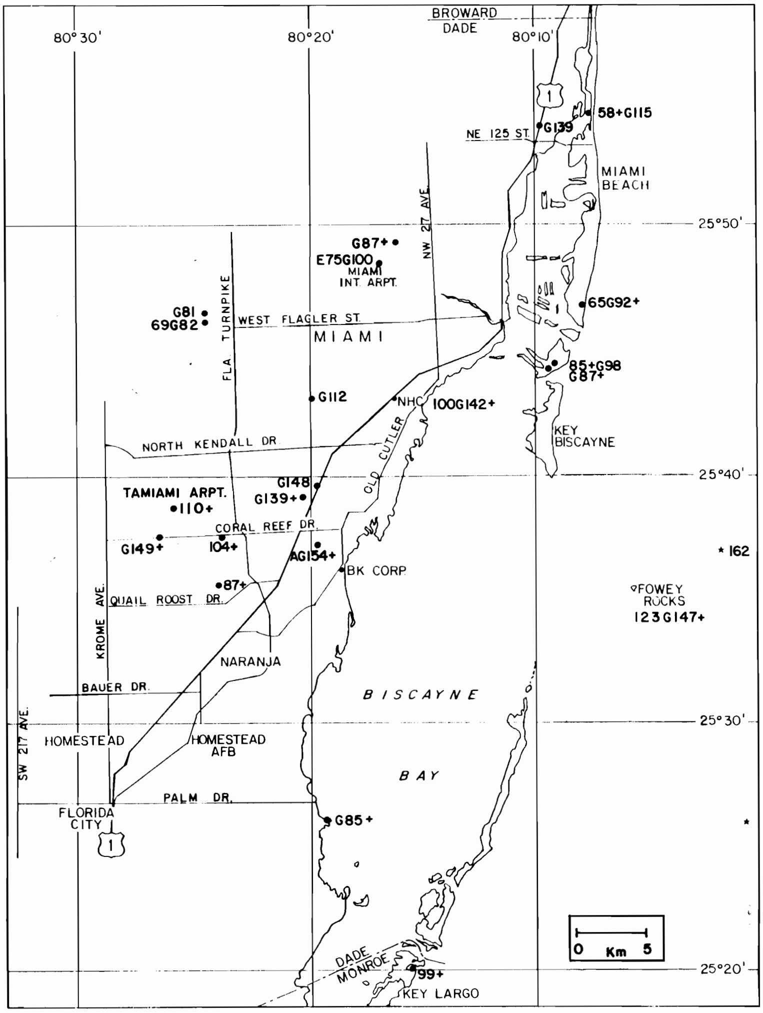

Fig. 6 Sustained wind speeds and gusts (G) in knots observed over south-east Florida in association with Hurricane Andrew. *Offshore reading of 162 kn occurred aboard reconnaissance aircraft. Plus signs follow observations taken where higher speeds may have occurred; 'E' indicates estimate; 'A' indicates reading adjusted to 154 kn (from 184 kn reported by observer).*

Mr Martens noted that the minimum pressure at his residence was approximately maintained for a 15-minute period ending near 0915 GMT. It is interesting that an analysis of an infra-red satellite picture for 0922 GMT (Fig. 7) shows that the location of the warmest pixels within *Andrew*'s eye (another potential indicator of the location of the lowest surface pressure) coincides almost exactly with the site of Mr Martens' home if a short (*i.e.* about 10-minute) time-to-space conversion using the hurricane's motion is applied. Based on these observations and an eastward extrapolation of the pressure pattern to the coastline, *Andrew*'s minimum pressure at landfall is currently estimated to be 922 mbar.

Curiously, Mr Martens' home and the warm spot on the satellite picture are located about 5 km to the north of where observers placed the longest period of calm surface wind. (The winds never dropped to calm at either Mrs Hall's or Mr Martens' residences, or further west at the site of the 926 mbar reading.) This spot is also to the north of the track of the geometric centre

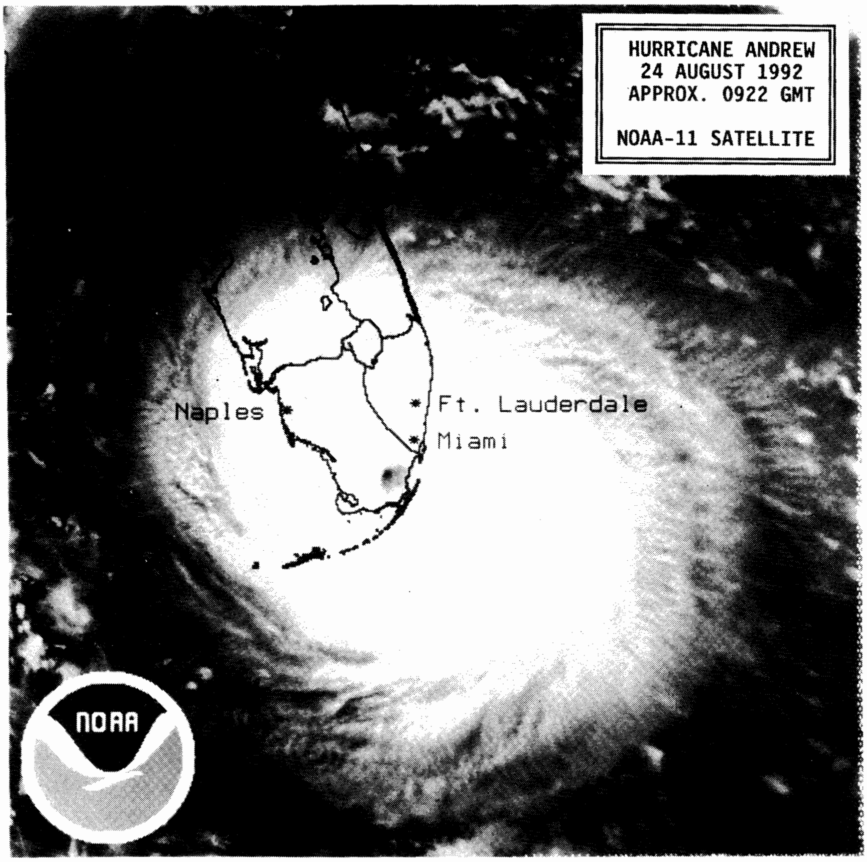

Fig. 7 Infra-red satellite picture of Hurricane Andrew *taken by the NOAA-11 polar-orbiting satellite at about 0922 GMT on 24 August 1992*

of the eye seen on radar reflectivity displays (see Fig. 3). One hypothesis that reconciles these observations was put forward by Dr Peter Black of the NOAA Hurricane Research Division (HRD). He suggests that a small, transitory, dynamically imbalanced perturbation was orbiting about the eye and that it was centred near the inside edge of the northern eyewall at the time of landfall. Similar features have occasionally been observed in other intense hurricanes, including Hurricane *Hugo* in 1989 (Black and Marks 1991). This hypothesis might also explain why the estimated landfall pressure was fully 10 mbar lower than the pressure reported on the final aircraft fix only an hour earlier. It is possible that the trajectory of the dropsonde did not intersect an embedded disturbance.

Other processes could have contributed to *Andrew*'s deepening. For example, increased low-level convergence related to enhanced friction at landfall can lead to stronger convection and associated pressure falls (*e.g.* Powell 1982; Parrish *et al.* 1982; Tuleya *et al.* 1984; Jones 1987), perhaps even briefly over land (Tuleya and Kurihara 1978).

In any case, in the USA this century only the Labor Day (Keys') Storm in 1935 (892mbar) and Hurricane *Camille* in 1969 (909mbar) had lower landfall central pressures than *Andrew* (Hebert *et al.* 1992).

Wind speed

The strongest winds associated with *Andrew* on 24 August probably occurred in the hurricane's northern eyewall. The relatively limited number of observations in that area greatly complicates the task of establishing *Andrew*'s maximum sustained wind speed and peak gust at landfall in Florida. Whilst a universally accepted value for *Andrew*'s wind speed at landfall may prove elusive, there is considerable evidence at this juncture to support an estimate of about 125 kn for the maximum sustained wind speed, with gusts to at least 150 kn (Fig. 6).

The strongest reported sustained wind near the surface occurred at the Fowey Rocks weather station at 0800 GMT (Fig. 6). The station sits about 20 km east of the shoreline and, at that time, was within the north-west part of *Andrew*'s eyewall. The 0800 GMT data included a 2-minute wind of 123 kn with a gust to 147 kn at a platform height of 39 m. The US National Data Buoy Center used a boundary-layer model to convert the sustained wind to a 2-minute wind of 108 kn at 10 m elevation. The peak 1-minute wind during that 2-minute period at Fowey Rocks might have been slightly higher than 108 kn.

It is unlikely that this point observation was so fortuitously situated that it represents a sampling of the absolute strongest wind. The Fowey Rocks log (not shown) indicates that the wind speed increased until 0800 GMT. Unfortunately, Fowey Rocks then ceased transmitting data, presumably because even stronger winds disabled the instrumentation. (A subsequent visual inspection indicated that the mast supporting the anemometer had become bent 90 degrees from vertical.) Radar reflectivity data suggest that the most intense portion of *Andrew*'s eyewall had not reached Fowey Rocks by 0800 GMT and that the wind speed could have continued to increase there for another 15 to 30 minutes. A similar conclusion can be reached from the pressure panels in Fig. 5 which indicate that the pressure at Fowey Rocks probably fell by about another 20 mbar from the 0800 GMT mark of 968 mbar.

Reconnaissance aircraft provided wind data at a flight level of about 2.5 km. The maximum wind speed along 10 seconds of flight track (often used by the NHC to represent a 1-minute wind speed at flight level) on the last pass prior to landfall was 162 kn, with an instantaneous speed of 170 kn observed. The 162 kn wind occurred at 0810 GMT in the eyewall region 20 km to the north of the centre of the eye. Like the observation from Fowey Rocks, the aircraft provided a series of 'point' observations (*i.e.* no lateral sampling). Almost certainly, somewhat higher wind speeds occurred elsewhere in the northern eyewall, a little to the left and/or to the right of the flight track. A wind speed at 2.5 km is usually reduced to obtain a surface wind estimate. Based on past operational procedures, the 162 kn flight-level wind is compatible with a 125 kn estimate of the sustained surface winds.

One of the most important wind speed reports came from Tamiami Airport, located about 15 km west of the shoreline. As mentioned earlier, routine weather observations ended at the airport before the full force of *Andrew*'s (northern) eyewall winds arrived. However, the official weather observer there, Mr Scott Morrison, remained on-station and continued to watch the wind speed dial. Mr Morrison notes that the wind speed indicator 'pegged' at a position a little beyond the dial's highest marking of 100 kn, at a point that he estimates corresponds to about 110 kn. He recounts that the needle was essentially fixed at that spot for three to five minutes, and then fell back to 0 when the anemometer failed. Mr Morrison's observations have been closely corroborated by two other people. He has also noted that the weather conditions deteriorated even further after that time and were at their worst about 30 minutes later. This information suggests that, in all likelihood, the maximum sustained wind speed at Tamiami Airport significantly exceeded 110 kn.

A number of the wind speeds reported by the public could not be substantiated and are excluded from Fig. 6. The reliability of some of the others suffers from problems that include non-standard averaging periods and instrument exposures, and equipment failures prior to the arrival of the strongest winds. Nevertheless, the wind observations discussed below appear credible at this time.

The highest observed sustained wind in the southern eyewall came from an anemometer on the mast of an anchored sailboat (see Fig. 6). For at least 13 minutes the anemometer there showed 99 kn, which was the maximum that the read-out could display. A small downward adjustment of the speed should probably be applied because the instrument was at 17 m above the surface rather than at the standard height of 10 m. On the other hand, the highest 1-minute wind during that 13-minute period could have been quite a bit stronger than 99 kn. Again, there may have been stronger winds elsewhere in the southern eyewall. Bear in mind that (to a first approximation for a westward-moving hurricane) the wind in the northern eyewall usually exceeds the wind in the southern eyewall by about twice the forward speed of the hurricane (Dunn and Miller 1964). In the case of *Andrew*, that difference is about 32 kn and suggests a maximum sustained wind a little stronger than 130 kn.

A similar wind speed report was received from a US Army communications centre located about 5 km to the south-east of Tamiami Airport, in an area that experienced the northern eyewall. The anemometer at the centre was at a height of 15–20 m and registered its maximum displayable speed, 104 kn, before the instrument failed (Fig. 6).

Several indirect measurements of the sustained wind speed are of interest. First, a standard empirical relationship between central pressure and wind speed (Kraft 1961) applied to 922 mbar yields around 135 kn. Second, the Dvorak technique classification performed by the NHC Tropical Satellite Analysis and Forecast Unit using an 0900 GMT satellite image gives 127 kn. Also, an analysis of the pressure pattern in Fig. 5(b) gives a maximum gradient wind of around 125 kn.

The strongest credible wind gust reported from near the surface occurred in the northern eyewall about 3 km inland at the home of Mr Randy Fairbank. He observed a gust of 184 kn only moments before a wall of his home collapsed, preventing further observation. The hurricane also destroyed the anemometer. To evaluate the accuracy of the instrument, three anemometers of the type used by Mr Fairbank were tested in a wind-tunnel at Virginia Polytechnic Institute and State University (VPI). Although the turbulent nature of the hurricane winds could not be replicated, the results of the wind-tunnel tests suggest that the gust Mr Fairbank observed was less than 184 kn and probably near 154 kn. Of course, stronger gusts may have occurred there at a later time, or at another site.

Strong winds also occurred outside of the eyewall, especially in association with convective bands (see Fig. 3). A peak gust of 139 kn was observed at a home near the northern end of Dade County (Fig. 6) on an anemometer of the type used by Mr Fairbank. Applying the reduction suggested by the wind-tunnel tests to 139 kn yields an estimate of 116 kn. This is similar to the 115 kn peak gust (a 5-second average) registered on a National Ocean Survey anemometer located not far to the east, at the coast.

Another strong gust (142 kn) was registered by an anemometer on top of the 12-storey building housing the NHC and the Miami National Weather Service Forecast Office. The gust occurred shortly before the anemometer failed and about the time that the National Weather Service radome was blown off the roof. The wind speed at the 10 m level there is not known and was probably affected by the building itself. Nevertheless, it was strong enough nearer the surface to pick up a parked car in the parking lot on the lee side of the building and drop it on top of two nearby automobiles. Incredibly, the winds at this site were outside of the eyewall by at least several kilometres. They clearly indicate the great ferocity of this record-breaking hurricane.

Acknowledgements

The many dedicated Floridians whose weather observations contributed to the analysis of Hurricane *Andrew* are gratefully recognised. Mr Sam Houston of the HRD led the post-storm collection of public observations. Mr Jerry Kranz performed the AOC barometer calibrations. Professor Tim Reinhold of Clemson University directed the VPI wind-tunnel tests of (Digitar) anemometers made available by Mr James Acquistapace of Davis Instruments. Ms Joan David, Mr Stanley Goldenberg and Mr Michael Black skilfully assisted in preparation of figures.

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The first meteorological research flight*

Maurice Crewe
National Meteorological Library

In 1992 there were various articles and functions to celebrate the 50th anniversary of the Met. Research Flight, but they were not the first to make a research flight by some 158 years. The earliest flight planned actually to study the atmosphere was on 30 November 1784 by Dr J. Jeffries (Fig. 1) and J.-P. Blanchard in a balloon.

At that time the balloon was a fairly new means of transport, since it was only in June 1783 that the Montgolfier brothers first demonstrated to the public that the 'levity' of smoke could raise fabric and paper globes into the air.

Meanwhile J.-A.-C. Charles and the two Robert brothers experimented with the new gas hydrogen to lift a balloon of varnished silk, and they showed it to the public on 27 August 1783. It was in fact seven years since that wealthy but unqualified eccentric Henry Cavendish had isolated hydrogen, among his other contributions to science.

Fig. 1 Dr J. Jeffries

* Based on a talk given at the Annual General Meeting of the Society's History Group in June 1992.