Tropical Cyclone Report
Hurricane Karl
(AL132010)
14-18 September 2010

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Karl was a strong Category 3 hurricane (on the Saffir-Simpson Hurricane Wind Scale) that formed over the northwestern Caribbean Sea and made landfall as a tropical storm along the east coast of the Yucatan Peninsula of Mexico. Karl then emerged over the Bay of Campeche and made a second landfall along the mainland coast of Mexico northwest of Veracruz as a major hurricane, causing significant damage in the region.

a. Synoptic History

Hurricane Karl originated from a broad low pressure system that formed from the interaction between a westward-moving tropical wave and an elongated trough of low pressure that extended northeastward across northern South America and into the southwestern North Atlantic Ocean. The tropical wave exited the African coast on 1 September and moved steadily westward for the next week or so, producing little convection during its journey across the tropical Atlantic. As the wave approached the southern Windward Islands early on 8 September, it slowed down and showers and thunderstorms began to develop near the wave axis. Later that day, the wave merged with the South American trough and the two features combined to form a broad surface low pressure system just east of the Windward Islands. Over the next few days, the low moved westward to west-northwestward across the Windward Islands and into Caribbean Sea, and produced intermittent small bands of deep convection, well removed from the surface center. Even though convection remained disorganized during this period, the overall surface wind field and vertical structure of the system became better defined. Early on 13 September, the development process became disrupted and NASA and NOAA research flights into the disturbance indicated that a surface low pressure system no longer existed beneath a well-defined mid-level circulation. Interruption of the genesis process was short-lived, however, and by late that same day central convection began to steadily increase, curved banding features improved, and a closed surface circulation redeveloped. It is estimated that a tropical depression formed at 1200 UTC 14 September over the northwestern Caribbean Sea about 325 n mi east of Chetumal, Mexico. The "best track" chart of the tropical cyclone's path is given in Figure 1, with the wind and pressure histories shown in Fig 2 and 3, respectively. The best track positions and intensities are listed in Table 1[1].

[1] A digital record of the complete best track, including wind radii, can be found on line at ftp://ftp.nhc.noaa.gov/atcf. Data for the current year's storms are located in the *btk* directory, while previous years' data are located in the *archive* directory.

Convective organization continued to improve and the system strengthened into a tropical storm just 6 h later. Karl moved westward toward the eastern Yucatan Peninsula of Mexico and gradually intensified right up until landfall occurred. Karl moved onshore the eastern coast of Yucatan near Rio Huach at approximately 1245 UTC 15 September with maximum sustained winds of 55 kt. Under the influence of a broad subtropical high pressure system located over the Gulf of Mexico and the southeastern United States, Karl moved west-northwestward across the Yucatan Peninsula and into the Bay of Campeche by 0600 UTC 16 September. Although Karl's intensity decreased as it made its 18-h trek over land, conventional and microwave satellite imagery (not shown) indicated that the cyclone's convective organization and vertical structure actually improved, with the appearance of an eye-like feature and an increase in convective banding. Later that morning at 1137 UTC, an U.S. Air Force Reserve reconnaissance mission into Karl confirmed the existence of an elliptical-shaped eye with an average diameter of about 20 n mi.

Almost as soon as the cyclone emerged over the warm waters of the Bay of Campeche, the combination of high sea-surface temperatures, low vertical wind shear, and very moist mid-tropospheric conditions triggered a period of rapid intensification, and Karl became a hurricane by 1800 UTC 16 September. The western extent of the subtropical ridge to the north of Karl strengthened and built southward, which caused the hurricane to make a turn toward the west-southwest early on 17 September. Karl continued to rapidly strengthen and reached major hurricane status shortly after 0600 UTC 17 September. Karl reached its peak intensity of 110 kt just 6 h later at 1200 UTC when the hurricane was located only 45 n mi northeast of Veracruz, Mexico.

Increasing northeasterly vertical wind shear and possible entrainment of dry air into the western portion of the cyclone caused Karl to weaken just prior to landfall. However, Karl was still a major hurricane when it made landfall along the Mexican coast about 10 n mi northwest of Veracruz at 1645 UTC 17 September. Karl continued its west-southwestward motion and weakened rapidly as the small hurricane interacted with the mountains of coastal Mexico. As Karl pushed farther inland, the cyclone became a tropical storm at 0000 UTC 18 September and a depression just 6 h later. Rapid weakening continued as the system moved across the rugged terrain of central Mexico and it dissipated after 0600 UTC that same day about 75 n mi west-southwest of Veracruz.

b. Meteorological Statistics

Observations in Karl (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 UW-CIMSS intensity estimates using the Advanced Microwave Sounding Unit (AMSU). In addition, flight-level, stepped frequency microwave radiometer (SFMR), and dropwindsonde observations from flights of the 53rd Weather Reconnaissance Squadron (53WRS) of the U. S. Air Force Reserve Command were also available. Research missions were also conducted by NASA and NOAA. Data and imagery from NOAA polar-orbiting satellites, Defense Meteorological Satellite Program (DMSP) satellites, National Aeronautics and Space Administration (NASA) satellites, including TRMM, and Aqua, the U.S. Navy WindSat, and the

European Space Agency's UMETSAT ASCAT, among other satellites, were also useful in constructing the best track of Karl, as were weather radar data from Mexico and Belize.

The 53WRS WC-130 aircraft fleet completed five aerial reconnaissance missions and provided 23 center fixes. On 16 September, a NOAA Aircraft Operations Center (AOC) WP-3 aircraft conducted a research flight into Karl and supplied an important center fix and other data in between the 53WRS scheduled reconnaissance missions. There were several missions conducted into the pre-Karl disturbance by both NASA DC-8 and NOAA G-IV aircraft as part of the PREDICT (Pre-Depression Investigation of Cloud-systems in the Tropics -- http://catalog.eol.ucar.edu/predict/missions/missions.html) tropical cyclone genesis research program. NASA also conducted a Global Hawk mission around Karl while the cyclone was over the Bay of Campeche.

Most ships avoided the strongest winds associated with Karl. As a result, only one ship report of tropical-force-winds was received – the cruise ship *Celebrity Solstice* (call sign **9HRJ9**) reported a sustained wind of 35 kt at 0700 UTC 14 September when it was located about 220 n mi north-northwest of the center. The oil platform *Ocean Nugget* (19.46^{o} N 92.07^{o} W), located over the Bay of Campeche about 20 n mi east-southeast of Karl's center, reported a sustained wind of 52 kt at 1330 UTC 16 September. Based on a time series of weather observations, the center of Karl likely passed over or just north of the *Ocean Nugget* at around 1300 UTC that day. Two NOAA buoys located in Veracruz harbor and over the southern Bay of Campeche also reported sustained tropical-storm-force winds. At the Veracruz, Mexico airport (MMVR), a sustained wind of 40 kt with a gust to 50 kt occurred at 1700 UTC 17 September as Karl was making landfall a few miles northwest of the station. Selected surface observations associated with Karl are given in Table 2.

After passing over the Yucatan Peninsula and into the Bay of Campeche, Karl underwent a period of rapid intensification. Between 0600 UTC 16 September and 1200 UTC 17 September, an intensity change of 65 kt occurred in only 30 h – more than double the standard threshold rate for rapid intensification of 30 kt/24 h. During this exceptional strengthening process, reconnaissance data indicate that Karl's eye contracted from an average diameter of 20 n mi down to 8 n mi. However, erosion of the western portion of Karl's eyewall was noted in Mexican radar imagery (Fig. 4) just prior to the hurricane making landfall. It is believed that this erosion was due to dry subsiding air coming off the Sierra Madre Oriental mountain range and being drawn into the cyclone's circulation, since reconnaissance aircraft data and microwave satellite imagery do not indicate any evidence of an eyewall replacement cycle.

With maximum sustained winds of 110 kt, Karl became the strongest hurricane (and the only major hurricane) ever recorded in the Bay of Campeche (i.e., south of 21^{o} N latitude). The previous strongest tropical cyclone in that area was Hurricane Item in 1950, which had maximum sustained winds of 95 kt.

Rainfall across the Yucatan Peninsula averaged 3-5 inches, which is roughly one-third of the rainfall totals that were observed across east-central mainland Mexico where Karl made its second and final landfall. There was a large area of 10-15 inch rainfall amounts that covered most of the northwestern half of the state of Veracruz. The maximum rainfall total measured was

17.83 inches at Mislanta (Fig. 5). The heavy rainfall extended well inland, and runoff from the Sierra Madre Mountains caused severe floods and mud slides throughout much of the Mexican state of Veracruz, and also in the states of Tabasco, Chiapas, Oaxaca, Puebla, Tlaxcala, Nuevo León, and Tamaulipas.

c. Casualty and Damage Statistics

Only a few reports of downed trees were received as a result of Karl's passage across the Yucatan Peninsula. However, Karl pummeled east-central Mexico with damaging winds and heavy rains. About 3,500 people sought refuge in shelters set up at schools throughout the state of Veracruz where the greatest impacts from Karl were felt. It is estimated that more than 40,000 people were left homeless (one report of 250,000-500,000 homeless could not be corroborated). More than 20,000 homes were flooded and more than 50,000 people lost electricity or water utilities due to powerlines blown down by the strong winds. Helicopter crews from the Mexican navy rescued about 40 families trapped on a hill that was surrounded by floodwaters in the town of San Pancho, north of the city of Veracruz. South of Veracruz in Cotaxtla, homes were flooded up to their roofs and at least seven persons were washed away in a nearby flood-swollen river. Recovery crews removed approximately 18,000 tons of debris throughout the state of Veracruz during post-storm cleanup operations.

Media reports indicate that a total of 22 people were killed, with most of the deaths occurring in the state of Veracruz. A 61-year-old woman and a 2-year-old girl were killed and two other people were injured when a mud slide buried a house in the town of Nexticapan. The insurance risk modeling company AIR Worldwide estimated total damage costs in Mexico at US$206 million.

d. Forecast and Warning Critique

The genesis of Karl was not forecast particularly well. The area of disturbed weather that eventually became Karl was first introduced in the Atlantic Tropical Weather Outlook at 1800 UTC 8 September (6 days prior to genesis) with a 10% chance of development. Probabilities steadily increased over the next 2-3 days and reached a medium (30%-50%) chance the next day, and reached a high (greater than 50%) chance of development on 11 September. The probability of development remained steady at 60% until 0600 UTC 12 September and decreased to a medium chance later that day. The probability of development remained at 40% for more than 36 h right up until genesis occurred. The primary forecast rationale for the lower probability of development after 12 September was the lack of sufficient organized deep convection near the center of the broad low pressure system. It is hoped that the numerous pre-genesis missions conducted during the PREDICT experiments can provide a better understanding of the reasons for lack of genesis between 9-13 September, and why genesis finally occurred on 14 September.

A verification of NHC official track forecasts (OFCL) for Karl is given in Table 3a. The official forecast track errors were comparable to the mean official errors for the previous 5-yr period. OFCL errors were slightly lower at 12 h and slightly higher at 24 h and beyond. The climatology and persistence model (OCD5) errors were considerably smaller than the previous 5-

yr OCD5 average at all forecast times. This implies that the track of Karl was not unusually difficult to forecast.

A homogeneous comparison of the official track errors with selected guidance models is given in Table 3b. Overall, the NHC official forecasts (OFCL) performed better than the majority of the model guidance at 12 h and 24 h, and worse than the majority of the most reliable forecast models at 48 h. The OFCL forecasts had a distinct right-of-track forecast bias for every forecast cycle. Similarly, the majority of the NHC model guidance, including the dynamical consensus model TVCN, also had a right-of-track bias. The official forecast and most of the dynamical models did not accurately forecast the strengthening of the western extent of the subtropical ridge that forced Karl on a west-southwestward track. In contrast, the best performing models were the typically less reliable GFNI (NOGAPS-based GFDL model) and BAMD models. Both models accurately predicted the sharp west-southwestward jog over the Bay of Campeche nearly 48 h before landfall occurred along the mainland Mexican coast.

A verification of NHC official intensity forecasts for Karl is given in Table 4a. Official forecast intensity errors were much greater than the mean official errors for the previous 5-yr period. In fact, OFCL intensity errors were more than double the long-term errors at 12-48 h and due to a low intensity bias. Similarly, OCD5 errors were considerably greater than the previous 5-yr OCD5 average at all forecast times. This indicates that the intensity of Karl was particularly difficult to forecast.

A homogeneous comparison of the official intensity errors with selected guidance models is given in Table 4b. The overwhelming majority of the intensity guidance was slightly better than the OFCL forecasts through 48 h and was much better at 72 h. The period of rapid intensification that occurred while Karl was over the Bay of Campeche was not anticipated nor explicitly forecast, and this was the reason for the unusually large intensity errors.

Watches and warnings associated with Karl are given in Table 5.

Table 1. Best track for Hurricane Karl, 14-18 September 2010.

Date/Time (UTC)	Latitude (°N)	Longitude (°W)	Pressure (mb)	Wind Speed (kt)	Stage
13 / 1800	16.3	78.5	1005	25	low
14 / 0000	16.6	79.8	1004	25	"
14 / 0600	17.0	81.1	1003	25	"
14 / 1200	17.6	82.3	1003	30	tropical depression
14 / 1800	18.1	83.6	1001	35	tropical storm
15 / 0000	18.3	85.0	999	40	"
15 / 0600	18.3	86.2	997	55	"
15 / 1200	18.5	87.6	991	55	"
15 / 1800	18.8	88.8	994	45	"
16 / 0000	19.2	90.1	997	40	"
16 / 0600	19.4	91.1	994	45	"
16 / 1200	19.6	92.2	986	55	"
16 / 1800	19.6	93.3	982	70	hurricane
17 / 0000	19.7	94.1	971	85	"
17 / 0600	19.7	94.9	966	95	"
17 / 1200	19.6	95.6	956	110	"
17 / 1500	19.4	96.0	970	110	"
17 / 1800	19.2	96.4	979	90	"
18 / 0000	18.7	97.1	995	60	tropical storm
18 / 0600	18.6	97.4	1005	25	tropical depression
18 / 1200					dissipated
17 / 1200	19.6	95.6	956	110	minimum pressure
15 / 1245	18.5	87.8	991	55	landfall along Yucatan coast near Rio Huach, Mexico
17 / 1645	19.3	96.2	976	100	landfall about 10 n mi northwest of Vera Cruz, Mexico

Table 2. Selected surface observations for Hurricane Karl, 14-18 September 2010.

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)			
Country								
International Civil Aviation Organization (ICAO) Sites								
Belize								
Belize City (MZBZ)								1.74
Cayman Islands								
Grand Cayman (MWCR)								0.94
Cuba								
Cabo San Antonio (WMO 78310)								3.43
Puerto Padre (WMO 78358)								1.46
Punta Lucrecia (WMO 78365)								2.24
Guatemala								
Flores/Santa Elena (MGFL)								1.26
Honduras								
Roatan (MHRO)								0.94
Mexico								
Chetumal, Yucatan (WMO MMCM)								7.05
Ciudad Mante (MMMD)								0.99
Coatzacoalcos (WMO 76741)								1.46
Felipe Carrillo Puerto (WMO 76698)								1.30
Jalapa (WMO 76687)								8.38
Matlapa (WMO 76585)								2.52
Orizaba (WMO 76737)								8.28
Rio Verde (WMO 76581)								3.75
Tampico (WMO 76548)								2.27
Tulancingo								1.62

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)			
(WMO MMTL)								
Tuxpan (WMO 76640)								5.59
Valladolid, Yucatan (WMO 76647)								0.83
Vera Cruz (WMO	17/1700	996.6	17/1700	40	50			9.21
Villahermosa (WMO 76743)								1.02
Villa Tamuin (WMO 76543)								2.91
Other								
Banco Chinchorro (18.65N 87.30W)	15/1045	996.8	15/1030	42	54			
Cayo Arcas (20.20N 91.55W)	16/1145	1002.7	16/1230	42	53			
Laguna Verde (19.72N 96.41W)	17/1245	995.5	17/1215	32	49			
Misantla								17.83
Ocean Nugget oil platform (19.46N 92.07W; elevation 114 ft/30 m)	16/1040 16/1330	995.3 1003.8	16/1040 16/1330	N 48 S 52	68 57			
Storm Chaser Josh Morgerman, 4 n mi northwest of Vera Cruz (19.216N 96.228W)	17/1650	985.9						
Buoys								
Vera Cruz, Mexico Harbor (VERV4 /19.20N 96.11W)	17/1600	992.6	17/1640	57[e]	82			
Sacrifice Island, Vera Cruz (SACV4 / 21.17N 96.09W)	17/1500	995.3	17/1450	41[e]	54			

[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).
[e] Anemometer height is 9 m; sustained wind averaging period is 10 min.

Table 3a. NHC official (OFCL) and climatology-persistence skill baseline (OCD5) track forecast errors (n mi) for Karl. Mean errors for the 5-yr period 2005-9 are shown for comparison. Official errors that are smaller than the 5-yr means are shown in boldface type.

	Forecast Period (h)						
	12	24	36	48	72	96	120
OFCL	**25.7**	54.2	83.6	120.2	159.2		
OCD5	30.1	57.2	89.1	124.9	273.3		
Forecasts	13	11	9	7	3		
OFCL (2005-9)	31.8	53.4	75.4	96.8	143.8	195.6	252.1
OCD5 (2005-9)	46.9	97.3	155.4	211.6	304.8	387.9	467.8

Table 3b. Homogeneous comparison of selected track forecast guidance models (n mi) for Karl. Errors smaller than the NHC official forecast are shown in boldface type. The number of official forecasts shown here will generally be smaller than that shown in Table 3a due to the homogeneity requirement.

Model ID	Forecast Period (h)						
	12	24	36	48	72	96	120
OFCL	21.8	53.3	87.8	139.0			
OCD5	26.4	**51.5**	**80.3**	**109.3**			
GFSI	30.5	57.4	89.5	**131.7**			
GHMI	34.0	76.7	101.0	166.1			
HWFI	35.6	78.0	116.7	194.6			
GFNI	24.0	**46.7**	**61.4**	**91.6**			
NGPI	29.0	54.6	95.6	**126.7**			
UKMI	37.6	70.5	91.9	**135.7**			
EGRI	35.4	69.6	103.0	152.5			
EMXI	32.4	68.7	107.7	149.6			
AEMI	29.6	65.3	98.2	146.8			
FSSE	25.7	**48.4**	**75.3**	**134.5**			
TCON	28.0	59.8	89.8	147.9			
TCCN	29.5	55.6	**79.2**	**132.0**			
TVCN	24.8	**52.2**	**79.1**	**134.3**			
TVCC	27.9	**52.3**	**73.4**	**124.8**			
GUNA	28.5	56.7	**84.4**	**135.1**			
BAMD	**19.5**	**40.8**	**70.7**	**95.3**			
BAMM	29.8	55.9	**87.7**	**128.4**			
BAMS	33.2	62.1	88.9	141.0			
Forecasts	9	8	6	4			

Table 4a. NHC official (OFCL) and climatology-persistence skill baseline (OCD5) intensity forecast errors (kt) for Karl. Mean errors for the 5-yr period 2005-9 are shown for comparison. Official errors that are smaller than the 5-yr means are shown in boldface type.

	Forecast Period (h)						
	12	24	36	48	72	96	120
OFCL	14.2	20.9	31.7	33.6	30.0		
OCD5	12.2	22.2	31.0	42.3	29.7		
Forecasts	13	11	9	7	3		
OFCL (2005-9)	7.0	10.7	13.1	15.2	18.6	18.7	20.1
OCD5 (2005-9)	8.6	12.5	15.8	18.2	21.0	22.7	21.7

Table 4b. Homogeneous comparison of selected intensity forecast guidance models (kt) for Karl. Errors smaller than the NHC official forecast are shown in boldface type. The number of official forecasts shown here will generally be smaller than that shown in Table 4a due to the homogeneity requirement.

Model ID	Forecast Period (h)						
	12	24	36	48	72	96	120
OFCL	14.2	23.0	33.8	33.3	27.5		
OCD5	**12.3**	24.1	**33.5**	43.5	**19.0**		
HWFI	16.3	**22.4**	**31.6**	43.8	31.5		
GHMI	**13.7**	**22.0**	**32.6**	35.3	**15.0**		
DSHP	**12.4**	**19.9**	**27.1**	**28.7**	**15.5**		
LGEM	**13.3**	**22.9**	**32.3**	**27.0**	35.0		
ICON	**12.8**	**21.1**	**30.9**	33.3	**16.5**		
FSSE	**13.0**	**20.0**	**31.4**	34.2	**23.0**		
Forecasts	12	10	8	6	2		

Table 5. Watch and warning summary for Hurricane Karl, 14-18 September 2010.

Date/Time (UTC)	Action	Location
14 / 2100	Tropical Storm Watch issued	Belize City to Mexico/Belize border
14 / 2100	Tropical Storm Warning issued	Chetumal to Cabo Catoche
15 / 1500	Tropical Storm Watch issued	Ciudad del Carmen to Celestun
15 / 1500	Tropical Storm Warning modified to	Chetumal to Punta Allen
15 / 2100	Tropical Storm Watch discontinued	Belize City to Mexico/Belize border
15 / 2100	Tropical Storm Warning discontinued	All
16 / 0300	Hurricane Watch issued	La Cruz to Barra de Nautla
16 / 0900	Tropical Storm Watch discontinued	All
16 / 0900	Hurricane Watch modified to	La Cruz to Palma Sola
16 / 1500	Tropical Storm Warning issued	Cabo Roja to La Cruz
16 / 1500	Tropical Storm Warning issued	Palma Sola to Veracruz
16 / 1500	Hurricane Watch modified to	Cabo Roja to La Cruz
16 / 1500	Hurricane Warning issued	Cabo Roja to Palma Sola
16 / 2100	Tropical Storm Warning modified to	Punta el Lagarto to Veracruz
16 / 2100	Hurricane Warning modified to	Cabo Roja to Veracruz
17 / 2100	Tropical Storm Warning discontinued	All
17 / 2100	Hurricane Watch discontinued	All
17 / 2100	Hurricane Warning discontinued	All

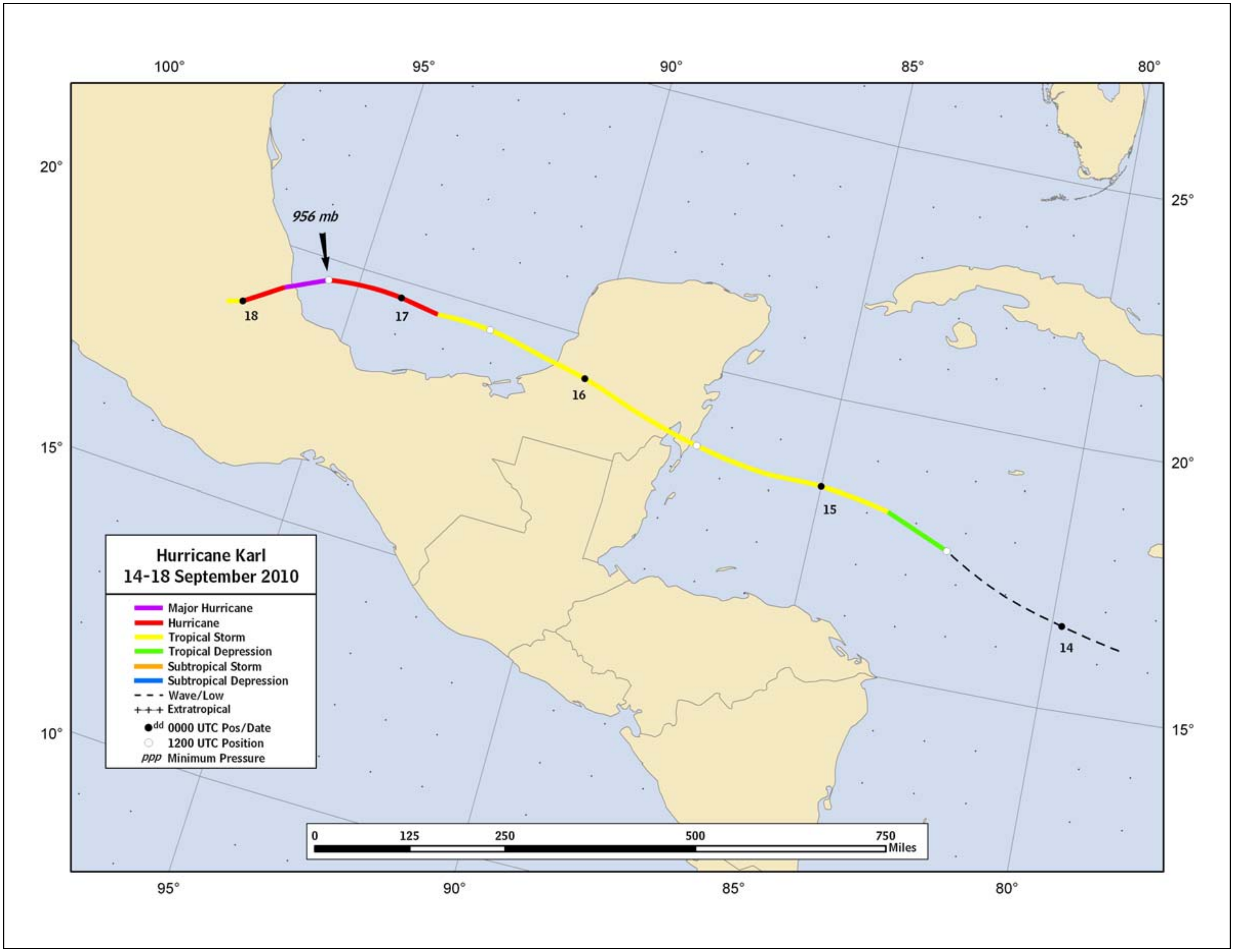

Figure 1. Best track positions for Hurricane Karl, 14-18 September 2010.

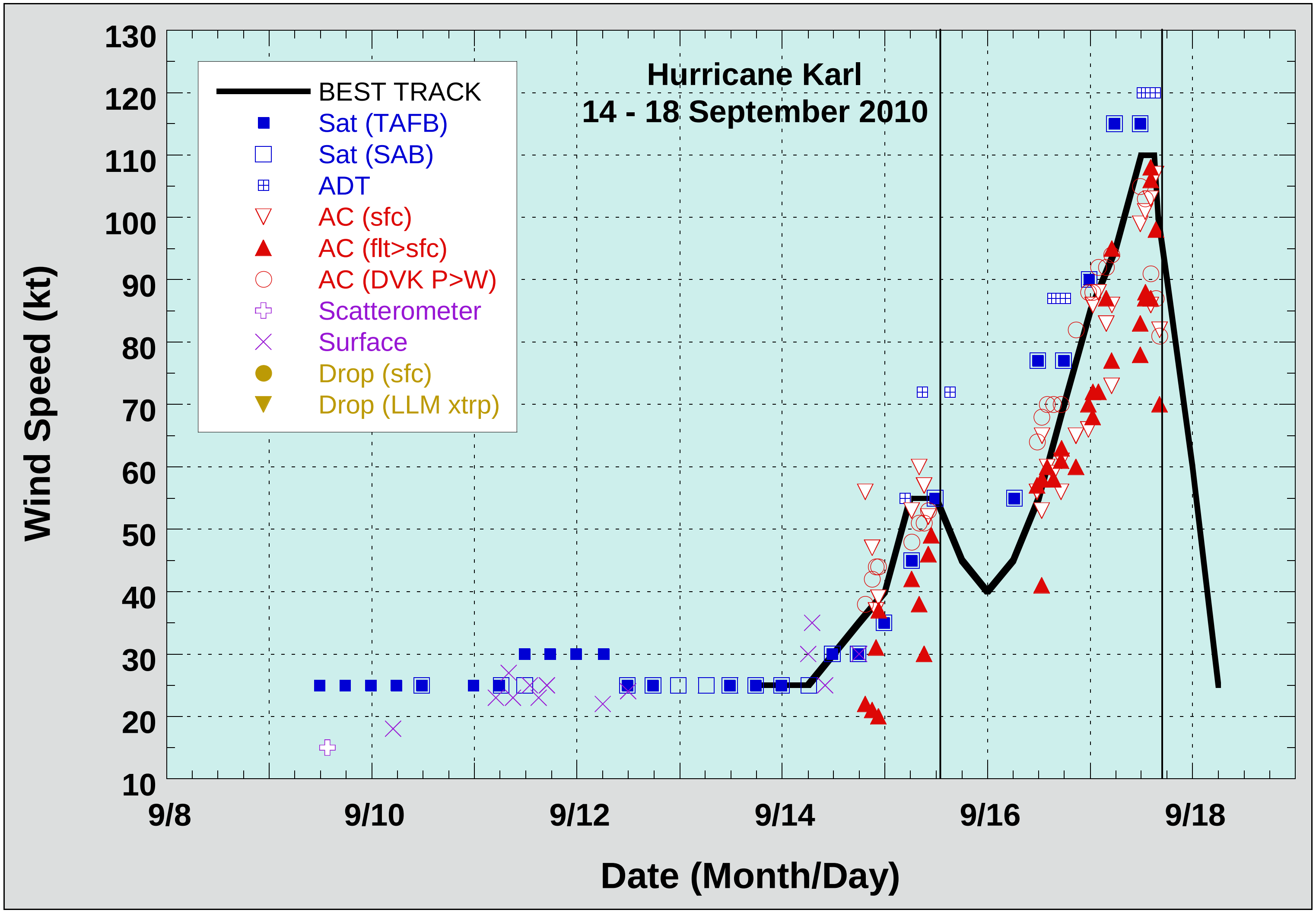

Figure 2. Selected wind observations and best track maximum sustained surface wind speed curve for Hurricane Karl, 14-18 September 2010. Aircraft observations have been adjusted for elevation using 90%, 80%, and 80% adjustment factors for observations from 700 mb, 850 mb, and 1500 ft, respectively. Advanced Dvorak Technique estimates represent linear averages over a two-hour period centered on the nominal observation time. Dashed vertical lines correspond to 0000 UTC. Solid vertical lines correspond to landfall times.

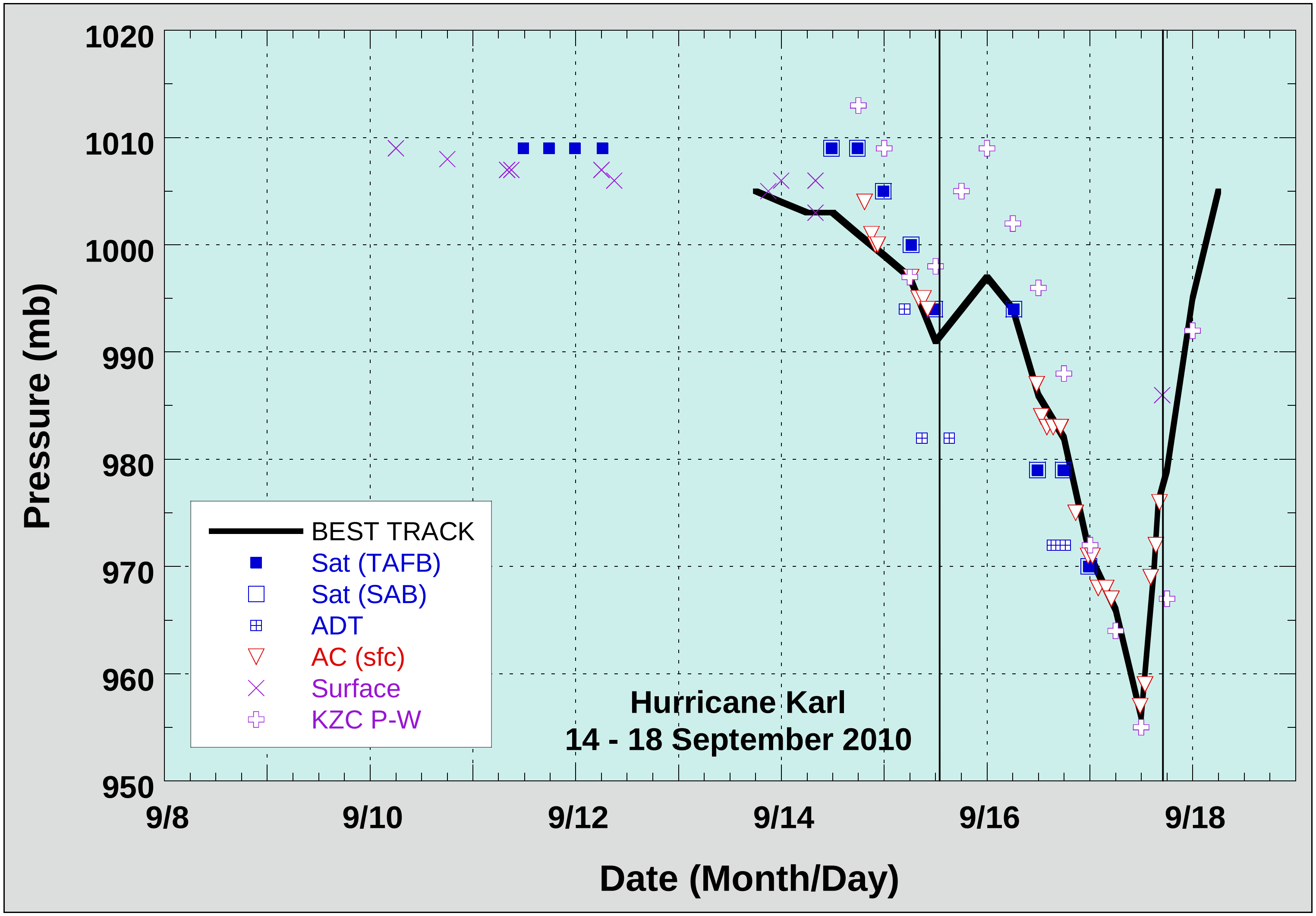

Figure 3. Selected pressure observations and best track minimum central pressure curve for Hurricane Karl, 14-18 September 2010. Advanced Dvorak Technique estimates represent linear averages over a two-hour period centered on the nominal observation time. Dashed vertical lines correspond to 0000 UTC. Solid vertical lines correspond to landfall times.

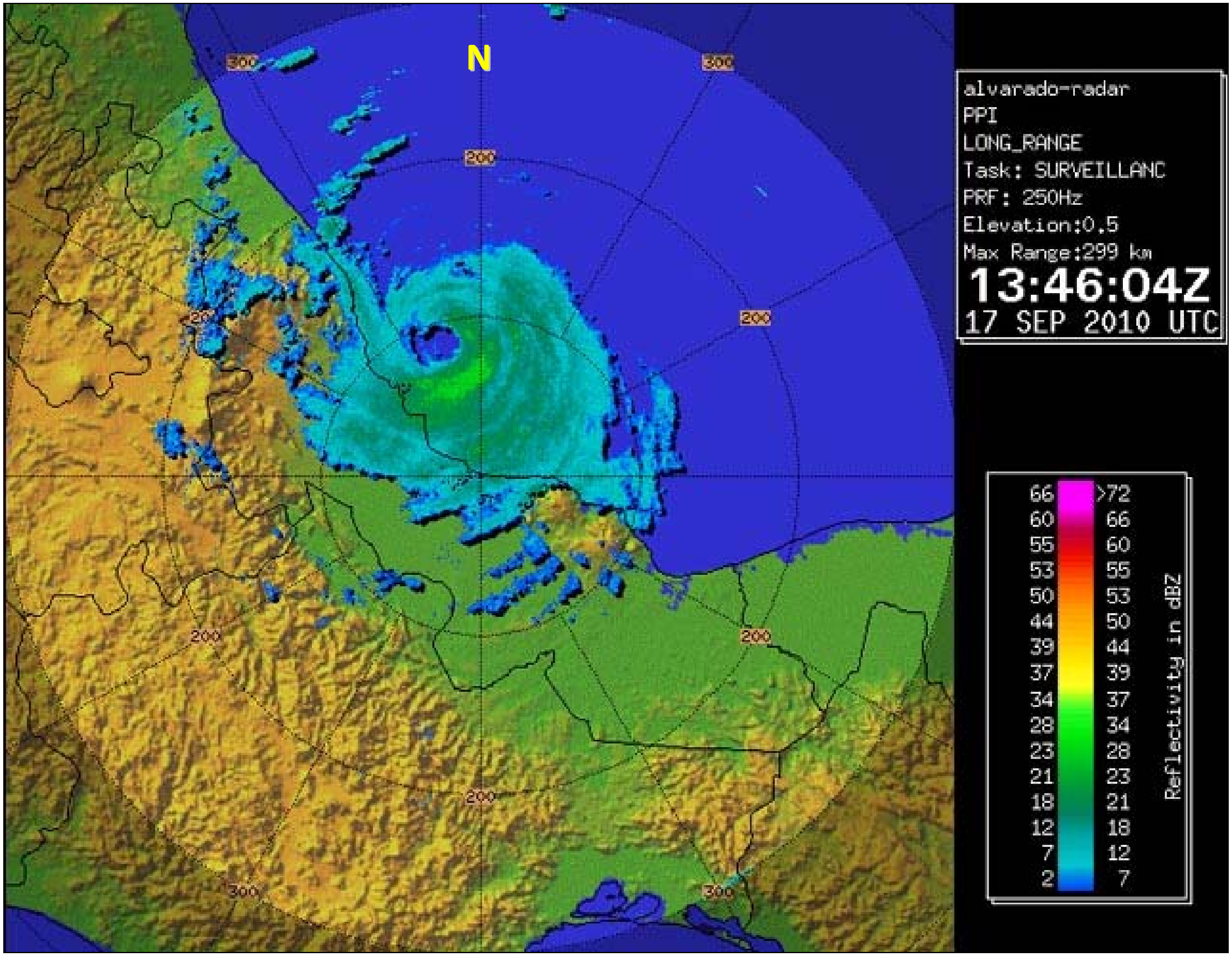

Figure 4. Alvarado, Mexico radar reflectivity image from 1346 UTC 17 September as Category 3 Hurricane Karl was bearing down on the coast of the State of Veracruz. (100 km/54 n mi range rings; image courtesy of Meteorological Service of Mexico)

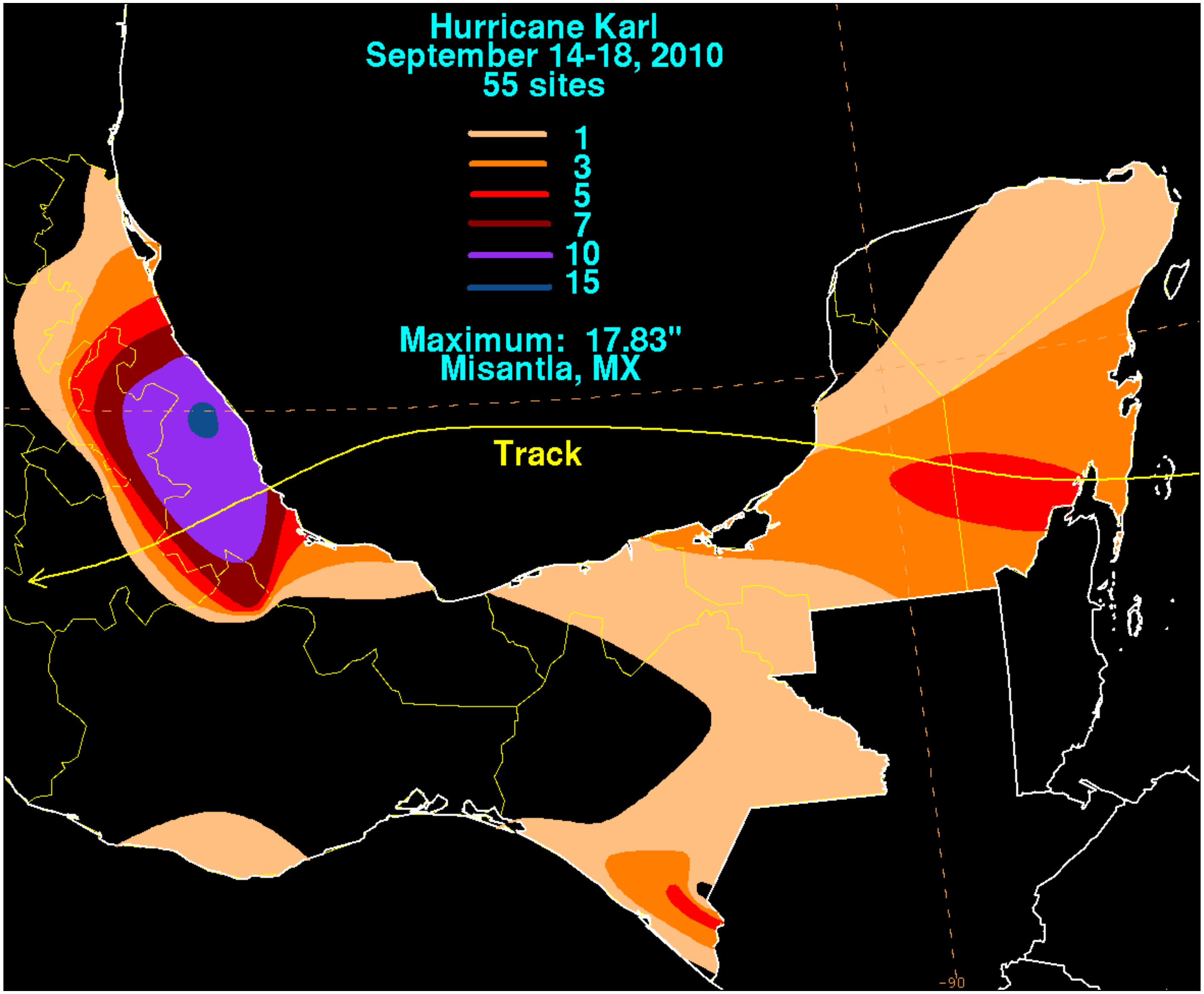

Figure 5. Storm total precipitation associated with Hurricane Karl, 14 – 18 September 2010, and its remnants. Figure courtesy of David Roth, NOAA Hydrometeorological Prediction Center.