Tropical Cyclone Report
Hurricane Keith
28 September - 6 October 2000

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Keith was a rapidly-intensifying tropical cyclone over the northwestern Caribbean Sea, reaching Category 4 on the Saffir-Simpson Hurricane Scale as it stalled just off the coast of Belize. Keith affected the coastal islands of Belize as a Category 3 hurricane, but weakened to a tropical storm before actually making landfall in mainland Belize. After weakening to a tropical depression while crossing the Yucatan Peninsula, Keith re-intensified over the southwestern Gulf of Mexico and made landfall in northeastern Mexico as a Category 1 hurricane.

a. Synoptic history

A tropical wave moved off the west coast of Africa on 16 September. The wave showed signs of organization over the Atlantic from 19-22 September, but strong vertical shear prevented development then. The wave continued westward into the Caribbean Sea and started to become better organized on 27 September, when the first Dvorak satellite intensity estimate was made. Development continued, and an Air Force Reserve Hurricane Hunter aircraft found that the system became a tropical depression about 60 n mi north-northeast of Cape Gracias a Dios, Nicaragua, around 1800 UTC 28 September (Table 1 and Figure 1). The depression moved northwestward, and a second flight around 1800 UTC 29 September indicated that the cyclone had become Tropical Storm Keith.

Rapid intensification began near that time, and Keith's central pressure fell from 1000 mb at 1814 UTC on the 29th to 939 mb at 0708 UTC 1 October -- a 61 mb fall in about 37 h. A 38 mb fall occurred from 1808 UTC on the 30th to the time of minimum pressure, which qualifies as explosive deepening as defined by Dunnavan (1981). Maximum winds reached 120 kt -- Category 4 on the Saffir-Simpson hurricane scale near the time of minimum pressure. During this rapid development, Keith slowed and turned westward, with the eye moving to a position just southeast of the coastal islands of Belize. A slight weakening occurred later on the 1st, and Keith was a Category 3 hurricane when the eyewall moved over Ambergris Cay and Caye Caulker, Belize near 1800 UTC.

Motion then became slow and erratic, with the eye of Keith meandering just off the Belize coast into 3 October. This was partly due to high pressure over the Gulf of Mexico blocking the hurricane's path, and partly due to formation of a tropical disturbance (later to become Tropical Storm Leslie) near western Cuba. The cyclone weakened dramatically during this time. Keith was a Category 1 hurricane when the center crossed Ambergris Cay, Belize near 2300 UTC on the 2nd and a 60-kt tropical storm when the center crossed the Belize mainland coast between Belize City and Chetumal, Mexico around 0300 UTC on the 3rd.

Once inland, Keith began moving west-northwestward, and this direction of general motion continued with a gradual acceleration until its final landfall. It weakened to a depression over the Yucatan Peninsula, then re-intensified to a tropical storm over the Bay of Campeche on 4 October. Keith regained hurricane status on 5 October, and maximum winds increased to 80 kt as the hurricane made landfall about 20 n mi north of Tampico Mexico around 1800 UTC that day. Keith again weakened over land, and the cyclone dissipated over northeastern Mexico the next day.

b. Meteorological statistics

Table 1 shows the best track positions and intensities for Keith, with the track plotted in Figure 1. Figures 2 and 3 depict the curves of minimum central sea-level pressure and maximum sustained one-minute average "surface" (10 m above ground level) winds, respectively, as a function of time. These figures also contain the data on which the curves are based: aircraft reconnaissance and dropsonde data from the Air Force Reserve Hurricane Hunters, and satellite-based Dvorak technique intensity estimates from the Tropical Analysis and Forecast Branch (TAFB), the Satellite Analysis Branch (SAB) of the National Environmental Satellite Data and Information Service (NESDIS), and the Air Force Weather Agency (AFWA).

The Hurricane Hunters flew 11 missions into Keith with a total of 34 center fixes. The maximum flight-level wind reported during the storm was 133 kt at 850 mb at 2220 UTC 1 October, while the maximum wind reported from dropsondes in the eyewall was 153 kt at 883 mb at 0705 UTC 1 October. The maximum surface wind estimated from the dropsondes was 115 kt at 0600 UTC 1 October. The best track minimum pressure was 939 mb, which requires further comment. Observed dropsonde pressures at peak intensity were 943 and 942 mb. However, the reported surface winds from those sondes were in excess of 40 kt, indicating they did not splash in the center of the eye. The 939 mb pressure is based on extrapolation of pressure values from the 700 mb flight level using the temperature and moisture data from the sondes.

The core of Keith missed most observing stations near the track. The maximum reported wind from any official station was 40 kt sustained with gusts to 55 kt at Tampico, Mexico at 1445 UTC 5 October. The few other significant land observations are summarized in Table 2. Amateur radio operators reported measured winds of 90-110 kt in San Pedro (on Ambergris Cay) and Caye Caulker, Belize on 1 October while under the eyewall. While these observations are significant, their reliability is uncertain and they are not included in Table 2. Also not included is a 35 kt report from a Mexican oil platform in the Bay of Campeche at 1700 UTC 4 October, as the height of the anemometer is unknown.

The only ship to report tropical storm-force winds in Keith was the **Edyth L** (call sign **C6YC**), which reported 60 kt winds and a 1009.0 mb pressure in the northwestern Caribbean Sea at 1800 UTC 30 September.

The only known storm surge observation was from Caye Caulker, where a 4-5 ft surge from the west occurred. Tides of 4 ft *below* normal were noted on the Belize mainland coast while Keith was just offshore of the coastal islands. The National Hurricane Center also received reports that northerly winds associated with Keith had temporarily blown the water out of the Bay of Chetumal

and people were walking on the exposed bay bottom. This was a potentially dangerous situation, as the water could have quickly returned had Keith moved and the winds shifted.

Keith's slow motion led to torrential rainfall over portions of Central America, especially Belize. The largest storm total was 32.67 in at the Philip Goodson International Airport in Belize City. Several other totals exceed 10 in. Table 2a summaries the available rainfall data.

c. Casualty and damage statistics

Reports from the Meteorological Service of Belize and the media indicate the death toll from Keith is 24: 5 in Belize, 12 in Nicaragua, 6 in Honduras, and 1 in Mexico. The deaths in Belize occurred when two catamarans broke loose during the storm. Five of the deaths in Honduras occurred when an aircraft disappeared near Roatan Island during the storm. The other deaths are apparently due to flooding from heavy rains. The estimated damage to property, agriculture, and tourism in Belize is near $225 million. Much of the property damage occurred on Ambergris Cay and Caye Caulker.

There are no reports of damage or casualties from Keith's final landfall in northeastern Mexico. Heavy rains in Guatemala caused flooding in ten towns, but no estimates of the damage are available.

d. Forecast and warning critique

Table 3 shows the average track forecast errors during Keith, including the official forecast error, the 10-year average forecast error, and the track guidance errors. The official forecast errors were better than the 10-year average at 12 and 24 h and significantly worse than the 10-year average at longer times. The official forecasts were worse than the CLImatology and PERsistence (CLIPER or CLIP in the table) forecasts and thus had no skill. Many of the numerical guidance models also outperformed the official forecast, with the most notable being the U.S. Navy version of the GFDL model (GFDN), which had errors of 25, 33, 68, 97, and 136 n mi at 12, 24, 36, 48, and 72 h respectively. This model likely performed well due to both it and its parent NOGAPS model (NGPS in the table) doing a better (although not perfect) job of catching Keith's westward motion. The AVN model and its associated guidance (including the GFDL) showed a consistent bias of being too far to the north partly due to mislocation of the vortex in the model.

NHC track forecasts of Keith also showed a consistent bias to the north, likely in response to the AVN, GFDL, and UKMET guidance. Figure 4 shows an example of the available guidance at 1200 UTC 2 October. Note that all the guidance forecasts a northward to northwestward motion even when initialized with a stationary storm, and that the official forecast followed the right side of the guidance. Also note that in this example the actual track was outside the envelope of the guidance. NHC's 72 h track forecast errors were never less than 225 n mi, and most were in the 325-390 n mi range. It should be noted that once Keith moved into the Gulf of Mexico the forecast accuracy improved considerably: a 36 h forecast issued 30 h before the final landfall had an error of 66 n mi and a 24 h forecast verifying at landfall had only a 70 n mi error, both better than the respective 10-year averages.

The official intensity forecast errors for Keith were 13, 22, 23, 18, and 23 kt for 12, 24, 36, 48, and 72 h. This is significantly worse than the 10-year average of 7, 11, 13, 16, and 19 kt at those times. The largest intensity forecast error was a 60 kt underforecast of the 36 h intensity from the 1800 UTC 29 September forecast. The poor forecasts had four causes: 1) Underestimating how quickly Keith would strengthen over the open Caribbean, 2) Incorrect track forecasts that led to forecasting a weakening Keith over the Yucatan Peninsula when the storm actually stayed over water, 3) An underestimation of how quickly Keith would weaken after it neared the coast of Belize, and 4) An underestimation of how much Keith would re-intensify over the Gulf of Mexico.

The poor track forecasts had an impact on watches and warnings. Watches and Warnings were posted for the Mexican portion of the Yucatan Peninsula late on the 29th and early on the 30th. However, most of these areas were not seriously affected by Keith. Hurricane warnings for the actual landfall area in Belize were issued about 24 h before the eyewall of Keith arrived over the coastal islands.

Table 4 lists the watches and warnings associated with Keith.

Acknowledgements

Carlos Fuller of the Meteorological Service of Belize provided many of the observations used in this report. James Franklin created several of the figures.

References

Dunnavan, G. M., 1981: Forecasting intense tropical cyclones using 700-mb equivalent potential temperature and sea-level pressure. NOCC/JTWC Technical Note 81-1, 12 pp.

Table 1. Best track, Hurricane Keith, 28 September - 6 October 2000.

Date/Time (UTC)	Latitude (°N)	Longitude (°W)	Pressure (mb)	Wind Speed (kt)	Stage
28 / 1800	16.1	82.9	1005	25	tropical depression
29 / 0000	16.2	83.3	1004	25	"
29 / 0600	16.6	83.6	1003	30	"
29 / 1200	16.9	84.0	1002	30	"
29 / 1800	17.4	84.8	1000	40	tropical storm
30 / 0000	17.7	85.4	993	45	"
30 / 0600	17.9	86.0	987	55	"
30 / 1200	17.9	86.4	982	65	hurricane
30 / 1800	17.9	86.7	977	75	"
01 / 0000	17.9	86.9	955	100	"
01 / 0600	17.9	87.2	941	120	"
01 / 1200	17.9	87.4	944	115	"
01 / 1800	17.9	87.7	950	110	"
02 / 0000	17.8	87.9	959	100	"
02 / 0600	17.6	87.8	974	80	"
02 / 1200	17.7	87.8	980	70	"
02 / 1800	17.7	87.9	987	65	"
03 / 0000	17.9	88.0	989	60	tropical storm
03 / 0600	18.0	88.4	990	45	"
03 / 1200	18.3	88.8	995	30	tropical depression
03 / 1800	18.6	89.5	998	30	"
04 / 0000	19.0	90.4	1000	25	"
04 / 0600	19.5	91.4	1000	30	"
04 / 1200	19.9	92.5	999	35	tropical storm
04 / 1800	20.3	93.5	996	40	"
05 / 0000	20.7	94.8	988	60	"
05 / 0600	21.2	96.1	987	65	hurricane
05 / 1200	21.8	97.0	983	75	"
05 / 1800	22.6	97.9	980	80	"
06 / 0000	23.2	99.0	988	45	tropical storm
06 / 0600	23.5	100.0	1002	30	tropical depression

Date/Time (UTC)	Latitude (°N)	Longitude (°W)	Pressure (mb)	Wind Speed (kt)	Stage
06 / 1200	23.8	101.0	1007	20	"
06 / 1800					dissipated
01/0700	17.9	87.3	939	120	minimum pressure
02/2300	17.9	88.0	988	65	landfall at Ambergris Cay, Belize
03/0300	17.9	88.2	990	60	landfall 25 n mi north of Belize City, Belize
05/1800	22.6	97.9	980	80	landfall 20 n mi north of Tampico, Mexico

Table 2.
Hurricane Keith selected surface observations, 28 September - 6 October 2000.

Location	Pres. (mb)	Date/ Time (UTC)	Sust. Wind (kts)	Peak Gust (kts)	Date/ Time (UTC)[a]	Storm Surge (ft)	Storm Tide (ft)	Total Rain (in)
Belize								
Philip Goodson Intl. Arpt., Belize City	994.0	01/0700	30	53	01/0400			32.67
Mexico								
Chetumal								9.65
Tampico	990.0	05/1545	40	55	05/1445			

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

Table 2a.
Hurricane Keith supplemental rainfall observations, 28 September - 6 October 2000.

Station	Storm-total rainfall (in)
Belize	
Libertad	7.46
Towerhill	8.01
Central Farm	10.41
Belmopan	12.94
Barton Creek	2.92
Chaa Creek	6.56
Belize Zoo	18.43
Melinda	6.56
Middlesex	10.00
Pomona	6.47
Mayan King	3.59
Savannah	2.42
Bigfalls Plan.	5.59
P.G.Agstat	1.87
Blue Creek O.Walk	17.64
Spanish Lookout	9.85
Rum Point	3.10
Consejo	8.90
St Johns College	24.69
Gallon Jug1	8.10
Gallon Jug2	8.20
Gallon Jug3	8.20
Gallon Jug4	9.60
Mexico	
Obregon	8.35
Juan Serabia	13.98
Sabinas	14.43

Table 3. Preliminary track forecast evaluation for Hurricane Keith - heterogeneous sample. Errors in nautical miles for tropical storm and hurricane stages with number of forecasts in parentheses. Numbers in bold italics represent forecast which were better than the official forecast.

Forecast Technique	**Period (hours)**				
	12	**24**	**36**	**48**	**72**
CLIP	***31*** (18)	***65*** (14)	***127*** (12)	***201*** (11)	***298*** (10)
GFDI	50 (18)	94 (14)	144 (12)	***191*** (11)	351 (10)
GFDL*	36 (18)	***72*** (14)	***118*** (12)	***169*** (11)	***273*** (10)
GFNI	36 (14)	***61*** (12)	***89*** (11)	***101*** (9)	***119*** (8)
GFDN*	***25*** (8)	***33*** (6)	***68*** (6)	***97*** (6)	***136*** (4)
GFUI	***30*** (8)	***55*** (6)	***91*** (5)	***139*** (5)	***221*** (9)
GFDU*	***21*** (5)	***37*** (4)	***58*** (3)	***82*** (3)	***171*** (3)
AVNI	52 (14)	101 (13)	157 (10)	***182*** (6)	398 (6)
AVNO*	62 (13)	105 (12)	151 (11)	***191*** (7)	421 (5)
BAMD	***25*** (17)	***56*** (13)	***73*** (11)	***130*** (10)	***297*** (10)
BAMM	35 (17)	***70*** (13)	***118*** (12)	***209*** (11)	454 (9)
BAMS	34 (18)	***72*** (14)	***114*** (12)	217 (11)	462 (10)
NGPI	35 (18)	77 (14)	***96*** (12)	***131*** (11)	***208*** (10)
NGPS*	39 (9)	***56*** (7)	***99*** (6)	***91*** (5)	***207*** (5)
UKMI	60 (18)	132 (14)	191 (12)	255 (11)	332 (10)
UKM*	60 (9)	116 (7)	194 (5)	243 (5)	357 (5)
GUNS	36 (18)	***72*** (14)	***106*** (12)	***147*** (11)	***253*** (10)
A90E	***30*** (18)	***50*** (14)	***102*** (12)	***174*** (11)	391 (10)
A98E	***29*** (18)	***51*** (14)	***96*** (12)	***163*** (11)	***288*** (10)
A9UK	***28*** (8)	***47*** (6)	***109*** (5)	***189*** (5)	400 (4)
LBAR	33 (18)	100 (14)	192 (12)	279 (11)	426 (10)
VBAR	32 (14)	88 (11)	173 (10)	253 (9)	244 (8)
FSSE*	51 (13)	89 (12)	***130*** (11)	***201*** (10)	***263*** (8)
NHC Official	32 (18)	73 (14)	137 (12)	214 (11)	329 (10)
NHC Official 10-Year Average (1990-1999)	46 (2057)	85 (1842)	122 (1650)	158 (1471)	235 (1165)

* Output from these models was unavailable at time of forecast issuance.

Table 4. Watch and warning summary, Hurricane Keith, 28 September - 6 October 2000.

Date/Time (UTC)	Action	Location
29/2100	Hurricane Watch Issued	Yucatan Peninsula of Mexico from Chetumal to Cabo Catoche.
30/1030	Hurricane Warning Issued	Yucatan Peninsula of Mexico from the Mexico/Belize border to Cabo Catoche.
30/1030	Hurricane Watch and Tropical Storm Warning Issued	Belize from Belize City to the Mexico/Belize Border.
30/1500	Hurricane Watch Issued	Yucatan Peninsula of Mexico from Cabo Catoche to Progreso.
30/1630	Hurricane Warning Issued	Belize from Belize City to the Mexico/Belize Border.
30/2100	Hurricane Warning Issued	Belize from Belize City to Monkey River Town.
03/0300	Hurricane Warning changed to Tropical Storm Warning	Yucatan Peninsula of Mexico from the Mexico/Belize border to Cabo Catoche.
03/0300	Hurricane Watch changed to Tropical Storm Watch	Yucatan Peninsula of Mexico from Cabo Catoche to Progreso.
03/0600	Hurricane Warning changed to Tropical Storm Warning	Belize from Monkey River Town to the Mexico/Belize border.
03/1500	All Watches/Warnings Discontinued	
04/1500	Tropical Storm Watch Issued	Mexico from Coatzacoalcos to Matamoros.
04/2100	Hurricane Warning Issued	Mexico from Tuxpan to La Pesca.
04/2100	Hurricane Watch Issued	Mexico from north of La Pesca to Matamoros.
04/2100	Tropical Storm Warning Issued	Mexico from south of Tuxpan to Veracruz.
05/0300	Hurricane Warning Issued	Mexico from north of La Pesca to Matamoros.

05/0300	Hurricane Watch Issued	Mexico from south of Tuxpan to Veracruz.
05/0300	Tropical Storm Watch Issued	Texas from Brownsville to Port Mansfield.
05/2100	Hurricane Warning Continues	Mexico from north of Tampico to La Pesca.
05/2100	All Other Watches/ Warnings Discontinued	
06/0000	Hurricane Warning changed to Tropical Storm Warning	Mexico from north of Tampico to La Pesca.
06/2100	Tropical Storm Warning Discontinued	Mexico from north of Tampico to La Pesca.

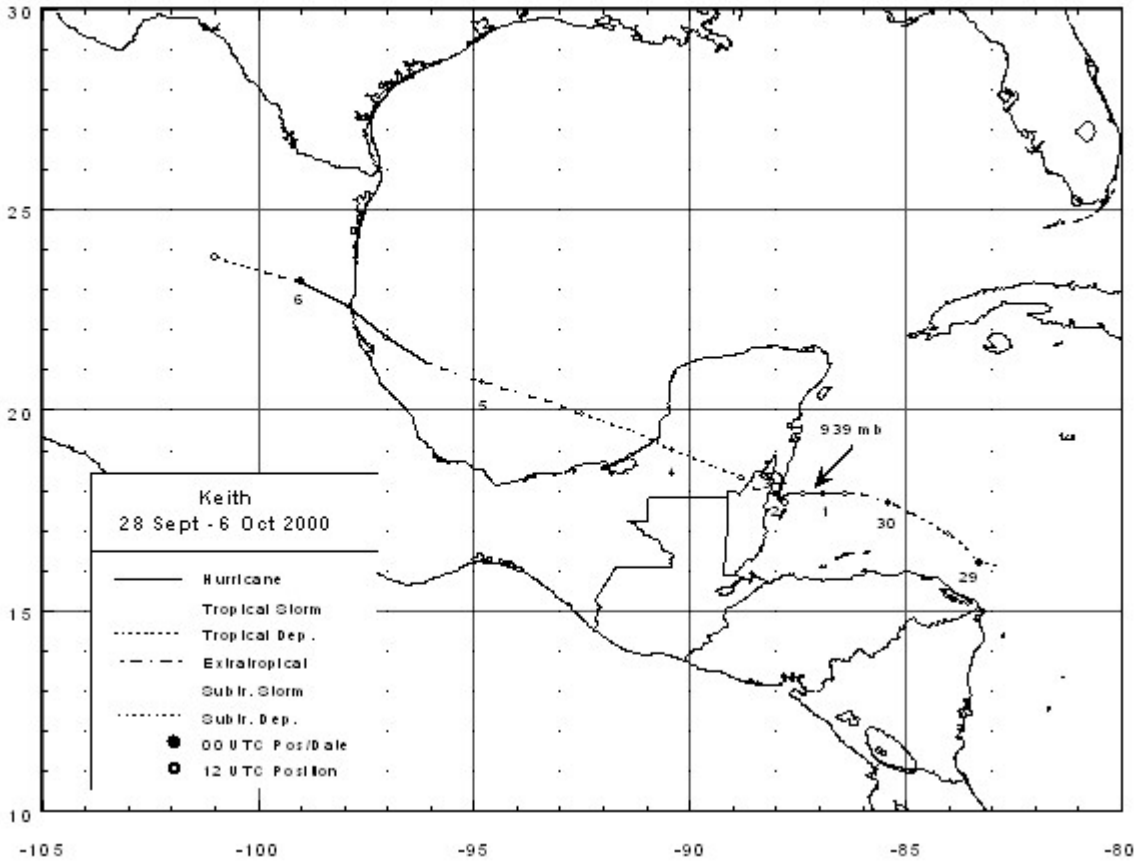

Figure 1. Best track for Hurricane Keith, 28 September - 6 October 2000.

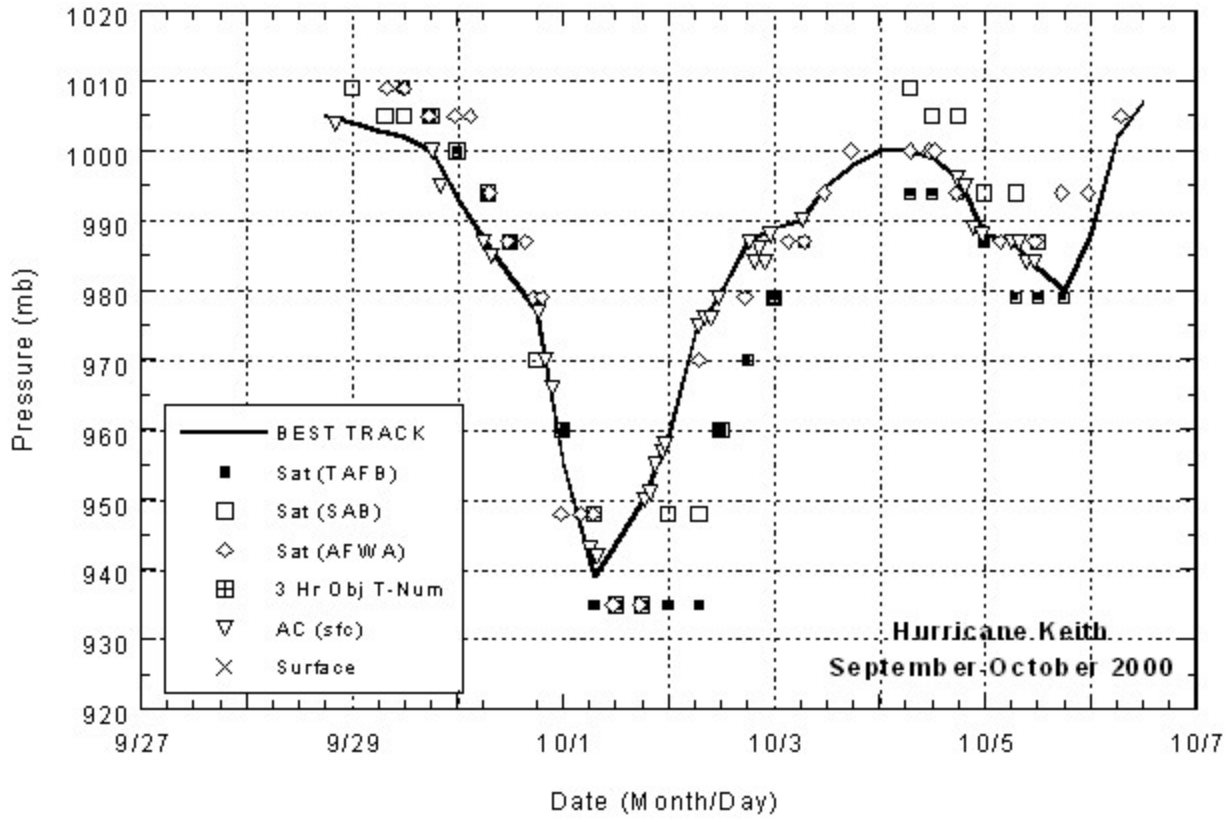

Figure 2. Best track minimum central pressure curve for Hurricane Keith, 28 September - 6 October 2000.

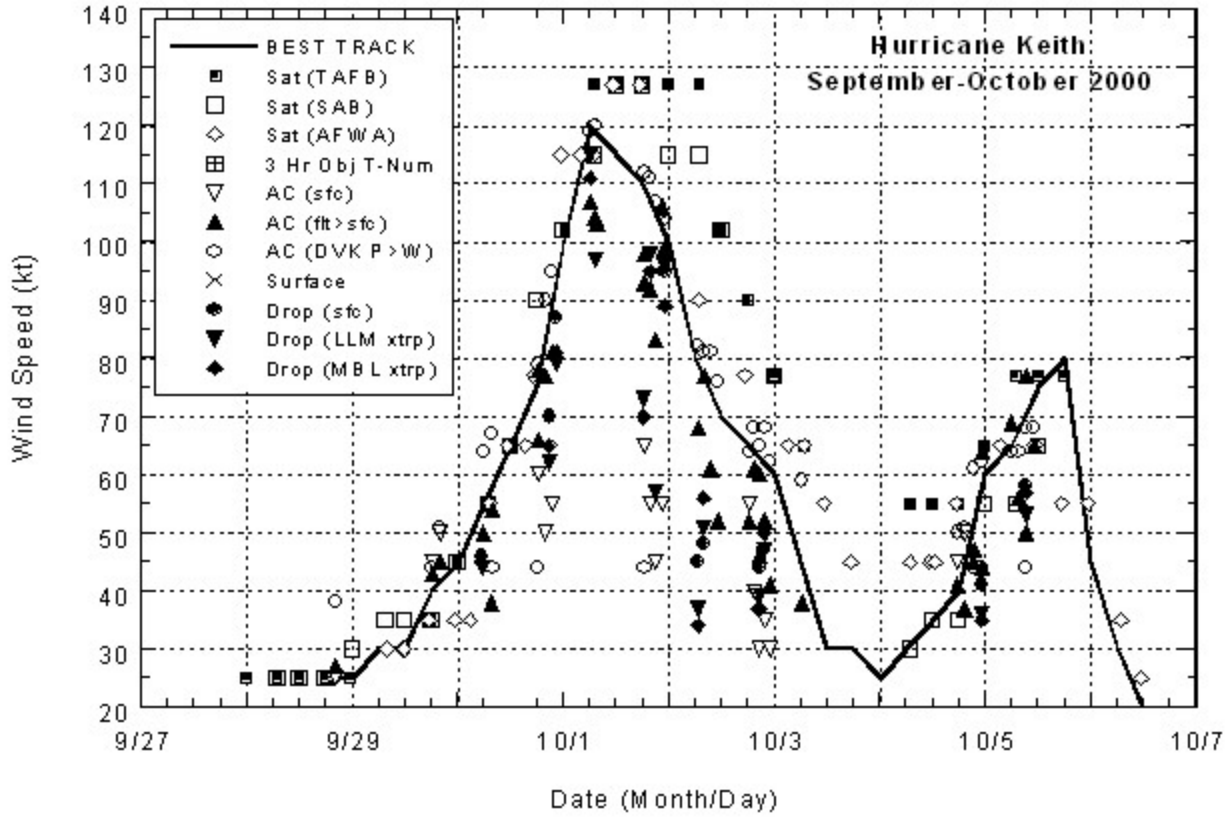

Figure 3. Best track maximum sustained 1-minute 10 meter wind speed curve for Hurricane Keith, 28 September - 6 October 2000.

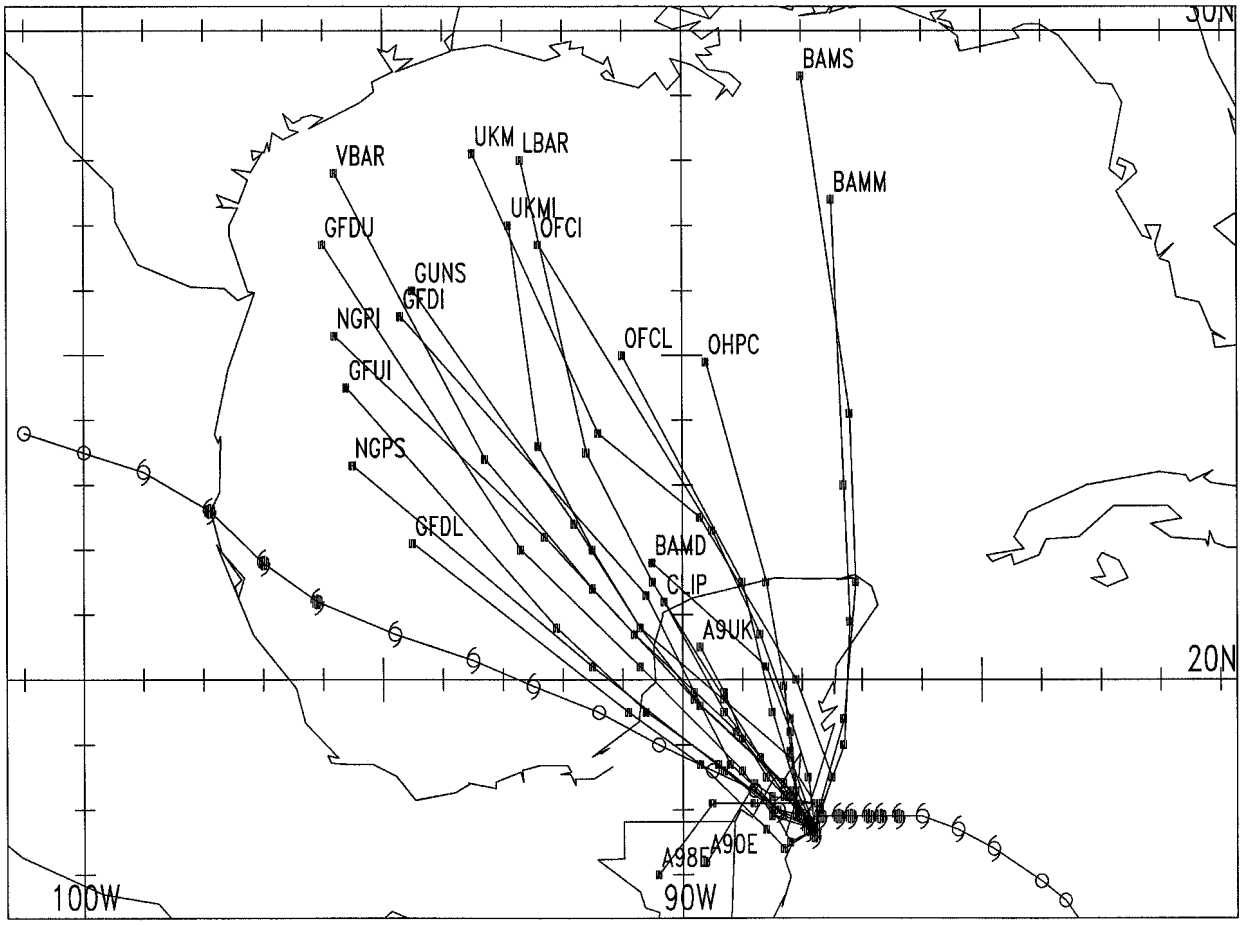

Figure 4. Hurricane track guidance for Hurricane Keith at 1200 UTC 2 October. Best track line marked by hurricane and tropical storm symbols.