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Evaluation of shoreline change using optical satellite images, case study of Progreso, Yucatan

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Tropical Cyclone Report
Hurricane Ivan
2-24 September 2004

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Ivan was a classical, long-lived Cape Verde hurricane that reached Category 5 strength three times on the Saffir-Simpson Hurricane Scale (SSHS). It was also the strongest hurricane on record that far south east of the Lesser Antilles. Ivan caused considerable damage and loss of life as it passed through the Caribbean Sea.

a. Synoptic History

Ivan developed from a large tropical wave that moved off the west coast of Africa on 31 August. Although the wave was accompanied by a surface pressure system and an impressive upper-level outflow pattern, associated convection was limited and not well organized. However, by early on 1 September, convective banding began to develop around the low-level center and Dvorak satellite classifications were initiated later that day. Favorable upper-level outflow and low shear environment was conducive for the formation of vigorous deep convection to develop and persist near the center, and it is estimated that a tropical depression formed around 1800 UTC 2 September. Figure 1 depicts the "best track" of the tropical cyclone's path. The wind and pressure histories are shown in Figs. 2a and 3a, respectively. Table 1 is a listing of the best track positions and intensities.

Despite a relatively low latitude (9.7^{o} N), development continued and it is estimated that the cyclone became Tropical Storm Ivan just 12 h later at 0600 UTC 3 September. Ivan continued on a generally westward motion south of 10^{o}N latitude and steadily strengthened, becoming a hurricane at 0600 UTC 5 September centered about 1000 n mi east of Tobago in the southern Windward Islands. After reaching hurricane strength, the rate of intensification increased dramatically and Ivan underwent an 18 h period of rapid intensification (rate $\geq$ 30 kt/24 h). Satellite intensity estimates suggest that the intensity increased 50 kt while the central pressure decreased 39 mb during that time and Ivan reached its first peak intensity of 115 kt at 0000 UTC 6 September. This made Ivan the southernmost major hurricane on record. However, almost as quickly as Ivan strengthened it also weakened -- as much 20 kt over the following 24 h. Conventional and microwave satellite data indicated the probable cause of the rapid weakening was due to mid-level dry air that got wrapped into the center of the hurricane and eroded the eyewall convection.

Immediately following the 24 h weakening period, Ivan began a second strengthening phase (Fig. 2b) that also contained a 12 h period of rapid intensification. During that time, Ivan was under surveillance by U.S. Air Force Reserve reconnaissance aircraft as the hurricane approached the southern Windward Islands. Reports from the aircrew indicated that Ivan had strengthened to a strong category 3 (SSHS) hurricane as the center passed about 6 n mi south-southwest of Grenada. The eye diameter at that time was about 10 n mi, and the strongest winds raked the southern portion of the island.

After passing Grenada and into the southeastern Caribbean Sea, the hurricane's intensity leveled off until 1800 UTC on 8 September when another brief period of rapid intensification

ensued. Reconnaissance aircraft data indicated Ivan reached its second peak intensity -- 140 kt and category 5 strength (SSHS) -- just 12 h later. This was the first of three occasions that Ivan reached the category 5 level. The previous west-northwestward motion of 14-15 kt gradually decreased while Ivan moved across the central Caribbean Sea toward Jamaica. Although a large subtropical ridge to the north remained intact, steering currents weakened and Ivan's forward speed decreased to less than 10 kt on 11 September while the hurricane made a turn to the west, keeping the center at least 20 n mi offshore the southern coast of the island. As Ivan passed south of Jamaica it weakened to category 4 strength, in part, due to an eyewall replacement or concentric eyewall cycle (Fig. 4a). The combination of the westward turn and weakening kept the strongest winds offshore.

Later that day Ivan began moving west-northwestward away from Jamaica. Ivan rapidly intensified to category 5 strength a second time while it remained in a low vertical shear environment, and reached its third peak intensity at 1800 UTC 11 September. However, Ivan only maintained its maximum intensity of 145 kt and category 5 status for 6 h before it weakened back to a category 4 hurricane on 12 September. The weakening trend was short-lived and Ivan re-strengthened to category 5 for its third and final time when it was about 80 n mi west of Grand Cayman Island. Although Ivan was weakening while the center passed south of Grand Cayman on 12 September, the hurricane still brought sustained winds just below category 5 strength (Table 3) to the island. This resulted in widespread wind damage, and a storm surge that completely over swept the island except for the extreme northeastern portion.

On 13 September, Ivan approached a weakness in the subtropical ridge over the central Gulf of Mexico and turned northwestward at a slower speed of 8-10 kt. As Ivan moved over the northwestern Caribbean Sea, the combination of the impressive upper-tropospheric outflow that was being enhanced by the south-southwesterly upper-level flow ahead of an approaching trough and the very warm water in that region probably helped the hurricane maintain category 5 strength for an unusually long 30 h. Once again major land areas were spared the full force of the hurricane because the 20 n mi diameter eye and strongest winds passed through the Yucatan channel just off the extreme western tip of Cuba (Fig. 4b). Hurricane force conditions were reported across portions of western Cuba, but the effects were far less than what occurred on Grenada, Jamaica, and Grand Cayman when Ivan passed those areas.

Shortly after emerging over the southern Gulf of Mexico early on 14 September, Ivan turned north-northwestward and then northward. A steady weakening trend also ensued as moderate southwesterly flow on the east side of a large mid- to upper-level trough over the central United States and northeastern Mexico gradually caused the vertical shear to increase across the hurricane. As Ivan neared the northern U.S. Gulf coast, the upper-level wind flow ahead of the trough became more westerly and strengthened to more than 30 kt, which helped to increase the shear even more and advect dry air into the inner core region. Despite the unfavorable environmental conditions, the presence of cooler shelf water just offshore and eyewall replacement cycles, Ivan weakened only slowly and made landfall as a 105 kt hurricane (category 3 on the SSHS; see Figs. 2c and 3b.) at approximately 0650 UTC 16 September, just west of Gulf Shores, Alabama. By this time, the eye diameter had increased to 40-50 n mi (Fig. 4c), which resulted in some of the strongest winds occurring over a narrow area near the southern Alabama-western Florida panhandle border.

After Ivan moved across the barrier islands of Alabama, the hurricane turned north-northeastward across eastern Mobile Bay and weakened into a tropical storm 12 h later over central Alabama. A gradual turn to the northeast occurred shortly thereafter and Ivan became a tropical depression by 0000 UTC 17 September over northeast Alabama. A northeastward motion at 10-14 kt continued for the next 36 h before Ivan merged with a frontal system and

became an extratropical low over the DelMarVa peninsula around 1800 UTC 18 September. However, even as a weak tropical depression, Ivan was a prodigious rain and tornado producer causing flash floods and tornado damage across much of the southeastern United States.

Even as an extratropical low, the remnant circulation of Ivan was identifiable in both surface and upper-air data. Over the next 3 days, the low moved south and southwestward and eventually crossed the southern Florida peninsula from the Atlantic the morning of 21 September and emerged over the southeastern Gulf of Mexico later that afternoon. As Ivan moved westward across the warm water of the Gulf, the low began to re-acquire warm core, tropical characteristics as showers and thunderstorms started developing near the well-defined low-level circulation center. During the morning of 22 September, Ivan completed a large anticyclonic loop and by 1800 UTC reconnaissance aircraft reports indicated that it had become a tropical depression again over the central Gulf of Mexico. Ivan regained tropical strength 6 h later when it was located about 120 n mi south of the mouth of the Mississippi River. Tropical Storm Ivan turned northwestward and made landfall as a tropical depression in extreme southwestern Louisiana around 0200 UTC 24 September. After landfall, Ivan quickly dissipated later that morning over the upper Texas coastal area about 20 n mi northwest of Beaumont. Including its extratropical phase, Ivan existed for 22.5 days and produced a track more than 5600 n mi long.

b. Meteorological Statistics

Observations in Ivan (Figs. 2 and 3) include satellite-based Dvorak technique intensity estimates from the Tropical Analysis and Forecast Branch (TAFB), the Satellite Analysis Branch (SAB) and the U. S. Air Force Weather Agency (AFWA), as well as flight-level and dropwindsonde observations from flights of the 53rd Weather Reconnaissance Squadron of the U. S. Air Force Reserve Command (AFRES), and flight-level and stepped frequency microwave radiometer (SFMR) observations from the NOAA Aircraft Operations Center. Microwave satellite imagery from NOAA polar-orbiting satellites, the NASA Tropical Rainfall Measuring Mission (TRMM), the NASA QuikSCAT, and Defense Meteorological Satellite Program (DMSP) satellites were also helpful in monitoring Ivan. In addition, National Weather Service Doppler radars (Slidell, LA, Mobile, AL, and Elgin AFB, FL) were extremely useful for tracking this tropical cyclone. An example is seen in Figure 4, a reflectivity image of Ivan shortly after the time of landfall on 16 September from the Mobile WSR-88D Doppler radar, which shows the large eye of the hurricane inland over extreme southern Alabama.

A total of 112 reconnaissance center investigations were made in Ivan – 95 by the U.S. Air Force Reserve and 17 by the NOAA Hurricane Hunters. In addition, the NOAA Gulfstream-IV jet aircraft conducted 12 synoptic surveillance flights around the periphery of the hurricane. The maximum flight-level (700 mb) wind observed was 161 kt at 1917 UTC 11 September, when Ivan was located about 45 n mi west-southwest of the western tip of Jamaica. However, during Ivan's traversal across the Caribbean Sea, there were 12 additional flight-level wind reports of 150 kt or greater. The lowest aircraft measured pressure was 910 mb at 0005 UTC 12 September, less than 5 h after the maximum flight-level wind was observed, and also at 2053 UTC 13 September, which was about 2 h after flight-level winds of 157 kt were measured on two separate flight legs. Several research flights were made by NOAA aircraft when Ivan was moving over the Gulf of Mexico. The maximum SFMR surface wind observed was 99 kt at 0135 UTC 16 September about 58 n mi south of the Alabama coast. In the Caribbean Sea area, the maximum observed wind over land was sustained 130 kt with a gust to 149 kt on Grand Cayman Island at 1345 UTC 12 September. A 10-min average wind of 116 kt was reported at Pedro Bank, which is about 50 n mi southwest of Kingston. This was also the upper limit of reporting range of the wind observing equipment. Doppler radar velocity data indicated wind speeds as high as 97 kt may have affected much of Jamaica, especially over the higher elevations. In the

United States, the strongest winds measured were an unofficial report from a storm chaser near Gulf Shores, Alabama of sustained 77 kt with a gust to 99 kt at 0602 UTC 16 September. Also, an unofficial wind gust of 126 kt at approximately 0600 UTC 16 September was observed by the sailboat **Odalisque** anchored in Wolf Bay north of Orange Beach, Alabama. The highest official wind report was 76 kt sustained with a gust to 93 kt at the Pensacola Naval Air Station, Florida at 0629 UTC 16 September.

The lowest pressures observed during Ivan's first U.S. landfall were unofficial reports 943.1 mb and 947.9 mb, which came from storm chasers based in Fairhope, Alabama. In addition, an automated weather observing station (AWOS) on the oil drilling platform **Ram Powell-VJ956**, located about 70 n mi south of Mobile Bay, Alabama (Table 3) reported a sustained wind of 102 kt with a gust to 135 kt at 2256 UTC 15 September at an elevation of 400 ft ASL. The instrument failed immediately after this report was obtained and remained inoperable for the next 4 days. Aircraft reconnaissance reports around that time suggest that the oil rig was located north-northeast of Ivan's center and just outside the radius of maximum winds.

Although Ivan was weakening as it made its first U.S. landfall, it is estimated to have been a category 3 hurricane when it reached the Alabama coast. As Ivan neared the U.S. Gulf coast on 15 and 16 September, the hurricane came under the surveillance of National Weather Service (NWS) WSR-88D Doppler radars located in Slidell, LA, Mobile, AL, and Eglin AFB, FL There was a robust and persistent velocity maximum located within vigorous convection in the northeastern quadrant of the outermost concentric eyewall as Ivan was coming ashore. For several hours prior to landfall, the velocities were actually higher in this area than in the vicinity of the inner eyewall. Within the outer eyewall existed several 1-2 n mi^2 patches of 120-122 kt inbound Doppler velocities (some individual gates contained 123.4 kt velocities) at around 6,000 ft ASL. Using 122 kt as being representative of a smoothed peak and applying a reduction factor of 0.85 (standard reconnaissance flight-level reduction for 6000 ft) yields a surface estimate of 104 kt. In addition to the Doppler radar velocity data, a 700 mb flight-level wind of 120-kt was observed just south of Gulf Shores, AL at 0724 UTC 16 September (Fig. 2c) in the same general area where the aforementioned maximum Doppler radar velocities were observed. The 120-kt flight-level wind converts to approximately a 108-kt surface wind using the standard 0.90 reduction factor from the 700 mb-level. A blend of those two equivalent surface wind values yields an intensity of 105 kt Ivan's first U.S. landfall. This intensity estimate is also consistent with the 99-kt SFMR surface wind data that was collected by a NOAA WP-3 aircraft more than 6 h before landfall. In addition, assuming a typical outward slope to the eyewall, the narrow band of strongest winds at landfall likely occurred over Perdido Key and Perdido Bay, which would have been to the west of the Pensacola Naval Air Station and to the east of the Florida Coastal Monitoring Program portable wind tower at Gulf Shores, Alabama.

Ship reports of winds of tropical storm force associated with Ivan are given in Table 2, and selected surface observations from land stations and data buoys are given in Tables 3, 4, and 5. With the exception of a couple of ships that had sought shelter in the harbors around Grenada, the majority of ships remained clear of Ivan's strong winds.

Heavy rainfall exceeding 10 inches occurred on several of the Caribbean Islands (Tables 3 and 5) and caused extensive freshwater flooding and/or mud slides. Some peak rainfall totals are 16.20 in from Tobago, 13.33 in from western Cuba, and 12.14 in from Grand Cayman. Across Jamaica, several locations received more than 25 in (635 mm) of rainfall. A few of the largest rainfall totals were 28.37 in (720.8 mm) at Ritchies, 27.92 in (709.4 mm) at Mavis Bank, and 26.83 in (681.5 mm) at both Craighead and Worthy Park. The Meteorological Service of Jamaica also "…noted that rainfall data representative of a number of stations in southern

parishes were lost due to damage done to rain gages by Hurricane Ivan." In the United States, rainfall totals generally ranged from 3-7 in along a large swath from Alabama and the Florida panhandle northeastward across the eastern Tennessee Valley and into the New England area (Fig. 6) In fact, when Ivan was an extratropical low pressure system, it produced rainfall totals in excess of 7 in as far north as New Hampshire and as far south as the Florida east coast. Even as a weakening tropical depression, Ivan produced rainfall amounts exceeding 7 in across eastern Texas. However, there were two isolated extreme rainfall reports exceeding 15 in -- 17.00 in at Cruso, North Carolina and 15.75 in at television station WEAR-TV3 in Pensacola, Florida. Widespread flooding resulted from Ivan's rains, which fell on already saturated ground caused by Tropical Storm Bonnie and Hurricane Frances that traversed much of the same area in August and early September.

An outbreak of 117 tornadoes -- with the bulk of the tornadoes on 17 September -- developed over a 3 day period in the United States, including 37 in Virginia, 25 in Georgia, 18 in Florida, 9 in Pennsylvania, 8 in Alabama, 7 in South Carolina, 6 in Maryland, 4 in North Carolina, and 3 in West Virginia. There were 26 tornadoes reported on 15 September, 32 tornadoes on 16 September, 57 tornadoes on 17 September, and 2 tornadoes (in Maryland) on 18 September. At least 8 people were killed and 17 injured by the tornadoes. On 15 September, some of the more significant tornado events occurred -- an F2 tornado occurred near Panama City Beach (Bay Co.), FL resulting in 1 death and 7 injuries; a second F2 tornado occurred near Blountstown (Calhoun Co.), FL resulting in 4 deaths and 1 injury; a third tornado (intensity undetermined) killed 2 people in Panama City, FL a little more than 1 h after the F2 tornado had struck the area.

Storm surge of 10-15 ft occurred along the coasts from Destin in the Florida panhandle westward to Mobile Bay/Baldwin County, Alabama. Storm surge values of 6-9 ft were observed from Destin eastward to St. Marks in the Florida Big Bend region. Lesser values of storm surge continued east and southward along the Florida west coast with 3.5 ft reported in Hillsborough Bay/Tampa Bay. There was also a possible record observed wave height of 52.5 ft reported by the NOAA Buoy 42040 located in the north central Gulf of Mexico south of Alabama. In addition, severe storm surge flooding of 8-10 ft with 20-30 ft waves caused more than 5-8 ft of water to cover Grand Cayman Island at times. This resulted in the airport and numerous homes being completely inundated by sea water.

c. Casualty and Damage Statistics

The forces of Ivan were directly responsible for 92 deaths – 39 in Grenada, 25 in United States, 17 in Jamaica, 4 in Dominican Republic, 3 in Venezuela, 2 in Cayman Islands, and 1 each in Tobago and Barbados. Concerning the deaths in the United States, 14 occurred in Florida, 8 in North Carolina, 2 in Georgia, and 1 in Mississippi. The breakdown of U.S. deaths by cause is as follows: tornado (7), storm surge (5), fresh water floods (4), mud slides (4), wind (3), and surf (2). Ivan was also indirectly responsible for 32 deaths in the United States.

Ivan caused extensive damage to coastal and inland areas of the United States. Portions of the Interstate 10 bridge system across Pensacola Bay, Florida were severely damaged in several locations as a result of severe wave action on top of the 10-15 ft storm surge. As much as a quarter-mile of the bridge collapsed into the bay. The U.S Highway 90 Causeway across the northern part of the bay was also heavily damaged. To the south of Pensacola, Florida, Perdido Key bore the brunt of Ivan's fury and was essentially leveled. Along the Alabama coast, high surf and wind caused extensive damage to Innerarity Point and Orange Beach. In the Alabama and Florida panhandle areas, widespread over wash occurred along much of the coastal highway

system. In addition, extensive beach erosion caused severe damage to or the destruction of numerous beachfront homes, as well as apartment and condominium buildings. Some buildings collapsed due to scouring of the sand from underneath the foundations caused by the inundating wave action. Thousands of homes the three-county coastal area of Baldwin, Escambia, and Santa Rosa were damaged or destroyed. Cleanup efforts alone in Escambia County resulted in debris piles that were more than three-quarters of a mile long and 70 feet high. In all, Ivan was the most destructive hurricane to affect this area in more than 100 years. Strong winds also spread well inland damaging homes, and downing tress and power lines. At one point, more than 1.8 million people were without power in nine states.

In addition to the damaged homes and businesses, Ivan also destroyed millions of acres of woodlands and forests. The Alabama Forestry Commission found damaged timber valued at about $610 million on 2.7 million acres. These figures include

-- *Pine pulpwood*: 7.5 million cubic feet

-- *Hardwood pulpwood*: 2.6 million cubic feet

-- *Pine sawtimber*: 351.5 million board feet

-- *Hardwood sawtimber*: 493 million board feet.

In the 200,000-acre Blackwater Forest, just east of Pensacola in the western Florida panhandle, more than 1.5 million board feet of timber were downed across 185,000 acres.

Ivan's effects were not just limited to coastal and inland areas. Offshore oil industry operations in the Gulf of Mexico were severely disrupted, and several oil drilling platforms and pipelines sustained varying degrees of damage. The normal daily flow of 475,000 barrels of oil and 1.8 billion cubic feet of natural gas, plus refining operations, were disrupted for more than 4 weeks. A total of 12 large pipelines and 6 drilling platforms sustained major damage; another 7 platforms were completely destroyed.

A total of 686,700 claims were filed and the American Insurance Services Group estimates (14 December 2004 re-survey) that insured losses in the United States from Hurricane Ivan totaled $7.11 billion, of which more than $4 billion occurred in Florida alone. Using a two-to-one ratio of insured damages yields an estimated U.S. loss of approximately $14.2 billion. In addition to the insured losses that occurred, the U.S. Naval Air Station at Pensacola, Florida sustained damage losses of $800-$900 million.

In the Caribbean region, extensive damage occurred to homes, buildings and other structures. The following are brief synopses of the reports received from some of the Caribbean islands:

Barbados – More than 176 homes completely destroyed; many homes lost their roofs; most coastal roads severely damaged due to erosion caused by the storm surge and wave action.

Cayman Islands -- 95 percent of the homes and other buildings (which generally follow South Florida's building codes) were damaged or destroyed;

Cuba -- roofs were torn off homes in extreme western Pinar del Rio Province; flooding damaged houses, and fishing and farm installations; mud slides

cut off at least two towns.

Grenada -- At least 80 percent of the 100,000 residents were without power; more than 14,000 homes were damaged or destroyed; 80 percent of the nutmeg trees were destroyed; a 17th century prison was also damaged allowing many of the inmates to briefly escape during the height of the storm; Ivan was the worse hurricane to strike the island since Hurricane Janet in 1955.

Jamaica -- At least 47,000 homes were damaged, of which 5,600 were completely destroyed; most of the islands utilities were damaged.

St. Vincent/ Grenadines – 50 homes severely damaged with 2 homes washed away into the sea; more than two-thirds of residents lost power.

Tobago -- At least 1 home collapsed and fell into the ocean; at least 45 homes lost their roofs; numerous trees and utility were blown down; 20 villages suffered various forms of damage

In the Caribbean Sea region, the Caribbean Development Bank (CDB) estimates the damage at more than US$3 billion -- US$1.85 billion in the Cayman Islands, US$815 million in Grenada, US$360 million in Jamaica, US$40 million in St. Vincent and the Grenadines, and US$2.6 million in St Lucia. No damage estimates were available from any of the other Windward Islands countries, Venezuela, or Cuba.

d. Forecast and Warning Critique

Average official track errors (with the number of cases in parentheses) for Ivan were 24 (63), 47 (61), 79 (59), 108 (56), 161 (52), 222 (48), and 289 (44) n mi for the 12, 24, 36, 48, 72, 96, and 120 h forecasts, respectively. In comparison, the longer-term average official track errors for the 10-yr period 1994-2003[1] are 44, 78, 112, 146, 217, 248, and 319 n mi. Table 6 contains the average errors from various numerical track forecast models for Ivan. The average NHC official track forecast (OFCL) errors for Ivan were better than the 10-yr average throughout the 120 h forecast cycle, especially through 72 h. However, most of the various numerical track forecast models, like the UKMET and FSU Superensemble (FSSE) models outperformed the NHC official track forecast at most times. On average, the FSSE model significantly outperformed the NHC official forecast at all times. Average official intensity errors were 9, 12, 13, 12, 15, 24 and 36 kt for the 12, 24, 36, 48, 72, 96, and 120 h forecasts, respectively. For comparison, the average official intensity errors over the 10-yr period 1994-2003 are 6, 10, 12, 15, 19, 20, and 21 kt, respectively. These intensity errors were greater than average at 96 and 120 h due to rapid intensification and greater than forecast intensities that occurred over the Caribbean Sea. Synoptic-scale analyses produced by the NOAA Global Forecast System (GFS) indicate that Ivan essentially remained underneath a 200 mb ridge axis as the hurricane traversed the Caribbean Sea. This resulted in implied relatively low 850-200 mb vertical wind shear values ($\leq$ 10 kt in many times periods) over the inner core region and also provided favorable upper-level outflow channels to the north and south. However, the Statistical Hurricane Intensity Prediction Scheme (SHIPS) model failed to capture both the early rapid intensification period and the lengthy period of category 4 and 5 strength. This may be due to the way the SHIPS model assesses the vertical shear across a tropical cyclone. During the period 7-14 September when significant intensification occurred, the SHIPS model assessed the vertical shear on

[1] Errors given for the 96 and 120 h periods are averages over the three-year period 2001-3.

numerous occasions to be 15-20 kt from a westerly direction. Typically when alleged westerly shear of this magnitude is present, little or no strengthening occurs and, more often, weakening transpires. The westerly vertical shear calculated by the SHIPS model may have been due, in part, to its inability to separate the strong upper-level outflow from the environmental flow in which the cyclone was embedded.

Official track forecasts had, in general, a persistent right-of-track bias for the first 11 days of Ivan's existence as a tropical cyclone (Fig. 5a). The official track forecasts relied heavily on the global model forecasts, which prematurely eroded the large and strong subtropical ridge to the north of Ivan that extended well westward across the Bahamas, Florida, and into the Gulf of Mexico. In fact, several of the GFS model forecast cycles consistently eroded the ridge across Bahamas and took Ivan well to the east of Florida, even as the hurricane was approaching Jamaica. The westward jog that Ivan made on 11 September appears to be, at least in part, the result of a mid- to upper-level cold low to the north of Hispaniola that moved slowly southwestward rather than weakening and lifting out to the northeast as some of the models had been forecasting. Despite the early right bias, once Ivan moved into the northwestern Caribbean Sea, the track forecasts gradually narrowed down the likely landfall region of the western Florida panhandle and Alabama coasts (Fig. 5b). Table 7 lists all of the watches and warnings issued for Ivan.

A hurricane watch was issued for the central U.S. Gulf coast more than 51 h prior to landfall on the Alabama coast. A hurricane warning was issued for the same area less than 42 h prior to landfall. Over the 72 h period leading up to the first U.S. landfall, there was a spread of only 95 n mi between the westernmost and easternmost forecast tracks. In fact, more than 75% of those forecasts targeted the Alabama coast as the most likely area where landfall was expected to occur. The result of these forecasts was that Ivan made landfall well within the area covered by the hurricane watch and warning.

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Table 1. Best track for Hurricane Ivan, 2-24 September 2004.

Date/Time (UTC)	Latitude (EN)	Longitude (EW)	Pressure (mb)	Wind Speed (kt)	Stage
02 / 1800	9.7	27.6	1009	25	tropical depression
03 / 0000	9.7	28.7	1007	30	"
03 / 0600	9.7	30.3	1005	35	tropical storm
03 / 1200	9.5	32.1	1003	40	"
03 / 1800	9.3	33.6	1000	45	"
04 / 0000	9.1	35.0	999	45	"
04 / 0600	8.9	36.5	997	50	"
04 / 1200	8.9	38.2	997	50	"
04 / 1800	9.0	39.9	994	55	"
05 / 0000	9.3	41.4	991	60	"
05 / 0600	9.5	43.4	987	65	hurricane
05 / 1200	9.8	45.1	977	85	"
05 / 1800	10.2	46.8	955	110	"
06 / 0000	10.6	48.5	948	115	"
06 / 0600	10.8	50.5	950	110	"
06 / 1200	11.0	52.5	955	110	"
06 / 1800	11.3	54.4	969	90	"
07 / 0000	11.2	56.1	964	90	"
07 / 0600	11.3	57.8	965	95	"
07 / 1200	11.6	59.4	963	100	"
07 / 1800	11.8	61.1	956	105	"
08 / 0000	12.0	62.6	950	115	"
08 / 0600	12.3	64.1	946	120	"
08 / 1200	12.6	65.5	955	120	"
08 / 1800	13.0	67.0	950	120	"
09 / 0000	13.3	68.3	938	130	"
09 / 0600	13.7	69.5	925	140	"
09 / 1200	14.2	70.8	919	140	"
09 / 1800	14.7	71.9	921	130	"
10 / 0000	15.2	72.8	923	130	"
10 / 0600	15.7	73.8	930	125	"
10 / 1200	16.2	74.7	934	125	"
10 / 1800	16.8	75.8	940	120	"
11 / 0000	17.3	76.5	926	135	"
11 / 0600	17.4	77.6	923	130	"
11 / 1200	17.7	78.4	925	125	"
11 / 1800	18.0	79.0	920	145	"
12 / 0000	18.2	79.6	910	145	"
12 / 0600	18.4	80.4	915	135	"
12 / 1200	18.8	81.2	919	135	"
12 / 1800	19.1	82.1	920	130	"
13 / 0000	19.5	82.8	916	140	"
13 / 0600	19.9	83.5	920	140	"
13 / 1200	20.4	84.1	915	140	"
13 / 1800	20.9	84.7	912	140	"
14 / 0000	21.6	85.1	914	140	"
14 / 0600	22.4	85.6	924	140	"

14 / 1200	23.0	86.0	930	125	“
14 / 1800	23.7	86.5	931	120	“
15 / 0000	24.7	87.0	928	120	“
15 / 0600	25.6	87.4	935	120	“
15 / 1200	26.7	87.9	939	115	“
15 / 1800	27.9	88.2	937	115	“
16 / 0000	28.9	88.2	931	110	“
16 / 0600	30.0	87.9	943	105	“
16 / 1200	31.4	87.7	965	70	“
16 / 1800	32.5	87.4	975	50	tropical storm
17 / 0000	33.8	86.5	986	30	tropical depression
17 / 0600	34.7	85.7	991	25	“
17 / 1200	35.4	84.0	994	20	“
17 / 1800	36.2	82.3	996	20	“
18 / 0000	37.0	80.5	999	20	“
18 / 0600	37.7	78.5	998	15	“
18 / 1200	38.4	76.7	1000	15	“
18 / 1800	38.0	75.5	1002	25	extratropical
19 / 0000	37.5	74.0	1003	35	“
19 / 0600	36.0	74.0	1005	35	“
19 / 1200	34.5	74.5	1008	35	“
19 / 1800	32.8	75.8	1008	35	“
20 / 0000	31.0	77.5	1008	35	“
20 / 0600	29.0	78.5	1008	35	“
20 / 1200	27.5	78.7	1009	30	“
20 / 1800	26.4	79.1	1009	25	“
21 / 0000	26.1	79.7	1009	25	“
21 / 0600	25.9	80.6	1009	25	“
21 / 1200	25.8	81.7	1009	25	“
21 / 1800	25.2	82.8	1010	25	low
22 / 0000	24.8	84.1	1010	25	“
22 / 0600	25.1	86.1	1010	25	“
22 / 1200	26.0	87.3	1010	25	“
22 / 1800	26.5	88.6	1008	30	tropical depression
23 / 0000	27.1	89.5	1007	35	tropical storm
23 / 0600	27.9	91.0	1007	35	“
23 / 1200	28.9	92.2	998	50	“
23 / 1800	29.2	92.7	1003	40	“
24 / 0000	29.6	93.2	1003	30	tropical depression
24 / 0600	30.1	94.2	1009	25	“
24 / 1200					dissipated inland
12 / 0000	18.2	79.6	910	145	minimum pressure
13 / 2100	21.2	84.8	910	140	minimum pressure
07 / 2130	11.9	61.8	952	110	closest point of approach, 6 n mi south-southwest of Prickly Point, Grenada
11 / 0330	17.4	77.2	924	130	closest point of approach, 20 n mi south of Portland Point, Jamaica

12 / 1415	18.9	81.5	920	130	closest point of approach, 22 n mi south-southwest of Georgetown, GCI
14 / 0100	21.7	85.2	916	140	closest point of approach, 15 n mi southwest of Cabo San Antonio, Cuba
16 / 0650	30.2	87.9	946	105	1st U.S. landfall near Pine Beach, AL, or 9 n mi west-southwest of Gulf Shores, AL
24 / 0200	29.8	83.6	1004	30	2nd U.S. landfall near Holly Beach, LA, or 10 n mi west of Cameron, LA

Table 2. Selected ship and drifting buoy reports with winds of at least 34 kt for Hurricane Ivan, 2-24 September 2004.

Date/Time (UTC)	Ship call sign	Latitude (ºN)	Longitude (ºW)	Wind dir/speed (kt)	Pressure (mb)
04 / 1100	13009	8.0	38.0	- - - / 36	- - -
08 / 0359	MV Son Monoy	10.7	66.2	320 / 40G50	- - -
08 / 1200	ZCDE4	11.6	62.7	120 / 47	1007.2
11 / 0600	WDA406	15.9	77.5	230 / 37	1002.1
12 / 0400	ATPN	16.8	80.2	010 / 46	1005.0
12 / 1500	P3JA8	17.7	81.8	250 / 53	997.5
13 / 1800	A8CO2	18.3	85.5	260 / 35	1006.8
13 / 2100	A8CO2	18.3	84.9	250 / 35	1005.9
14 / 0000	C6DM2	17.9	86.8	280 / 44	1002.0
14 / 1000	LAZK4	22.6	88.8	020 / 44	999.0
14 / 1400	WPPO	25.5	84.2	090 / 45	1004.0
14 / 1500	HZRX	24.5	83.3	110 / 52	1004.3
14 / 1700	WPPO	25.3	83.9	120 / 47	1004.0
14 / 1800	HZRX	24.1	82.7	120 / 52	1004.4
14 / 2300	WPPO	24.7	83.4	140 / 52	1004.2
15 / 0900	H3SM	27.1	90.2	020 / 39	999.7
15 / 1200	LANT5	24.2	85.1	180 / 43	1005.0
15 / 1500	H3SM	27.0	90.0	360 / 50	963.0
15 / 1800	H3SM	27.0	90.2	330 / 43	963.7
15 / 1800	SPLL1	28.9	90.5	010 / 39	1002.2
15 / 2100	H3SM	27.0	90.2	320 / 46	998.0
16 / 0000	H3SM	27.0	90.2	290 / 42	1001.3
19 / 0600	C6YC	37.5	74.5	010 / 37	1010.5
19 / 1200	DHBN	40.4	70.7	020 / 35	1016.0
20 / 0600	A8CF2	34.7	72.3	020 / 37	1017.0
20 / 0600	VRXL6	33.4	73.0	200 / 35	1015.5
20 / 0600	WGXO	29.5	79.6	040 / 37	1011.0

Table 3. Selected surface observations for Hurricane Ivan, 2-24 September 2004.

Location	Minimum Sea Level Pressure		Maximum Surface Wind Speed			Storm surge (ft)[c]	Storm tide (ft)[d]	Total rain (in)
	Date/time (UTC)	Press. (mb)	Date/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)			
Windward Islands								
Dominica								
Hewanorra (TLPL)			07/1700+	37				
Grenada								
Point Salines (TGPY)			07/2000	45	81			
			07/2100	64	101			
			07/2300	49	67			
Jamaica								
Craighead								26.83
Kingston (MKJP)	11/0129	991.5	11/0217*	55				
Mavis Bank								27.92
Negril Point	11/????	986.8						
Pedro Bank	11/????	979.5	11/????	116				
Ritchies								28.37
Rose Hill								25.80
South Central coastal areas						4-6		
Worthy Park								26.83
Cayman Islands								
Cayman Brac	12/0300	997.0	12/0200	44	58			4.92
Grand Cayman	12/1345	970.0	12/1500	130	149	8-10		12.14
Cuba								
Cabo de San Antonio			14/0050#	96	104			
Cuba – Francia (78309)	14/0000	1001.6	14/0043	45	56			10.16
La Fe (78321)	13/1850	1001.0	13/1248	51	64			6.26
La Palma (78316)	14/0100	1000.3	14/0620	49	61			4.43
Isabel Rubio (78313)	14/0200	990.1	14/0200	61	76			13.33
Nueva Gerona (Isle of Youth)	13/1800	1000.1	13/1457	55	69			5.66
Pinar del Rio (78315)	13/2310	997.7	14/0140	54	67			7.69
Pinar del Rio Prov. (s. coast)						6-12		
P.R.S. Diego (78317)	13/2340	1001.5	14/0140	42	52			5.55
Punta del Este (78324)	13/2200	1000.7	14/0030	49	61			4.75
San Juan y Martinez (78314)	14/0100	996.0	13/2340	47	59			5.69
Santa Lucia (78312)	14/0200	994.7	14/0220	61	76			6.00

Alabama								
Alabaster (KEET)	17/0053	991.7						6.00
Alberta								6.85
Alexander City (KALX)			16/1500		36			
Andalusia (HAM Radio)								9.96
Anniston (ANNA1)								7.64
Anniston (KANB)	17/0053	991.5						
Ariton Co-op (ARTA1)								5.32
Baldwin County						10-15		
Bellwood Co-op (BELA1)								5.48
Bessie								5.81
Birmingham (KBHM)	17/0053	989.6	16/1653		42			9.81
Blakely (Co-op (BLKG1)								6.50
Blount Springs								5.29
Brookley/Mobile (KBFM)	16/0656	956.0						
Coden								6.30
Cullman (K3A1)			16/1740+		39			
Daleville Co-op (DALA1)								5.82
Daphne								7.50
Dothan (KDHN)	16/0752	1000.6	16/1900	38	47			5.94
Elba Co-op (EBBA1)								5.48
Evergreen (EVRA1)								7.55
Fairhope (awis)			16/0418		63			
Flat Rock (FLRA1)								8.04
Florence (C0168)			17/0050+		37			
Fort Payne 6NE (LRWA1)								7.30
Fort Payne (K4A9)			16/1920		45			
Gadsden (KGAD)			16/1735		37			
Geneva Co-op (GVAA1)								8.20
Grand Bay (awis)			16/0517		62			
Helena								4.72
Huntsville (KHSV)	16/2353	994.3	16/2153		40			
Huntsville (KMDQ)			16/2242+		35			
Jackson Shoals								4.05
Ketona								9.69
Lauderdale (RLDM6)			16/1113		47			
Lower Bryant Landing (NOS)						3.4		
Manchester								4.35
Maxwell AFB (KMXF)	16/1755	989.9	16/1257	31	57			9.78

Millers Ferry (MRFA1)								11.66
Mobile (KMOB)	16/0725	964.4	16/0644	51	65			5.56
Mobile (2S KMOB)								9.90
Mobile (3S KMOB)								6.30
Mobile (7S KMOB)								6.53
Mobile (10S KMOB)								8.00
Mobile County						6-9		
Montgomery (KMGM)	16/1753	989.5	16/1353	32	50			
Muscle Shoals (KMSL)	16/2253	998.7	16/2110		40			
Newton Co-op (NEWA1)								5.47
Ozark/Ft. Rucker (KOZR)	16/1055	999.8	16/0955		38			6.10
Ram Powell VK-956 Oil Rig – 400 ft elev. (29.05N 88.10W)	15/2256*	952.6	15/2256*	102	135			
Robertsdale								9.35
Selma (SELA1)								8.87
Semmes (awis)	16/0830	967.5	16/0500	49	51			5.00
Silverhill (3S)								10.16
Spanish Fort			16/0800		51			8.00
Talladega								5.60
Tannehill								9.76
Troy (KTOI)	16/1755	994.7	16/1128+		37			
Trussville (TRSA1)								8.97
Tuscaloosa (KTCL)	16/1353	996.7	16/1453+		43			
Valley Head (VYHA1)								8.27
Wing 6NE (OPNA1)			16/1022+		58			
Wedowee								5.20
Florida								
Apalachicola (KAAF)								4.11
Baker (BAKF1)								10.41
Bay County						8-10		
Big Pine key								2.12
Bristol Co-op (BRLF1)								7.00
Bruce Co-op (BRUF1)								7.05
Chipley Co-op (CHPF1)								5.42
Crestview (CRVF1)								7.68
Crestview (HAM radio)								8.40
Cross City (KCTY)			16/1918		31			
Dixie County						4		
Eglin AFB (KVPS)	16/0755	991.6	16/0755	46	70			7.43
Escambia County						10-15		

Franklin County						3-5		
Ft. Walton (HAM radio)								6.06
Gulf County (St. Joseph State Park)						4-6		
Hillsborough Co. (Hills. Bay)						3.5		
Huntsville (KHSV)								3.73
Jefferson County						4		
Key West (KEYW)			14/0903	36	46			1.11
Key West (KEYW-Atlantic)						1.0		
Levy County (Cedar Key)						1.91		
Lowry Mill Co-op (LOWA1)								7.33
Marianna Co-op (MALF1)								5.28
Mayport Naval Stn. (KNRB)			21/0355+		34			
Milligan (MLGF1)								11.31
Mossy Head Co-op (MHDF1)								9.26
Munson								6.50
Nettles Island (NETF1)								7.62
Niceville								6.55
Okaloosa County						6-9		
Panama City (KPFN)	16/0853	999.9	16/1700	30	60			
Pensacola (KPNS)	16/0645	970.2	16/0650	67	87			
Pensacola NAS (KNPA)	16/0656	965.8	16/0629	76	93			8.00
Pensacola (WEAR-TV)								15.79
Perry (K40J)			16/1749		41			
Saint Augustine (KSGJ)			21/0300		36			
Santa Rosa County						10-15		
Sarasota (KSRQ)			16/1255		30			
Seminole 5NE								8.10
Tallahassee (KTLH)			16/1605	33	47			
Taylor County						4		
Walton County						8-10		
Wakulla County						4-5		
Georgia								
Albany (KABY)			16/1803		36			
Athens (KAHN)			16/2333		39			
Atlanta-Falcon (KFFC)			17/0122		34			
Atlanta-Hatrsfield (KATL)			16/2357		39			
Atlanta-McCollum (KRYY)			16/2347		35			
Atlanta-Peachtree (KPDK)			16/2125		38			
Byromville (BYRG1)			16/2105		34			

Canton/Cherokee Co. (K47A)			16/2122		35			
Chickamauga (FTOG1)								7.75
Clayton 4NE (TULG1)			18/0206		43			
Clayton 10W (TCLG1)								7.87
Columbus (KCSG)	16/2151	997.1	16/2227+		39			
Elberton (K27A)			17/0101		37			
Ellijay 7NW (MTNG1)								7.24
Fort Benning AAF (KLSF)			16/2355		36			
Gainesville (KGVL)			16/2253		39			
Helen (HELG1)								8.57
Helen 7N (BRSG1)			17/0306		61			
Hurst 3SE (HSTG1)								8.42
Lafayette 5SW (LFYG1)								7.28
Lagrange (KLGC)			16/2140		34			
Lawrenceville (KLZU)			16/2150		40			
Mountain City 2N (MTCG1)								7.10
Nacoochee (NACG1)								9.20
Pine Mountain (PIMG1)								7.80
Preston Co-op (PRSG1)								5.57
Rome (KRMG)	17/0553	994.5						
Suches 6NW (TCCG1)			17/0005		39			
Tallula Falls (TLUG1)								7.88
Thomaston-Upson (KOPN)			16/2101		38			
Titus (TUSG1)								9.27
Valdosta (KVLD)			16/1907		37			
Washington 5NW (WSNG1)			17/202		35			
Winder (KWDR)			16/2240		39			
Kentucky								
Greenup (GNUK2)								6.26
Louisiana								
Barataria Bay			15/1700		44			
Bootheville (KBVE)			15/1551	31	42			
Bootheville – LSU Citrus AG			16/0000		52			1.05
Buras								2.50
Calcasieu Pass – East Jetty						1.7		
Cameron Heliport (K7R5)			23/2325		34			
Cameron Prairie NWR								4.14
Cocodrie			16/0000		36			
Deridder								3.00

Elmer 2SW								3.75
Franklin 3NW								3.04
Hackberry 8SSW (HAKL1)			24/0140		36			
Galliano – Little Lake			15/2300		41			
Grand Isle – East Point						1.7		
Laffitte – Lake Salvador			16/0300		34			
Lake Charles (KLCH)	23/2346	1012.5	24/0217	23	30			1.16
Lake Pontchartrain – Mandeville			16/0030	30	33			
Lake Pontchartrain – mid lake			16/0330	35	46			
Marco Polo GC608 Oil Rig – 300 ft elev. (27.36N 90.19W)			15/2100&	54				
New Orleans (KNEW)	16/0125	994.2	16/0206	41	48			0.08
New Orleans (KMSY)	16/0644	998.0	15/2138	33	40			Trace
Pointe a la Hache – northeast Bay Gardene			16/0400		60			
Rockefeller NWR								3.22
Slidell (KASD)	16/0147	994.2	16/0011	32	37			0.26
SW Pass (NOS)						3.0		
Maryland								
AP259 APRSWXNET (39.0N 76.3W)			18/1700		36			
Patuxent NAS (KNHK)			18/2355		35			
Mississippi								
Biloxi Bay – NOAA/NOS						3.2		
Biloxi Harbor – Pointe Cadet			16/0245	47	68			
Columbus (KGTR)			16/1815+		46			
Columbus AFB (KCBM)	16/1955	995.8	16/1855		35			
Gautier – U.S. Hwy 90			16/0700*		51			
Gholson 8W (GHLM6)								5.35
Gulfport (KGPT)	16/0703*	983.7	16/0059*	40	53			1.70
Keesler AFB (KBIX)	16/0655	982.9	16/0644	42	62			3.28
NAS Meridian (KNMM)	16/1555	992.0	16/1255	30	51			
Ocean Springs – Ft. Bayou			16/0415		43			
Orange Grove – Interstate 10			16/0715		46			
Pascagoula 3NNE								5.70
Pascagoula/Jackson Co. EOC (top of 2-story building)			16/0600		76			6.29
Pascagoula (KPQL)	16/0536*	975.6	15/2349*	37	51			1.15
Pass Christian – USCG Merril Shell Bank Lighthouse			16/0500		64			
Van Cleave (BCVM6)								3.73
Waveland –NOAA/NOS			16/0242	34	49	3.4		

Waveland –Hancock Co. EOC			16/0430		53			
New Hampshire								
Jaffrey (AFN)								7.30
New Jersey								
Columbia (CMBN4)								5.50
New York								
Deposit (DEPN6)								5.37
Fishs Eddy (FSHN6)								5.40
Stuyvesant 5N (STYN6)								5.11
Windham (WDMN6)								5.45
North Carolina								
Andrew-Murphy (KRHP)			17/0524		39			
AP341 RAWS (36.1N 81.9W)			17/0330		41			
Asheville (KAVL)			17/0535+		42			
Black Mtn (MMTN7)								9.05
Boone (KTNB)			17/0801		45			
Burgaw 11E (BKIN7)			17/2213		36			
Burlington (KBUY)			17/1727		44			
C1587 RAWS (35.8N 78.9W)			17/1746		39			
Canton 10 SSW (SNBN7)								8.92
Charlotte Int'l (KCLT)			17/0851		35			
Cruso								17.00
Cullowhee (CUWN7)			17/0610+		42			
Daniel Ridge (DNRN7)								8.25
Elizabeth City (KECG)			18/0254		36			
Fayetteville 11WNW (FBRN7)			17/2007+		36			
Fayetteville (KFAY)			17/2023+		41			
Guion Farms AFS (GUIN7)			17/0610		44			
H0002 RAWS (36.4N 81.5W)			17/0510		37			
Hawk – IFLOWS (HAKN7)								7.12
Highlands (C0930)			17/0155		41			
Highlands-IFLOWS (HILN7)								8.16
Highlands (TVA)								11.83
Hogback (IHBN7)								8.92
Jacksonville (KOAJ)			17/1835		35			
Jefferson (KGEV)			18/0441+		41			
Jonas Ridge (JSRN7)								8.95
Kill Devil Hills (KFFA)			19/0900		38			
Kure Beach 3W (SUNN7)			18/0058		39			

Laurel Springs (LRLN7)			17/0810*		51			
Mackall AAF (KHFF)			17/1555		34			
Manteo (KMQI)			18/1100+		37			
New Bern (KEWN)			18/0107+		35			
Plumtree (PLMN7)								8.08
Purlear 2N (RVZN7)			18/0810+		42			
Raleigh-Durham (KRDU)			17/1951		36			
Rich Mountain (RCMN7)								8.08
Rosman 6E (CFFN7)								7.83
Shallotte 7NE (NATN7)			17/2259		38			
Shelby (KEHO)			17/0720		35			
Spruce Pine 3SE (SPPN7)								7.20
TS156 RAWS (35.8N 82.7W)			17/0908		42			
Whiteville (WHIN7)			17/2045		35			
Yancey (YNCN7)								7.50
Ohio								
Albany (ABNO1)								8.53
Pennsylvania								
Acmetonia (ACMP1)								7.51
Ansonville (ANSP1)								7.29
Blakeslee (TBYP1)								8.20
Cristy Manor 2SE (CRCP1)								7.15
Elimsport (ELIP1)								7.60
Fort Indiantown Gap (FIGP1)								7.90
Hugos Corners (HGCP1)								7.40
Loyalsockville (LOYP1)								5.40
Pine Grove 1SW (PGVP1)								7.70
Scrub Oak (SCBP1)								8.32
South Carolina								
Anderson (KAND)			17/0040		38			
Greenville (KGMU)			17/0253		37			
Greenwood (KGRD)			17/0556		34			
Greer (KGSP)			17/0303		40			
North Myrtle Beach (KCRE)			17/2208		38			
Tennessee								
Crossville (CSST1)			17/0606		34			
Burns (BURT1)			17/0406+*		56			
Charleston (CHTT1)								7.39
Chattanooga (KCHA)	17/0853	994.7						

Chickamauga Dam (CKDT1)								7.63
Coker Creek (CCKT1)			17/06744+		42			
Dayton (DAYT1)								7.65
Decatur (DECT1)								7.86
Lenoir City 5NW (LCLT1)			17/0505		39			
Lewisburg (LSBT1)			17/0106		35			
McDonald								11.03
Morristown 3NNE (HCOT1)			17/0505		36			
Pikeville 7NW (BLDT1)			17/0105		41			
Sweetwater (SWET1)								8.99
Watts Bardam (WBOT1)								7.52
Whitwell 7SE (PCFT1)			16/2106		51			
Texas								
Beaumont (KBPT)	24/0425	1008.8	24/0339	23	30			1.05
Beckville (BEKT2)								7.86
Bon Weir								2.70
Eagle Point – Galveston Bay						1.7		
Galveston Pier 21						1.6		
Houston Hobby (KHOU)	23/2156	1012.9	23/2344		23			0.62
Jamaica Bch Co-op (JBHT2)	23/2230	1012.7	22/0932		29			Trace
Matagorda Island (MIRT2)			24/0512		47			
Sabine Pass North						1.4		
Sam Rayburn Reservoir								3.49
Silsbee 4N								2.00
Steinhagen Lake (TBLT2)								7.07
Toledo Bend Reservoir								2.34
Weches-Houston Co.								1.92
Virginia								
Big Meadows (BGMV2)								5.72
Dulles/Wash. Int'l (KIAD)			17/2212+		37			
Hillsville (KHLX)			17/0900		42			
Hot Springs (KHSP)			18/0500		34			
Langley AFB (KLFI)			19/0155		36			
Leesburg (KJYO)			18/1541		36			
Manassas (KHEF)			18/1955		38			
Martinsville (KMTV)			18/0520		34			
Meadows of Dan (AP852)			18/1815		41			
Melfa (KMFV)			18/0420		37			
Norfolk Int'l (KORF)			19/0351+		35			

Norfolk Naval Stn (KNGU)			19/0755	30	38			
Oceana NAS (KNTU)			18/2256		37			
Reagan/Wash.Int'l (KDCA)			18/2051+		35			
Richmond Int'l (KRIC)			18/0012+		35			
Stafford (KRMN)			18/1720		37			
Strasburg (STGV2)								5.50
TS121 RAWS (37.9N 81.9W)			17/2214		34			
West Virginia								
Buckhannon (KW22)			18/0200+		42			
Charleston (KCRW)			17/2154		32			
Clarksburg (KCKB)			18/0053+		37			
Gallipois Dam (GALW2)								5.94
Moundsville (MOUW2)								7.68

[a] Date/time is for sustained wind when both sustained and gust are listed.
[b] Except as noted, sustained wind averaging periods for C-MAN and land-based ASOS reports are 2 min; buoy averaging periods are 8 min.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above National Geodetic Vertical Datum (1929 mean sea level).
+ Last of several occurrences
# Approximate time
* Instrument failed after report
$ 10-min average
& 30-minute averaging period

Table 4. Selected fixed buoy and C-MAN observations for Hurricane Ivan, 2-24 September 2004.

Location	Minimum Sea Level Pressure		Maximum Surface Wind Speed			Storm surge (ft)[c]	Storm tide (ft)[d]	Total rain (in)
	Date/ time (UTC)	Press. (mb)	Date/ time (UTC)[a]	Sustained (kt)[b]	Gust (kt)			
C-MAN								
BURL1 (28.9N 89.4W)	15/2300	983.6	15/2310	72	87			
			16/0000	69				
			15/2300	68				
	23/0500	1013.8	23/0300	35				
			23/0500	35				
CDRF1 (29.1N 83.0W)			16/1217		31			
CLKN7 (34.6N 76.5W)			18/0228		34			
CHLV2 (36.9N 75.7W)	18/0400	1001.8	18/0350	38	48			
			18/2230	39	45			
			19/0500	39	45			
DPIA1 (30.2N 88.1W)	16/0705	952.7	16/0405	63	89			
			16/0505	63				
DUCN7 (36.2N 75.7W)			18/0330	33	47			
	19/0300	1011.4	19/0400	38				
GDIL1 (29.3N 90.0W)	16/0000	994.2	15/2310	46	61			
			16/0200	43				
GLPT2 (29.3N 94.8W)	23/2200	1012.2	22/0900		32	1.6		
ILDL1 (29.0N 90.5W)	23/0900	1013.7	23/0900	35				
MRSL1 (29.4N 92.1W)	23/1200	1012.0	23/1200	32	38			
SANF1 (24.5N 81.9W)	13/1200	1010.9	13/1200	36	42			
SAUF1 (29.9N 81.3W)			20/0130	30	38			
			20/1950	31	41			
SGOF1 (29.4N 84.9W)	15/2100	1005.2	15/2200	49	62			
SHPF1 (30.1N 84.3W)			16/1454		31			
SIPM6 (30.3N 89.0W)	15/2300#	997.4	15/2300#	38				
SPLL1 (28.9N 90.5W)	16/0200	999.6	16/0200	42				
	23/0700	1011.9	23/0700	36				
TPLM2 (38.9N 76.4W)			18/0332		35			
			18/1740	34	41			
TYBG1 (31.6N 79.9W)	21/0726	1016.6	21/0726	35				
Buoys								
41012 (30.0N 80.6W)			20/1750	29	39			
42001 (25.8N 89.7W)	15/1050	995.2	15/0950	37				

42003 (26.0N 85.9W)	15/0750	993.5	15/0230	55	72			
42007 (30.1N 88.8W)	16/0350#	976.0	16/0350	49	68			
			16/0530	49*				
42035 (29.3N 94.4W)	23/2250	1012.2	16/0900		30			
42036 (28.5N 84.5W)			15/2020	34	49			
42039 (28.8N 86.1W)	15/2350	995.1	15/2150	45	62			
			15/2350	45				
42040 (29.2N 88.2W)	16/0150	955.3	15/2300	55	73			
			16/0950	54				
	16/0050	956.3						
42041 (27.5N 90.5W)	15/1950	997.6	15/1950	35*				
44017 (40.7N 72.0W)	18/1650	1006.9	18/1650	35				

[a] Date/time is for sustained wind when both sustained and gust are listed.

[b] Except as noted, sustained wind averaging periods for C-MAN and land-based ASOS reports are 2 min; buoy averaging
periods are 8 min.

[c] Storm surge is water height above normal astronomical tide level.

[d] Storm tide is water height above National Geodetic Vertical Datum (1929 mean sea level).

* Last of several occurrences

Instrument failed after report

Table 5. Unofficial observations for Hurricane Ivan, 2-24 September 2004.

Location	Minimum Sea Level Pressure		Maximum Surface Wind Speed			Storm surge (ft)[c]	Storm tide (ft)[d]	Total rain (in)
	Date/ time (UTC)	Press. (mb)	Date/ time (UTC)[a]	Sustained (kt)[b]	Gust (kt)			
Windward Islands								
Grenada								
Calivigny Island	07/1955	969.0	07/1955	80	100			
4 SE Princkly Bay			07/2230	70				
St. Georges Harbour	07/1950	978.0	07/2230	60				
Tobago								
HAM Radio 9Y4PDE								16.20
Trinidad								
HAM radio VE7KSN	07/2159	980.0						
Jamaica								
2W Kingston (HAM rpt)			10/2300	39	59			
Kingston (HAM rpt)			11/0055		57			
Kingston Downtown (HAM rpt)			10/2350	est. 74	est. 109			
3W Montego Bay (HAM rpt)			11/0139	est. 87				
Cuba								
Cabo de San Antonio			14/????	est. 116	est. 146			
Punta del Holandes			14/????	est. 100	est. 116			
Mexico								
Cancun (HAM rpt)			13/0225	44				
Isla Mujeres (HAM rpt)			13/2200	38				
Alabama								
Fairhope (storm chaser)	16/????	943.1						
Fairhope - WEMITE 2 (30.5N 87.89W)			16/0342	42	62			
Fairhope - Florida Coastal Monitoring Program (FCMP) - Tower 2 (30.48N 87.87W)			16/0644	59	77			
FCMP Tower2 – Fairhope (30.48N 87.88W)			16/0644	59	77			
Gulf Shores Arpt –DOW3 (30.29N 87.67W)			16/????	73	95			
Gulf Shores Arpt – WEMITE 1 (30.3N 87.66W)			16/0615	70	89			
Gulf Shores - Mark Sudduth/HIRT (30.25N 87.75W)	15/2017	1003.9	15/2017	32	57			

	16/0647	947.2	16/0602*	77	99			
Mobile (Wallace Tunnel)			16/0940		51			
Mobile (WKRG-TV)			16/0604		64			
Mobile Bay (USNS Fisher – ship in dry dock)	16/0830	957.0						
USS Alabama (battleship)			16/0635*		91			
Sailboat *Odalisque* anchored in Wolf Bay/ Orange Beach, AL (72 ft)			16/0600#		126			
Wolf Field Airport – MIPS (30.35N 87.54W)			16/0515	66	87			
Florida								
Carabelle Beach (HAM rpt)	15/2216	999.0	15/2216	28	37			
Cudjoe Key – SKYWARN			13/1348		36			
Destin Arpt – SBCCOM/CR5000 (30.4N 86.48W)			16/0652	60	77			
Eglin AFB Sensors								
5 S Harold	16/0850	981.4						
10 S Harold	16/0740	982.1	16/0710		78			5.72
10 N Mary Esther	16/0820	986.8	16/0730		75			
5 NE Seminole	16/0920	992.1	16/0940		75			8.10
5 SW Mossy Head	16/0900	991.0						
8 SW Mossy Head			16/0710		60			
10 S Mossy Head	16/0900	994.2						8.92
2 SW Mary Esther (200 ft)			16/0850		103			
Molino Volunteer Fire Dept.			16/0855		70			
Pensacola - Florida Coastal Monitoring Program (FCMP) Tower 1 (30.48N 87.19W)			16/0649	69	92			
Pensacola P.D. (70 ft)			16/0644		108			13.50
			16/0312		97			
			16/0700		92			
St. George Island (HAM rpt)	16/0150	1005	16/0150	39				
West Pensacola			16/????		84			
Georgia								
Greenville (HAM rpt)			16/1730		48			
Newnan	16/2215	963.1	17/0011		45			
Mississippi								
Gulfport Arpt – SBCCOM/CR23X (30.4N 80.1W)			16/0415	44	62			
Pascagoula EOC (on 2-story bldg)			16/0600		76			

[a] Date/time is for sustained wind when both sustained and gust are listed.
[b] Except as noted, sustained wind averaging periods for C-MAN and land-based ASOS reports are 2 min; buoy averaging periods are 8 min.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above National Geodetic Vertical Datum (1929 mean sea level).
* Instrument failed afterwards.
# Approximate time.

Table 6. Preliminary forecast evaluation (heterogeneous sample) for Hurricane Ivan, 9-14 August 2004. Forecast errors (n mi) are followed by the number of forecasts in parentheses. Errors smaller than the NHC official forecasts are shown in bold-face type. Verification includes the depression stage.

Forecast Technique	Forecast Period (h)						
	12	24	36	48	72	96	120
CLP5	25 (62)	51 (60)	86 (58)	121 (55)	175 (51)	229 (47)	296 (44)
GFNI	27 (57)	57 (55)	95 (55)	134 (53)	219 (49)	325 (45)	443 (41)
GFDI	28 (60)	52 (58)	**77** (57)	**94** (55)	**147** (51)	**204** (47)	**261** (43)
GFDL	29 (61)	52 (59)	**76** (57)	**92** (56)	**136** (52)	**195** (48)	**252** (44)
GFDN	29 (56)	51 (54)	79 (53)	118 (53)	198 (49)	298 (45)	412 (41)
GFSI	29 (60)	55 (58)	79 (57)	**100** (55)	**154** (51)	**212** (47)	**285** (43)
GFSO	32 (63)	56 (61)	80 (58)	**99** (56)	**147** (52)	**198** (48)	**268** (43)
AEMI	27 (60)	49 (58)	**73** (57)	**95** (55)	**151** (51)	**203** (47)	**252** (43)
NGPI	26 (59)	54 (57)	86 (56)	119 (54)	200 (50)	304 (46)	449 (42)
NGPS	29 (61)	52 (59)	82 (56)	109 (54)	186 (50)	278 (46)	413 (42)
UKMI	24 (58)	47 (56)	**72** (55)	**92** (53)	**147** (49)	**214** (45)	**286** (41)
UKM	26 (30)	**44** (29)	**66** (28)	**87** (28)	**133** (26)	**189** (24)	**279** (22)
A98E	27 (61)	**43** (59)	**72** (57)	**103** (55)	**179** (51)	248 (47)	349 (44)
A9UK	27 (28)	**43** (27)	**71** (26)	**95** (25)	149 (23)		
BAMD	31 (61)	54 (59)	**78** (57)	**96** (55)	**147** (51)	**219** (47)	300 (44)
BAMM	32 (61)	53 (59)	86 (57)	116 (55)	172 (51)	**214** (47)	**283** (44)
BAMS	48 (61)	93 (59)	142 (57)	179 (55)	236 (51)	251 (47)	**286** (44)
CONU	**22** (60)	47 (58)	**74** (57)	**97** (55)	**154** (51)	224 (47)	307 (43)
GUNA	**22** (58)	**45** (56)	**71** (55)	**92** (53)	**147** (49)	**213** (45)	289 (41)
FSSE	**21** (53)	**38** (51)	**58** (51)	**81** (51)	**126** (47)	**171** (43)	**199** (38)
OFCL	24 (63)	47 (61)	79 (59)	108 (56)	161 (52)	222 (48)	289 (44)
NHC Official, 1994-2003 mean (number of cases)	44 (3172)	78 (2894)	112 (2636)	146 (2368)	217 (1929)	248 (421)	319 (341)

Table 7. Watch and warning summary for Hurricane Ivan. 2-24 September 2004.

Date/Time (UTC)	Action	Location
5/2100	Hurricane Watch Issued	Barbados
6/0000	Tropical Storm Watch Issued	Grenada and Dependencies
6/0300	Hurricane Watch Issued	St. Lucia
6/1200	Tropical Storm Warning Issued	St. Vincent and Grenadines
6/1200	Hurricane Watch Issued	Martinique
6/1200	Tropical Storm Warning Issued	Tobago, Grenada and Dependencies
6/1500	Hurricane Warning Issued	Barbados, St. Vincent, Grenadines, St. Lucia, Tobago, Grenada and Dependencies
6/1500	Tropical Storm Warning Issued	Trinidad
7/0300	Tropical Storm Warning Issued	Martinique
7/0600	Tropical Storm Warning Issued	St. Lucia, St. Vincent, Grenadines, Grenada and Dependencies
7/0900	Tropical Storm Warning Issued	Barbados
7/1500	Hurricane Watch Issued	Bonaire, Curacao, Aruba
7/2100	Tropical Storm Warning Issued	Tobago, Bonaire, Curacao, Aruba
7/2100	Hurricane Watch and Tropical Storm Warning Issued	Guajira Peninsula Northern Coast of Venezuela
7/2245	Tropical Storm Warning Discontinued	Martinique
8/0000	Tropical Storm Warning Discontinued	Trinidad, Tobago
8/0300	Hurricane Warning Issued	Bonaire, Curacao, Aruba
8/0300	Tropical Storm Warning Discontinued	St. Lucia

8/0900	Tropical Storm Warning Discontinued	Barbados, St. Vincent, Grenadines, Grenada and Dependencies
8/0900	Tropical Storm Watch Issued	Santo Domingo to D.R./Haiti Border
8/1500	Hurricane Watch Issued	D.R./Haiti Border to Port-Au-Prince
8/2100	Hurricane Watch Issued	Jamaica
9/0300	Hurricane Watch Issued	Cayman Islands
9/0300	Tropical Storm Warning Issued	D.R./Haiti Border to Port-Au-Prince
9/1500	Hurricane Warning Issued	Jamaica
9/1500	Hurricane Watch Issued	Barahona to D.R./Haiti Border
9/1500	Hurricane Warning Discontinued	Bonaire, Curacao, Aruba
9/1500	Hurricane Watch and Tropical Storm Warning Discontinued	Guajira Peninsula Northern Coast of Venezuela
9/1500	Hurricane Watch Issued	Matanzas eastward
9/2100	Hurricane Warning Issued	Cayman Islands
10/1500	Hurricane Watch	All Cuba and Isle of Youth
10/1500	Tropical Storm Warning Issued	Cabo Cruz to Santiago De Cuba
10/1500	All Watches/Warnings Discontinued	Dominican Republic
11/0900	Tropical Storm Warning Extended West	Cabo Cruz to Cienfuegos
11/0900	Tropical Storm Warning Discontinued	Haiti
11/1500	Hurricane Warning Issued	Ciago De Avila to Pinar Del Rio and Isle of Youth
12/0300	Tropical Storm Warning Issued	Jamaica
12/1500	Tropical Storm Warning Discontinued	Jamaica

12/1500	Tropical Storm Watch Issued	7 mile Bridge to Dry Tortugas
12/2100	Hurricane Watch and Tropical Storm Warning Issued	Tulum to Progreso (Yucatan)
13/0900	Hurricane Warning Issued	Tulum to Progreso
13/1500	Hurricane Warning Discontinued	Cayman Islands
14/0000	Hurricane Warning Adjusted	Havana east to Pinar Del Rio and Isle of Youth
14/0300	Hurricane Watch Issued	Morgan City, LA to St. Marks, FL
14/1500	Tropical Storm Warning Issued	Tulum to Progreso (Yucatan)
14/1800	Tropical Storm Warning Issued	Havana east to Pinar Del Rio and Isle of Youth
14/2100	Hurricane Warning Issued	Grand Isle, LA to Apalachicola, FL
14/2100	Hurricane Watch Issued	Morgan City, LA to Grand Isle, LA
14/2100	Tropical Storm Warning Issued	Intracoastal City, LA to Grand Isle, LA Apalachicola, FL to Yankeetown, FL
14/2100	All Watches/Warnings Discontinued	Yucatan, Cuba
15/0300	Tropical Storm Watch Discontinued	7 mile Bridge to Dry Tortugas
15/2100	Tropical Storm Warning Discontinued	Morgan City, LA to Intracoastal City, LA
16/0900	All Watches and Warnings Discontinued	West of Grand Isle, LA
16/0900	Tropical Storm Warning Issued	Mouth of Pearl River, LA to Grand Isle, LA
16/1200	Tropical Storm Warning Discontinued	Apalachicola, FL to Yankeetown, FL
16/1500	Tropical Storm Warning Issued	Mouth of Pearl River, LA to Apalachicola, FL
16/1500	Tropical Storm Warning Discontinued	Grand Isle, LA to Mouth of Pearl River, LA
16/1800	Tropical Storm Warning Discontinued	West of MS/LA Border

16/2100	Tropical Storm Warning Discontinued	MS/LA Border to Apalachicola, FL
22/2300	Tropical Storm Warning Issued	Mouth of MS River to Sargent, TX
23/1500	Tropical Storm Warning Discontinued	Mouth of MS River to Morgan City, LA
23/2100	Tropical Storm Warning Discontinued	San Luis Pass, TX to Sargent, TX
24/0300	All Warnings Discontinued	Remaining Coastal (San Luis Pass, TX to Morgan City, LA)

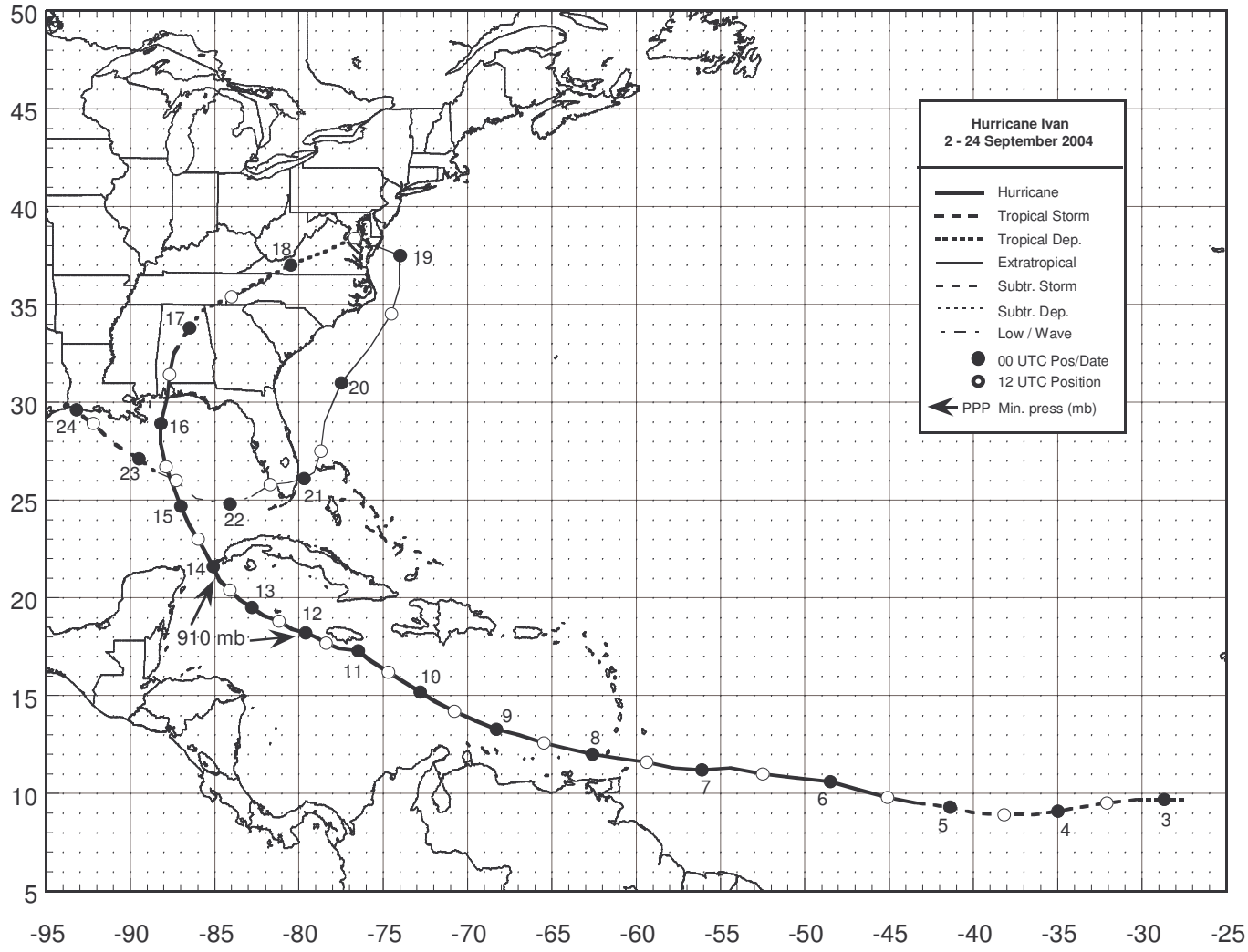

Figure 1. Best track positions for Hurricane Ivan, 2-24 September 2004.

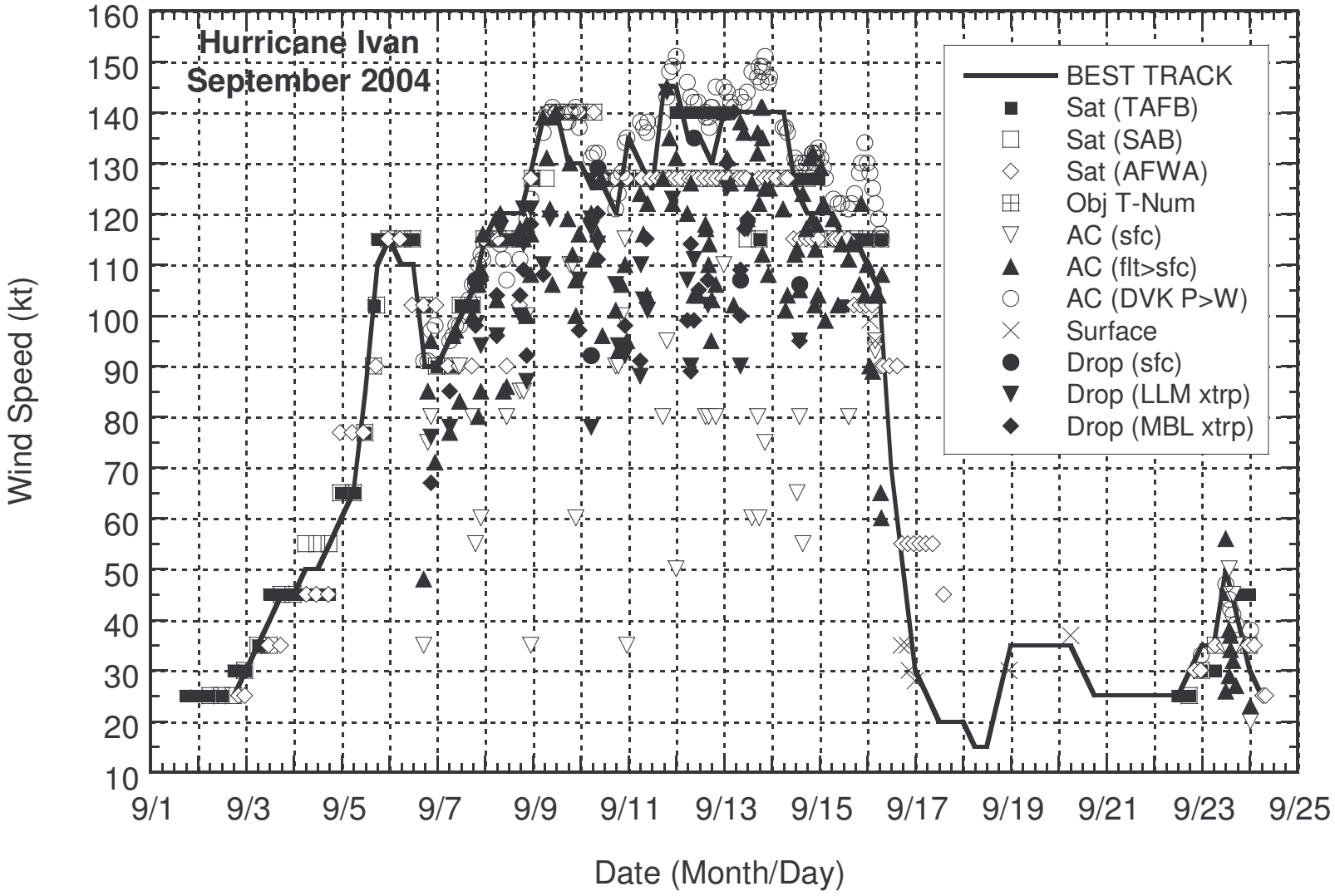

Figure 2a. Selected wind observations and best track maximum sustained surface wind speed curve for Hurricane Ivan, 2-24 September 2004. Aircraft observations have been adjusted for elevation using 90%, 80%, and 80% reduction factors for observations from 700 mb, 850 mb, and 1500 ft, respectively.

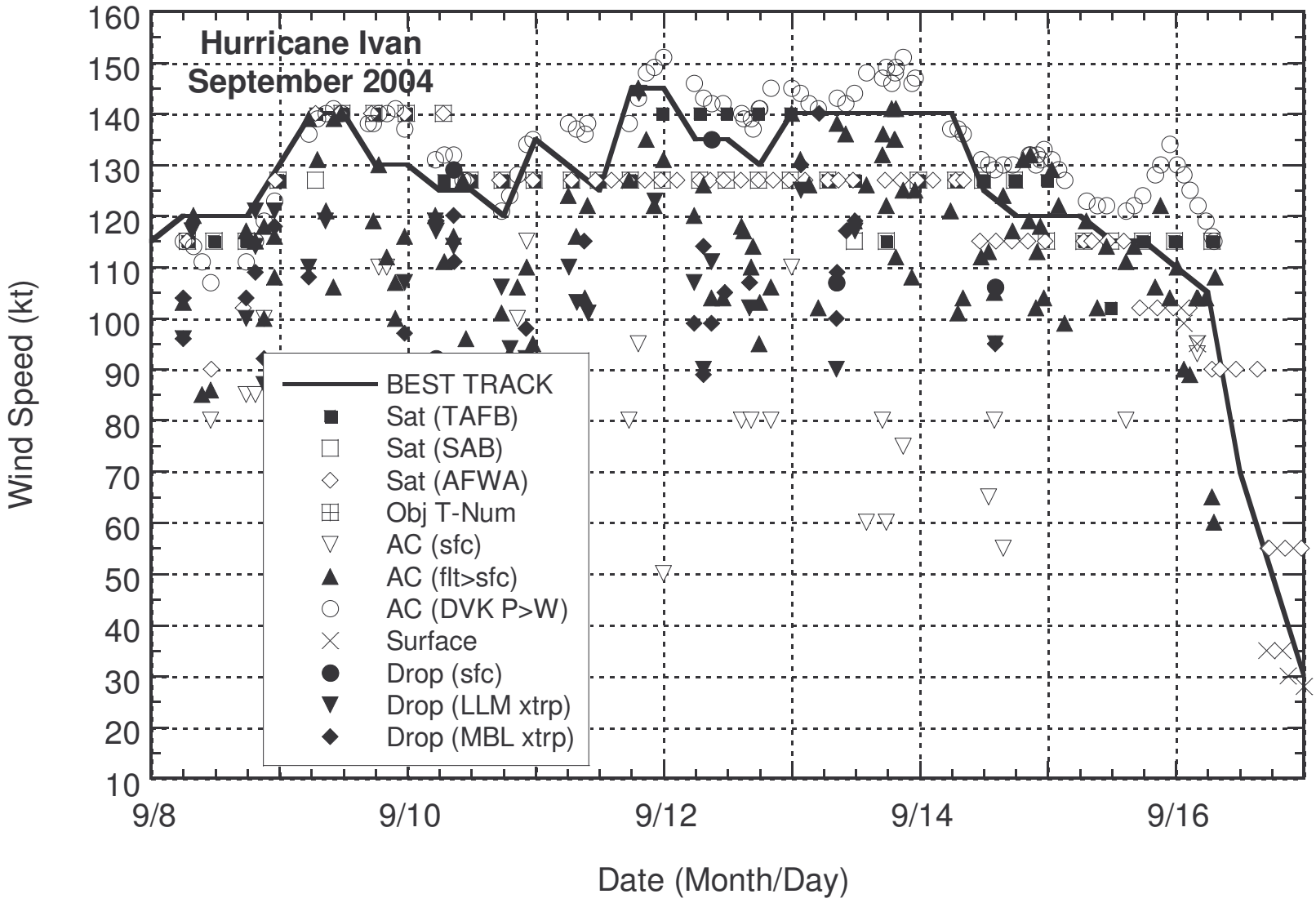

Figure 2b. Selected wind observations and best track maximum sustained surface wind speed curve for Hurricane Ivan during the peak intensity period of 9-16 September 2004.

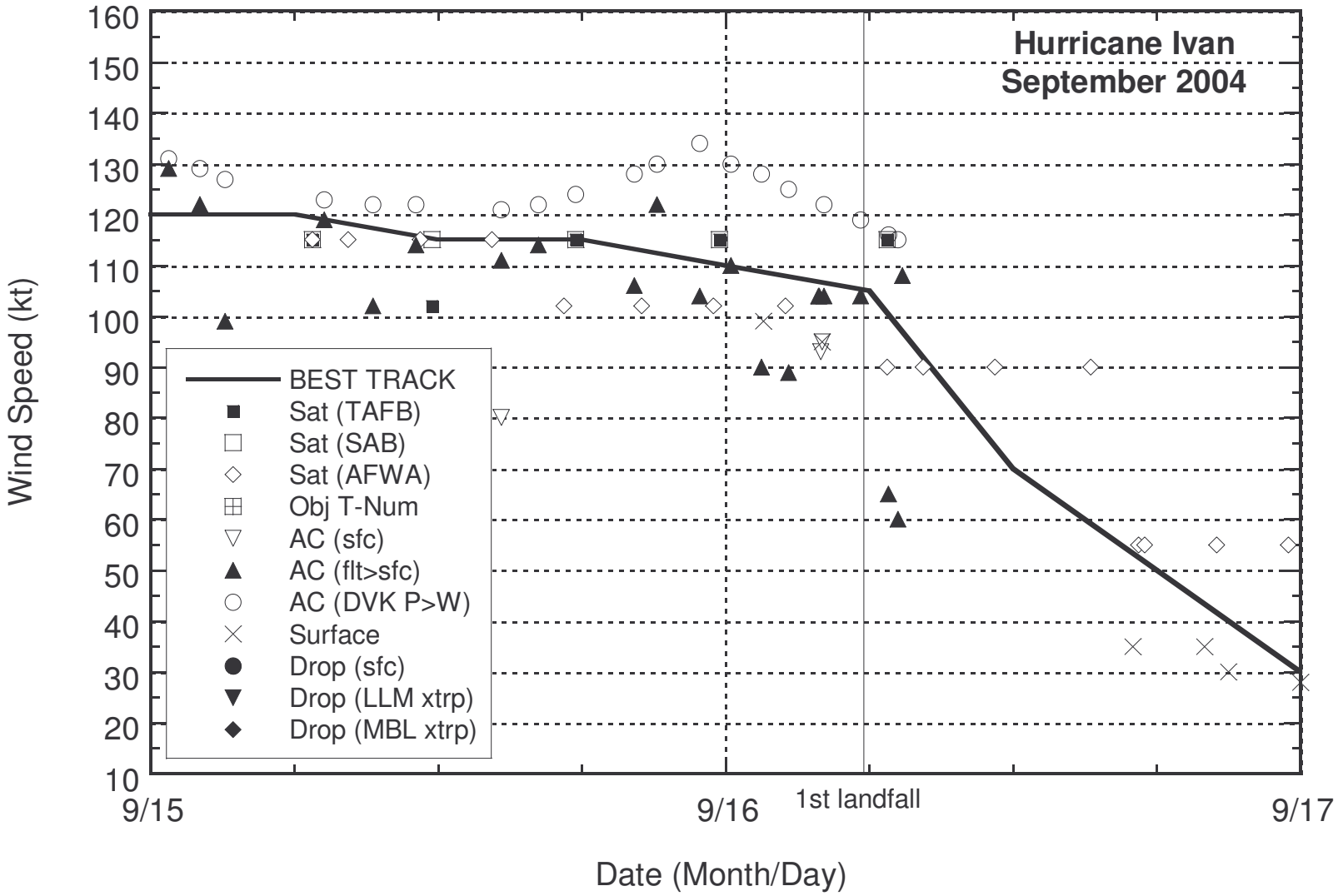

Figure 2c. Selected wind observations and best track maximum sustained surface wind speed curve for Hurricane Ivan approximately 24h prior to and 18 h after landfall (15-17 September 2004) along the Alabama coast. The highest surface winds occurred along the extreme western Florida panhandle coastal areas, well east of where the center actually made landfall along the Alabama coast.

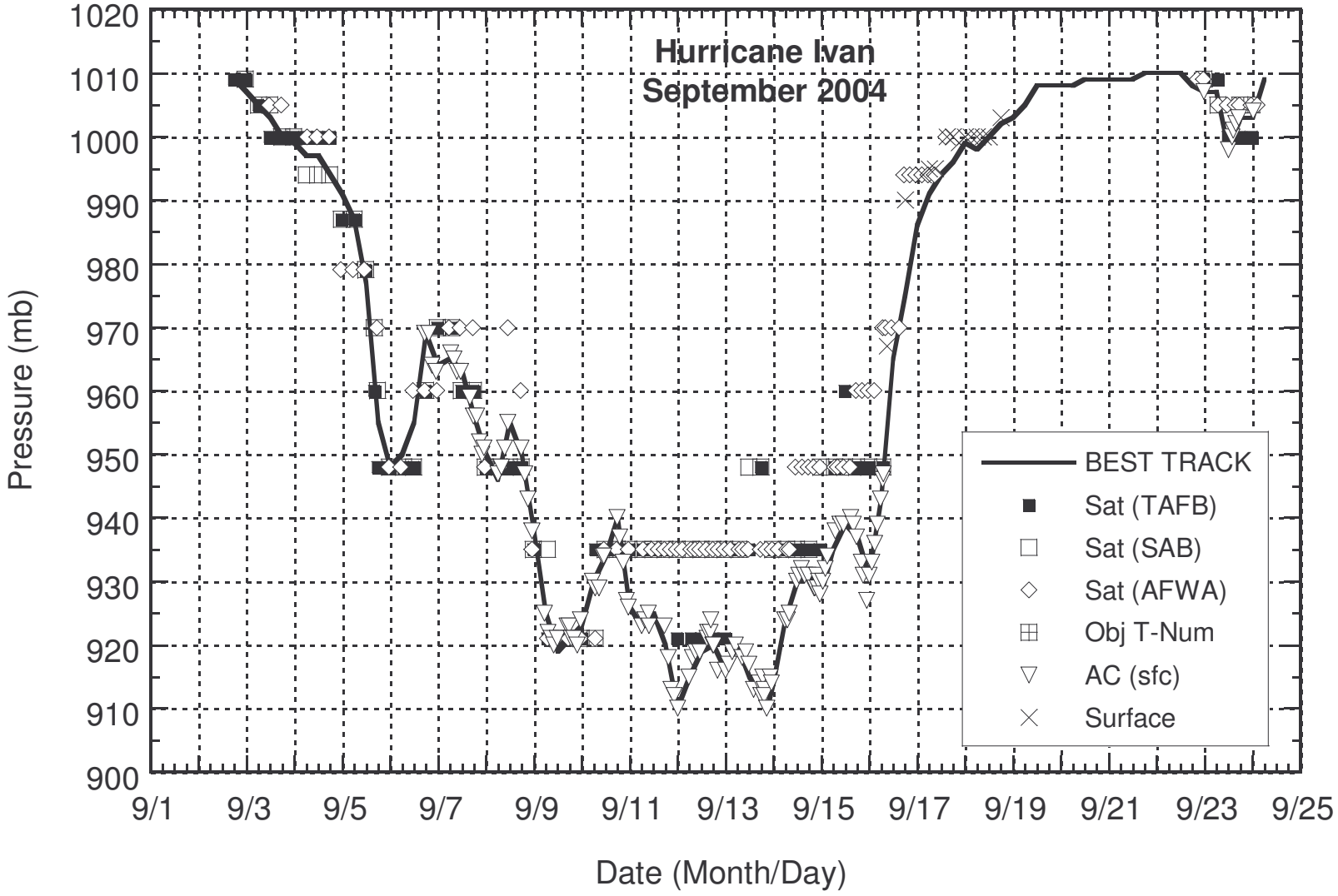

Figure 3a. Pressure observations and minimum central pressure curve for Hurricane Ivan, 2-24 September 2004.

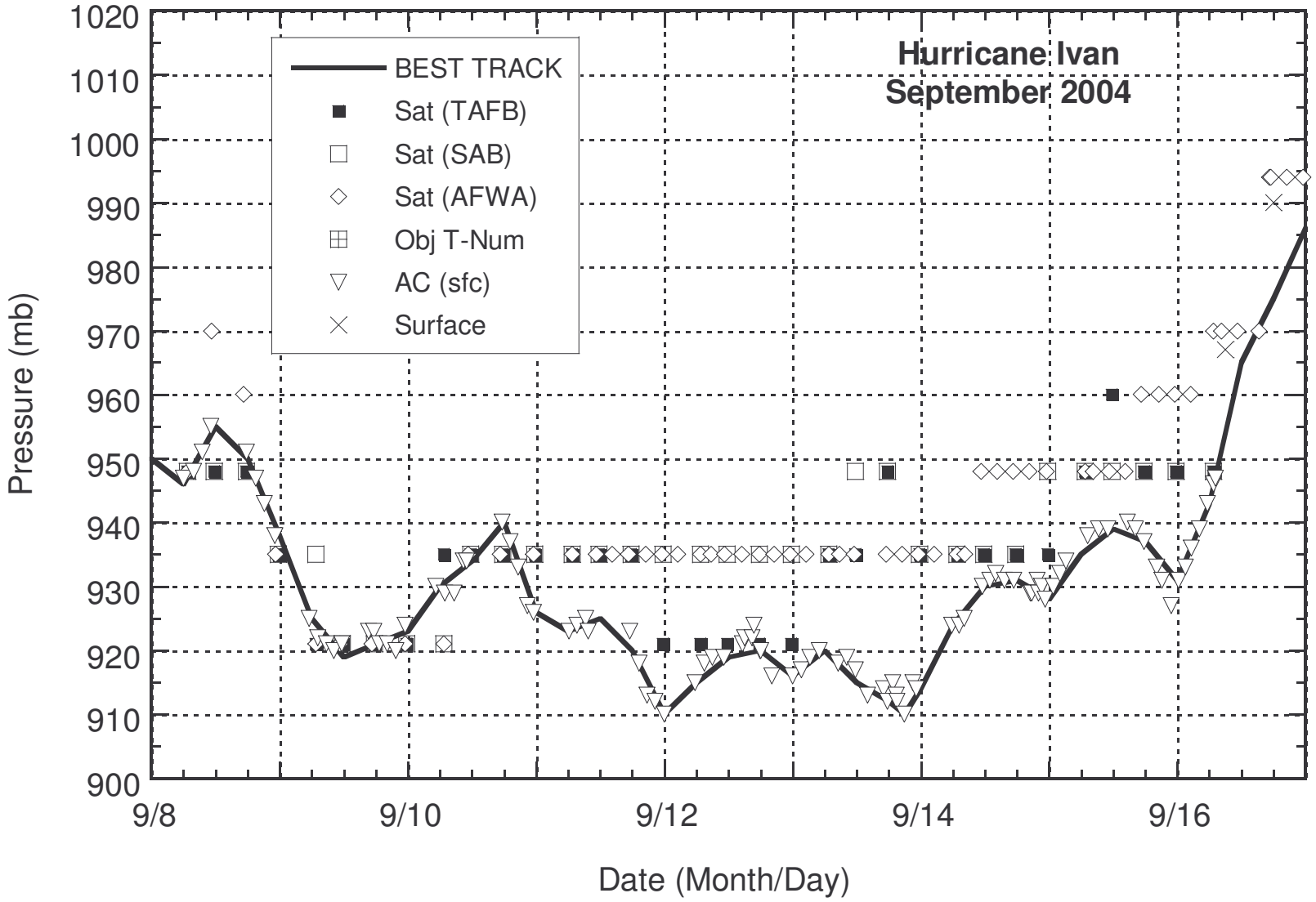

Figure 3b. Pressure observations and minimum central pressure curve for Hurricane Ivan during its period of greatest intensity (9-16 September 2004).

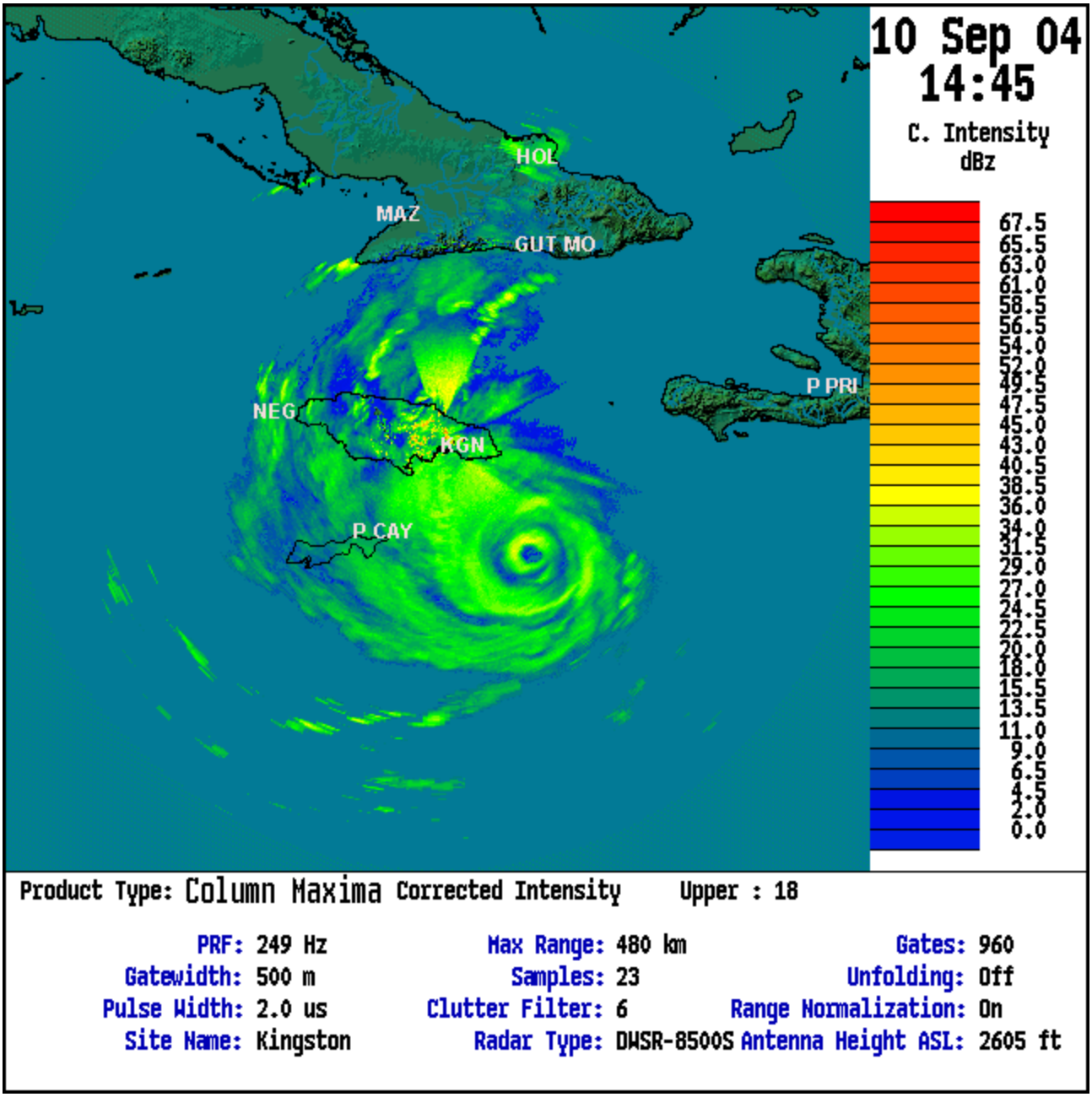

Figure 4a. Radar reflectivity image from Kingston, Jamaica at 1444 UTC 10 September 2004 as Ivan was approaching the island from the southeast. Ivan had weakened from a category 5 hurricane down to category 4 hurricane with sustained winds of 125 kt at this time. Note the two concentric eyewalls that likely were the cause of the short term weakening (image courtesy of the Jamaica Meteorological Service).

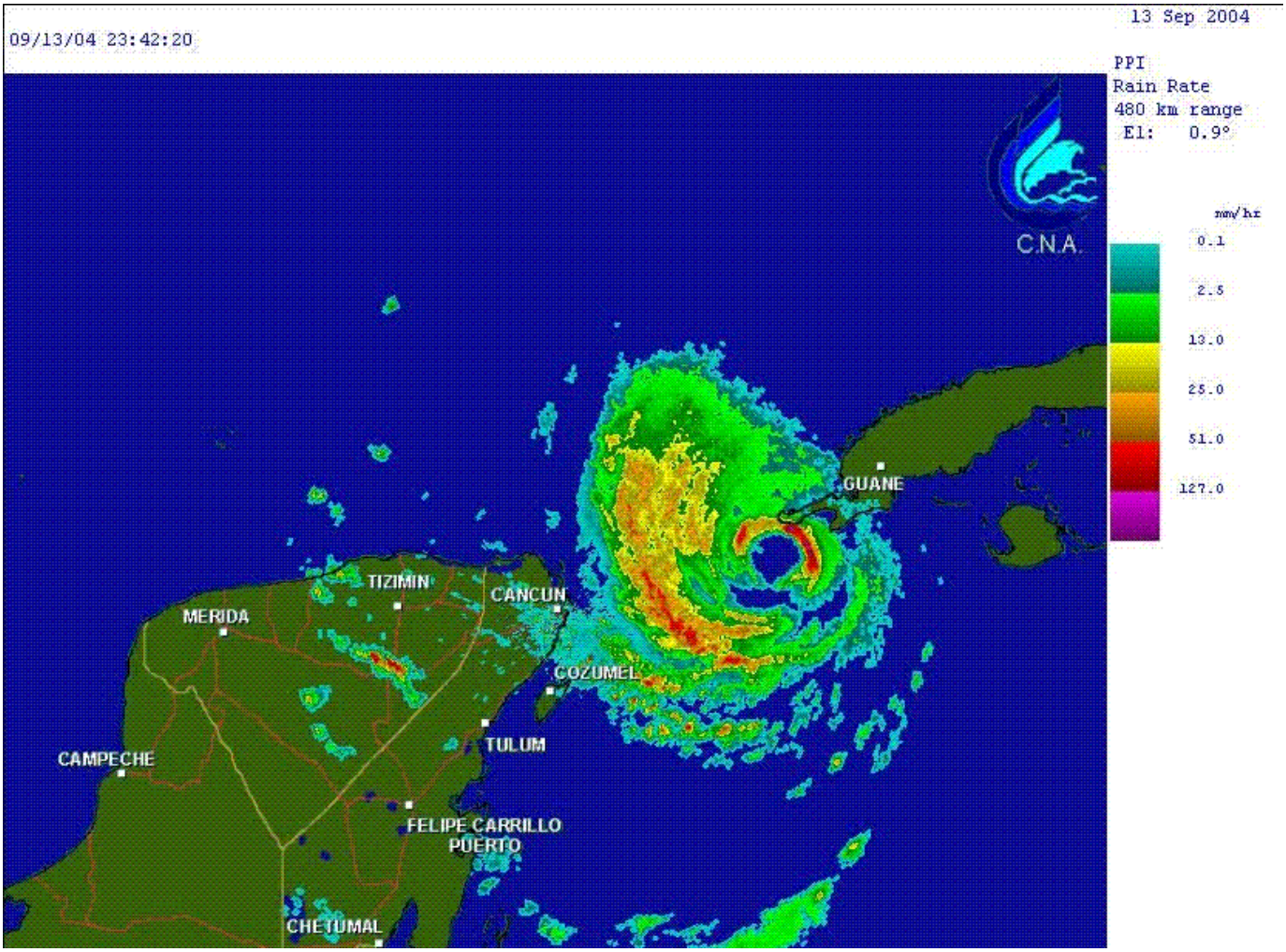

Figure 4b. Radar reflectivity image from Cancun, Mexico at 2342 UTC 13 September 2004. Ivan was a category 5 hurricane with sustained winds of 140 kt and a pressure of 914 mb at this time (image courtesy of the National Meteorological Service of Mexico).

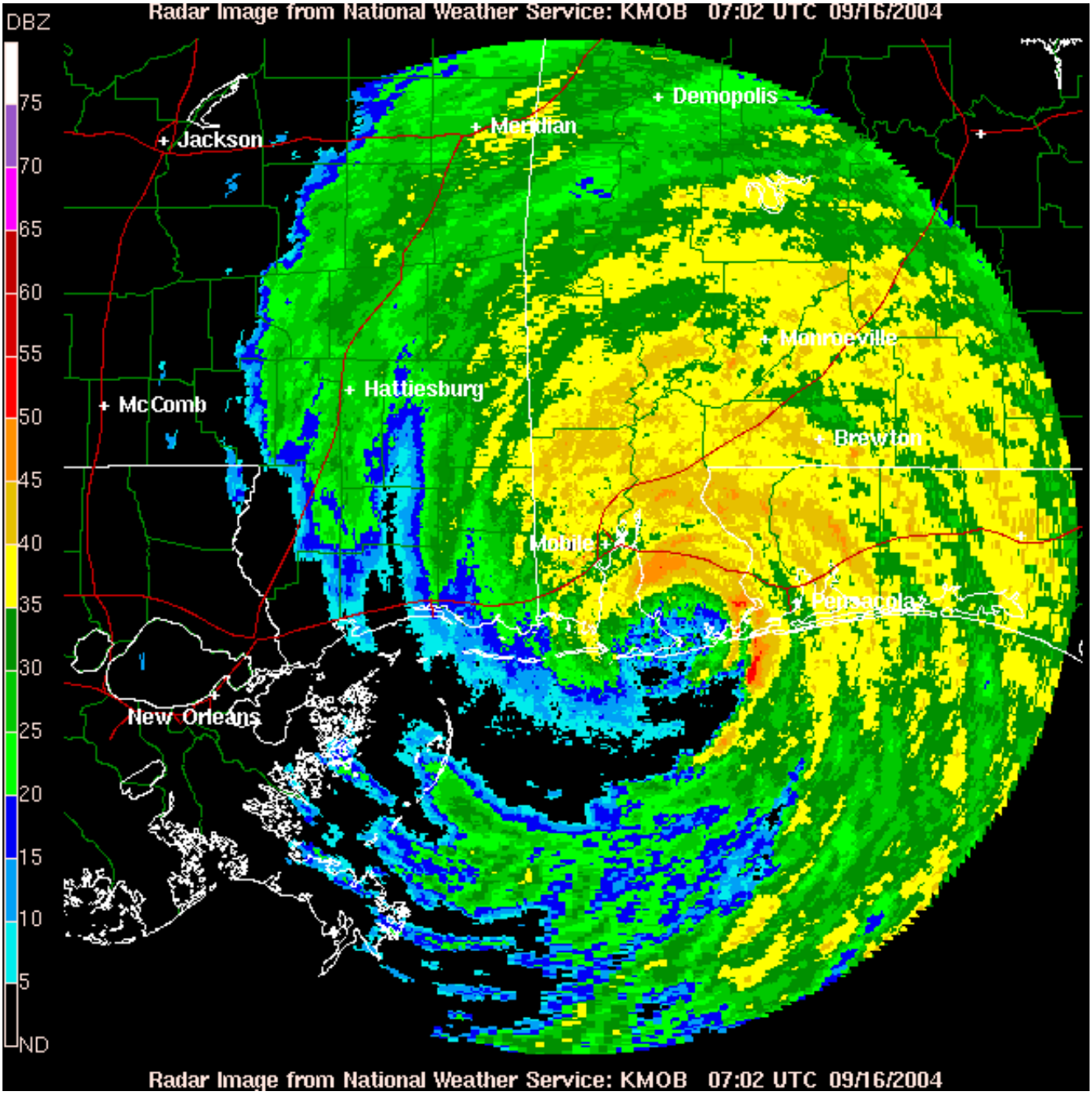

Figure 4c. Reflectivity image of Hurricane Ivan from the Mobile, AL National Weather Service Forecast Office WSR-88D Doppler radar at 0702 UTC 16 September 2004 -- less than 15 min after the time of landfall along the Alabama coast. The center of the broad eye of the hurricane was inland over extreme southern Alabama at this time. An Air Force Reserve reconnaissance aircraft reported flight-level winds of 120 just offshore in the strong convective band (red 50 dBZ areas) southwest of Pensacola, Florida kt about 20 min after the time of this image. Peak Doppler radar velocities ranged from 120-123 kt at 6,000 ft ASL as Ivan moved onshore.

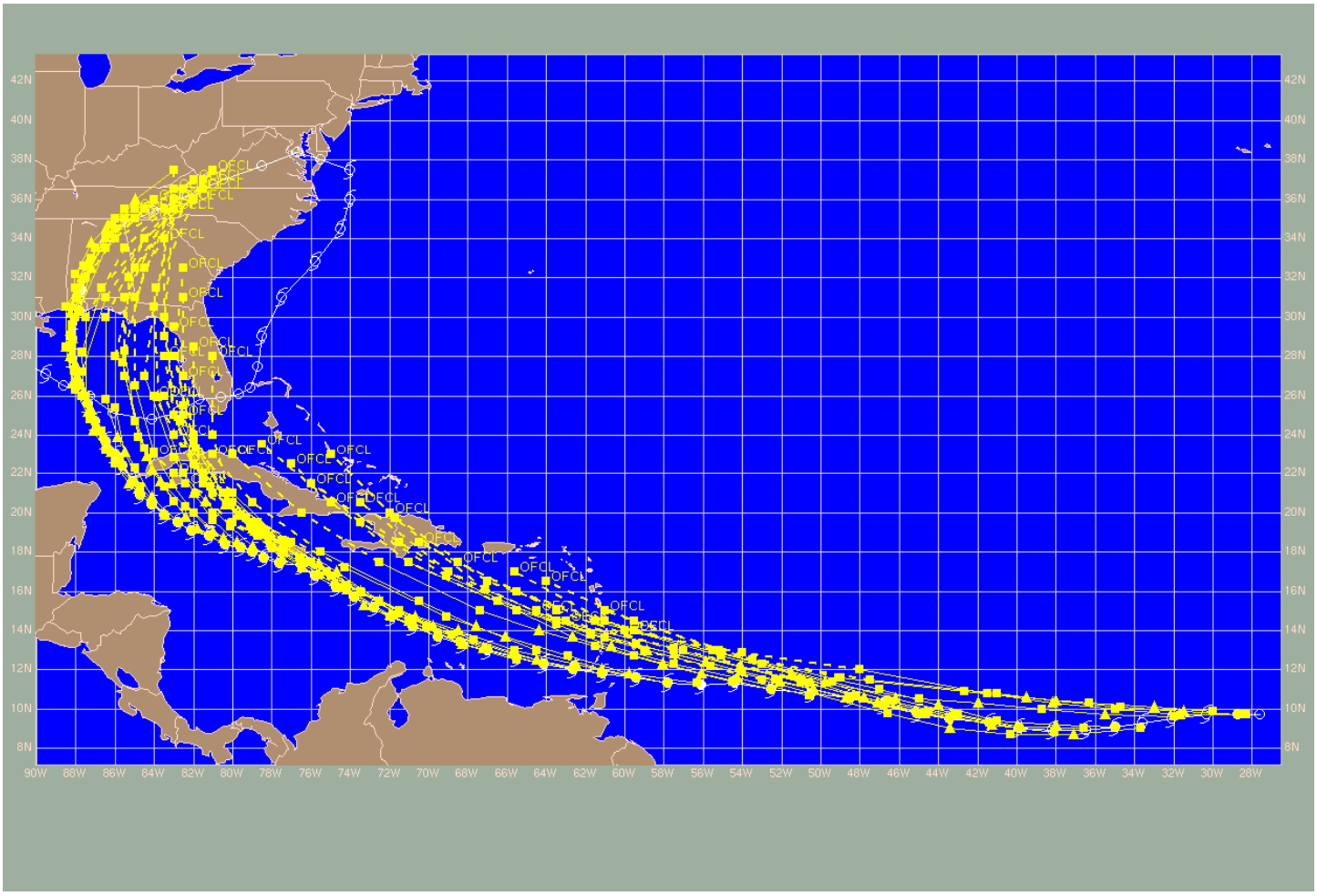

Figure 5a. NHC Official forecast tracks (OFCL) for Hurricane Ivan during the period 1800 UTC 02 through 0600 UTC 16 September 2004 (1st U.S. landfall). Note the persistent right-of-track bias from the outset as a result of most of the global models prematurely eroding the subtropical ridge to the north of the hurricane.

Figure 5b. NHC Official forecast tracks (OFCL) for Hurricane Ivan during the period 0600 UTC 13 September to 0000 UTC 16 September 2004. Note the small spread in the forecast tracks (from 72 h through 6 h prior to landfall), which targeted the Alabama and extreme western Florida panhandle coastal areas as the most likely region where landfall would occur.

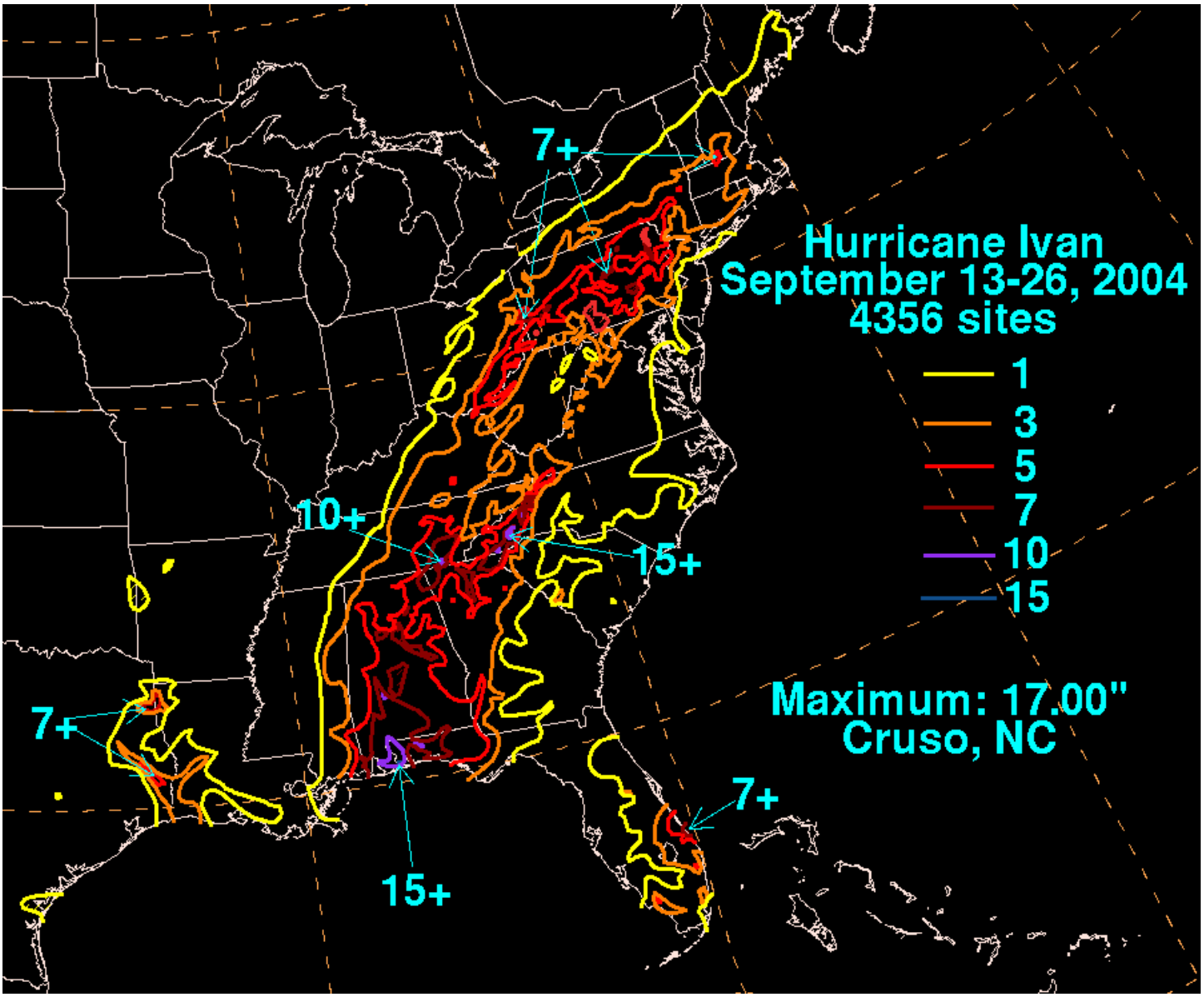

Figure 6. United States rainfall totals for Hurricane Ivan (image courtesy of NOAA Hydrometeorological Prediction Center).