

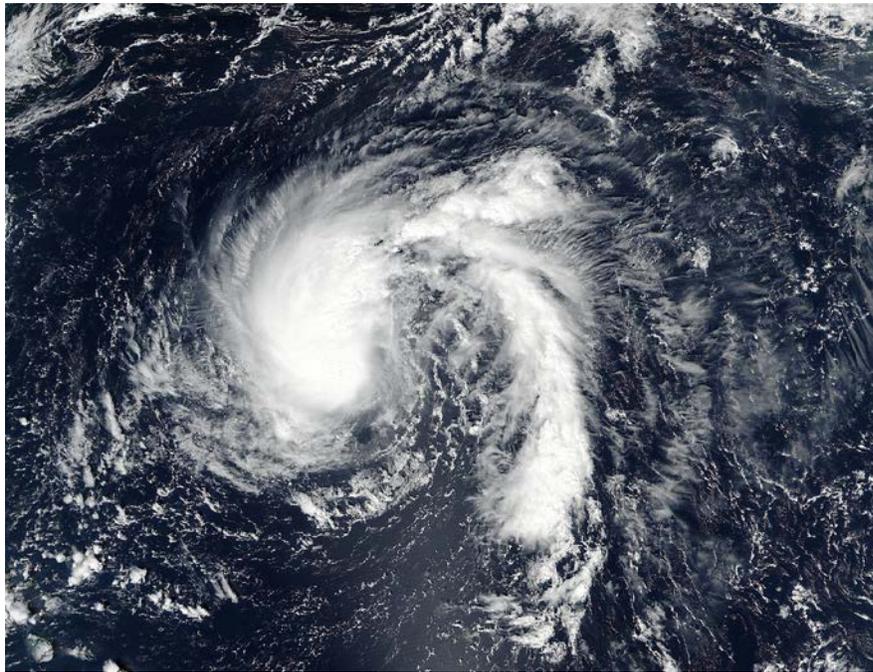


# NATIONAL HURRICANE CENTER TROPICAL CYCLONE REPORT

## TROPICAL STORM KARL (AL122016)

14 – 25 September 2016

Richard J. Pasch and David A. Zelinsky  
National Hurricane Center  
4 January 2017



TROPICAL STORM KARL NEAR BERMUDA AT 1715 UTC 23 SEPTEMBER 2016. IMAGE COURTESY OF NASA.

Karl was a long-lived tropical storm that passed near Bermuda.

# Tropical Storm Karl

14 – 25 SEPTEMBER 2016

## SYNOPTIC HISTORY

Karl formed from a tropical wave that crossed the western coast of Africa on 12 September. That same day, the wave spawned a low pressure system a few hundred n mi east-southeast of the Cabo Verde Islands around 1800 UTC. The low moved slowly northwestward for a day or so, and by 0600 UTC 14 September, the system acquired enough organized deep convection to be classified as a tropical depression while centered near the eastern Cabo Verde Islands. The “best track” chart of the tropical cyclone’s path is given in Fig. 1, with the wind and pressure histories shown in Figs. 2 and 3, respectively. The best track positions and intensities are listed in Table 1<sup>1</sup>.

Shortly after formation, the cyclone began moving west-northwestward at a faster forward speed. Westerly to southwesterly vertical wind shear associated with an upper-level low inhibited significant intensification of the system, although the depression was able to strengthen into a tropical storm by 0600 UTC 15 September. Karl moved on a mainly westward track over the tropical Atlantic for several days, to the south of a mid-level subtropical ridge, with no significant change in strength while continuing to experience strong southwesterly shear. At times, the circulation of the tropical cyclone was not very well defined, but the center, which was situated southwest of the main area of deep convection almost all of the time from 15 to 20 September, remained reasonably trackable. Early on 21 September, Karl moved very near a new upper-level low to its west, and the tropical cyclone weakened to a depression.

The cyclone turned toward the northwest and remained below storm strength for a day or so, but late on 22 September the upper-level low moved southward, resulting in more favorable upper-level winds over Karl. The system’s cloud pattern became better organized, and the cyclone regained tropical storm strength around 1800 UTC that day. Karl intensified further while turning toward the north and northeast around the western periphery of a mid-level anticyclone, and the storm passed about 40 n mi southeast of Bermuda around 0900 UTC 24 September with maximum winds near 55 kt. While accelerating toward the east-northeast, Karl reached its peak intensity of 60 kt by 0600 UTC 25 September, but almost immediately after that the system became embedded within a frontal zone and became an extratropical cyclone around 1200 UTC 25 September. The cyclone moved rapidly northeastward and merged with another extratropical low pressure system over the north Atlantic, well to the east-southeast of Newfoundland, after 0000 UTC 26 September.

---

<sup>1</sup> 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 *bt* directory, while previous years’ data are located in the *archive* directory.

## METEOROLOGICAL STATISTICS

Observations in Karl (Figs. 2 and 3) include subjective satellite-based Dvorak technique intensity estimates from the Tropical Analysis and Forecast Branch (TAFB) and the Satellite Analysis Branch (SAB), and objective Advanced Dvorak Technique (ADT) estimates from the Cooperative Institute for Meteorological Satellite Studies/University of Wisconsin-Madison. Observations also include flight-level, stepped frequency microwave radiometer (SFMR), and dropwindsonde observations from flights of the 53<sup>rd</sup> Weather Reconnaissance Squadron of the U. S. Air Force Reserve Command, the NOAA Aircraft Operations Center, and dropwindsonde observations from the NASA Global Hawk unmanned aircraft. Data and imagery from NOAA polar-orbiting satellites including the Advanced Microwave Sounding Unit (AMSU), the NASA Global Precipitation Mission (GPM), the European Space Agency's Advanced Scatterometer (ASCAT), and Defense Meteorological Satellite Program (DMSP) satellites, among others, were also useful in constructing the best track of Karl. The storm's analyzed peak intensity of 60 kt is based on a blend of subjective and objective Dvorak estimates.

A single ship, BATFR18, reported 41 kt winds and a pressure of 1015.8 mb at 1100 UTC 17 September, while located about 200 n mi northeast of the center of Karl.

The Bermuda Weather Service estimated maximum sustained winds of about 40 kt on Bermuda on the morning of 24 September. A maximum wind gust of 59 kt was reported at Harbor Radio/MAROPS in St. Georges.

Karl produced nearly 5 inches of rain across Bermuda, with the Bermuda Weather Service recording 4.71 inches of rain at their location.

## CASUALTY AND DAMAGE STATISTICS

Karl produced only slight damage in Bermuda, and there were no reports of casualties associated with the storm. Approximately 800 customers briefly lost power due to a mainline fault believed to be caused by rainfall (that fell in an already wet September for the island), rather than by high winds.

## FORECAST AND WARNING CRITIQUE

The genesis of Karl was poorly forecast (Table 2). The low from which Karl formed was introduced into both the 5-day and 2-day Tropical Weather Outlook 30 h prior to genesis. The probability of genesis was increased to medium 18 h and 6 h prior to genesis in the 5-day and 2-day outlooks, respectively. The system was only assessed to have a high probability of formation 6 h after genesis was determined to have occurred in post-analysis. The low forecast bias can

be attributed in part to the location in which genesis occurred. The wave that led to the formation of Karl moved off the coast of Africa only 48 h prior to genesis, and the global models often struggle to distinguish developing waves from non-developing waves when they are still over Africa. For this reason, NHC forecasters are cautious about introducing a system into the Tropical Weather Outlook with high genesis probabilities until after it crosses the coast of Africa. In this case, the signal from the models was inconsistent until about 24 h prior to genesis.

A verification of NHC official track forecasts for Karl is given in Table 3a. Official forecast track errors were generally lower than the mean official errors for the previous 5-yr period, especially for forecasts beyond 24 h. A homogeneous comparison of the official track errors with selected guidance models is given in Table 3b. Although OCD5 errors were comparable to the past 5-yr period, many of the guidance models, especially the consensus models, had very low errors. The simple consensus TVCA was a particularly good performer during Karl. This contributed to the low errors of the NHC official forecasts.

A verification of NHC official intensity forecasts for Karl is given in Table 4a. Official forecast intensity errors were lower than the mean official errors for the previous 5-yr period for forecasts verifying at 48 h and less, although official forecast intensity errors were greater than the mean official errors for the previous 5-yr period for forecasts verifying at 72 h and beyond. A homogeneous comparison of the official intensity errors with selected guidance models is given in Table 4b. OCD5 and most of the model guidance had high errors for Karl for 48 h and beyond, suggesting that this storm was more difficult than usual to forecast. Although the estimated maximum winds for Karl were 40 kt or less for 9 straight days following genesis, nearly all of the guidance models consistently forecast strengthening during that time, resulting in a substantial high bias in the models and the official forecast (Figure 4). In general, the global models incorrectly forecast the upper-level winds to become more conducive for strengthening while Karl was over the tropical Atlantic. This resulted in the high bias of the statistical-dynamical intensity models, and in the official forecasts as well. In fact, the intensity consensus, IVCN, had an average high bias of nearly 30 kt at 120 h. The best performing intensity aid, EMXI, is based on a tracker applied to a coarse ECMWF gridded forecast. As a result, that aid rarely shows large changes in intensity, even if the ECMWF model itself forecasts the storm in question to strengthen or weaken. Since Karl changed little in intensity for such a long period of time, the EMXI errors were accordingly low.

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



Table 1. Best track for Tropical Storm Karl, 14-25 September 2016.

Date/Time (UTC)	Latitude (°N)	Longitude (°W)	Pressure (mb)	Wind Speed (kt)	Stage
12 / 1800	13.1	19.0	1010	20	low
13 / 0000	13.3	19.3	1010	20	"
13 / 0600	13.6	19.6	1010	20	"
13 / 1200	14.1	20.0	1010	25	"
13 / 1800	14.8	20.8	1009	25	"
14 / 0000	15.5	21.9	1009	25	"
14 / 0600	16.2	23.2	1009	25	tropical depression
14 / 1200	16.8	24.5	1009	30	"
14 / 1800	17.2	25.8	1009	30	"
15 / 0000	17.4	27.3	1009	30	"
15 / 0600	17.5	28.7	1008	35	tropical storm
15 / 1200	17.6	29.8	1007	35	"
15 / 1800	17.7	30.8	1006	35	"
16 / 0000	17.8	31.8	1004	40	"
16 / 0600	18.0	32.8	1004	40	"
16 / 1200	18.3	33.8	1004	40	"
16 / 1800	18.5	34.9	1004	40	"
17 / 0000	18.4	36.2	1004	40	"
17 / 0600	18.3	37.4	1004	40	"
17 / 1200	18.2	38.6	1004	40	"
17 / 1800	18.1	39.7	1005	40	"
18 / 0000	17.9	40.7	1006	35	"
18 / 0600	17.9	41.8	1006	35	"
18 / 1200	18.0	42.9	1006	35	"
18 / 1800	18.1	44.3	1006	35	"



19 / 0000	18.1	45.6	1006	35	"
19 / 0600	18.2	46.8	1006	35	"
19 / 1200	18.4	47.8	1006	35	"
19 / 1800	19.0	48.9	1006	35	"
20 / 0000	19.7	50.3	1006	35	"
20 / 0600	20.0	52.1	1006	35	"
20 / 1200	20.0	53.7	1006	35	"
20 / 1800	20.0	54.9	1006	35	"
21 / 0000	20.0	56.0	1006	35	"
21 / 0600	20.2	56.9	1006	30	tropical depression
21 / 1200	20.8	57.5	1007	30	"
21 / 1800	21.5	58.2	1007	30	"
22 / 0000	22.5	59.2	1007	30	"
22 / 0600	23.5	60.3	1007	30	"
22 / 1200	24.4	61.7	1007	30	"
22 / 1800	25.3	62.9	1005	35	tropical storm
23 / 0000	26.4	63.7	1001	40	"
23 / 0600	27.3	64.3	997	50	"
23 / 1200	28.2	64.9	992	50	"
23 / 1800	29.2	65.3	988	55	"
24 / 0000	30.3	65.3	990	55	"
24 / 0600	31.5	64.8	990	55	"
24 / 1200	32.2	63.3	994	55	"
24 / 1800	32.9	61.5	994	55	"
25 / 0000	33.8	59.3	992	55	"
25 / 0600	35.8	55.1	990	60	"
25 / 1200	38.1	50.4	986	60	extratropical
25 / 1800	41.0	45.0	980	60	"
26 / 0000	45.0	39.9	986	55	"



26 / 0600					absorbed
23 / 1800	29.2	65.3	988	55	minimum pressure
25 / 0600	35.8	55.1	990	60	maximum wind



Table 2. Number of hours in advance of formation associated with the first NHC Tropical Weather Outlook forecast in the indicated likelihood category. Note that the timings for the “Low” category do not include forecasts of a 0% chance of genesis.

	Hours Before Genesis	
	48-Hour Outlook	120-Hour Outlook
Low (<40%)	30	30
Medium (40%-60%)	6	18
High (>60%)	-	-



Table 3a. NHC official (OFCL) and climatology-persistence skill baseline (OCD5) track forecast errors (n mi) for Tropical Storm Karl, 14-25 September 2016. Mean errors for the previous 5-yr period 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	32.6	48.8	<b>57.4</b>	<b>66.2</b>	<b>75.1</b>	<b>94.2</b>	<b>132.6</b>
OCD5	53.9	103.3	149.6	190.0	278.2	435.3	538.0
Forecasts	42	40	38	36	32	28	24
OFCL (2011-15)	28.4	45.0	60.4	77.1	113.1	157.8	210.0
OCD5 (2011-15)	48.3	101.5	161.5	222.6	329.8	412.6	483.9

Table 3b. Homogeneous comparison of selected track forecast guidance models (in n mi) for Tropical Storm Karl, 14-25 September 2016. 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	35.9	52.5	61.9	62.9	67.1	92.9	137.4
OCD5	56.2	100.4	141.7	152.0	226.3	347.8	413.0
BAMS	44.1	70.8	84.0	91.4	108.5	138.3	211.0
BAMM	37.7	58.6	64.7	76.9	77.0	<b>82.5</b>	<b>71.3</b>
BAMD	40.2	65.5	91.6	93.8	95.3	106.7	<b>115.4</b>
TVCA	<b>33.6</b>	<b>51.8</b>	65.5	<b>55.9</b>	<b>55.4</b>	<b>88.2</b>	<b>114.1</b>
GFEX	<b>35.6</b>	52.8	65.2	<b>61.7</b>	74.0	113.0	166.2
TVCX	<b>33.4</b>	52.5	66.4	<b>57.0</b>	<b>59.7</b>	<b>92.8</b>	<b>112.2</b>
HCCA	<b>35.2</b>	53.5	66.4	<b>60.7</b>	79.1	132.7	198.7
FSSE	<b>34.9</b>	56.9	75.0	65.0	67.5	101.8	150.8
AEMI	<b>33.0</b>	52.5	66.7	71.4	80.3	99.3	165.8
GFNI	46.1	65.2	81.6	92.1	110.1	148.7	198.7
NVGI	46.9	72.3	84.4	86.7	75.8	122.4	220.2
CMCI	35.9	67.8	77.2	86.7	91.2	118.4	<b>137.3</b>
EMXI	41.4	61.9	75.3	83.6	112.1	157.5	174.3
EGRI	<b>31.3</b>	<b>47.2</b>	62.3	<b>62.7</b>	100.8	145.1	178.4
GFSI	<b>35.4</b>	56.6	74.1	74.5	88.9	102.4	192.0
HWFI	42.3	69.8	89.8	86.8	75.6	<b>75.7</b>	141.6
GHMI	40.3	63.6	84.9	85.7	90.3	128.4	162.6
CTCI	36.5	59.8	73.7	<b>60.1</b>	82.2	99.3	163.4
Forecasts	22	20	19	17	16	16	15



Table 4a. NHC official (OFCL) and climatology-persistence skill baseline (OCD5) intensity forecast errors (kt) for Tropical Storm Karl, 14-25 September 2016. Mean errors for the previous 5-yr period 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	<b>2.9</b>	<b>5.1</b>	<b>8.8</b>	<b>11.5</b>	15.9	22.0	25.8
OCD5	3.9	6.9	9.7	12.4	16.3	21.4	24.3
Forecasts	42	40	38	36	32	28	24
OFCL (2011-15)	6.2	9.4	11.5	13.3	14.6	14.6	15.8
OCD5 (2011-15)	7.3	10.8	13.3	15.3	17.7	17.8	17.6

Table 4b. Homogeneous comparison of selected intensity forecast guidance models (in kt) for Tropical Storm Karl, 14-25 September 2016. 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 5a due to the homogeneity requirement.

Model ID	Forecast Period (h)						
	12	24	36	48	72	96	120
OFCL	1.8	4.8	9.7	14.7	22.2	29.4	32.3
OCD5	3.2	6.9	11.7	15.9	<b>20.8</b>	<b>22.6</b>	<b>24.4</b>
IVCN	2.8	5.0	<b>8.9</b>	<b>11.9</b>	<b>18.3</b>	<b>26.0</b>	35.3
LGEM	2.5	<b>4.4</b>	<b>6.8</b>	<b>9.7</b>	<b>18.6</b>	30.3	39.3
DSHP	3.0	6.3	10.6	14.9	22.9	29.6	<b>31.5</b>
HCCA	2.6	<b>3.5</b>	<b>5.7</b>	<b>8.9</b>	<b>14.0</b>	<b>16.9</b>	<b>19.1</b>
GFNI	3.9	7.4	13.1	20.2	28.3	35.2	42.7
EMXI	2.7	<b>3.3</b>	<b>4.2</b>	<b>5.1</b>	<b>5.4</b>	<b>5.2</b>	<b>4.2</b>
GFSI	3.8	<b>4.2</b>	<b>5.5</b>	<b>4.2</b>	<b>4.6</b>	<b>8.6</b>	<b>15.2</b>
HWFI	2.6	<b>3.6</b>	<b>5.1</b>	<b>8.0</b>	<b>10.9</b>	<b>19.0</b>	33.6
GHMI	3.9	7.9	15.4	17.7	25.4	34.1	43.3
CTCI	3.7	5.9	<b>9.4</b>	<b>10.2</b>	<b>13.1</b>	<b>15.8</b>	<b>27.7</b>
FSSE	3.8	9.1	13.4	15.8	<b>17.6</b>	<b>18.7</b>	<b>21.6</b>
Forecasts	22	20	19	17	16	16	15



Table 5. Watch and warning summary for Tropical Storm Karl, 14-25 September 2016.

<b>Date/Time (UTC)</b>	<b>Action</b>	<b>Location</b>
<b>22 / 1500</b>	Tropical Storm Watch issued	Bermuda
<b>22 / 2100</b>	Tropical Storm Watch changed to Tropical Storm Warning	Bermuda
<b>23 / 1500</b>	Hurricane Watch issued	Bermuda
<b>24 / 0900</b>	Hurricane Watch discontinued	Bermuda
<b>24 / 1500</b>	Tropical Storm Warning discontinued	All

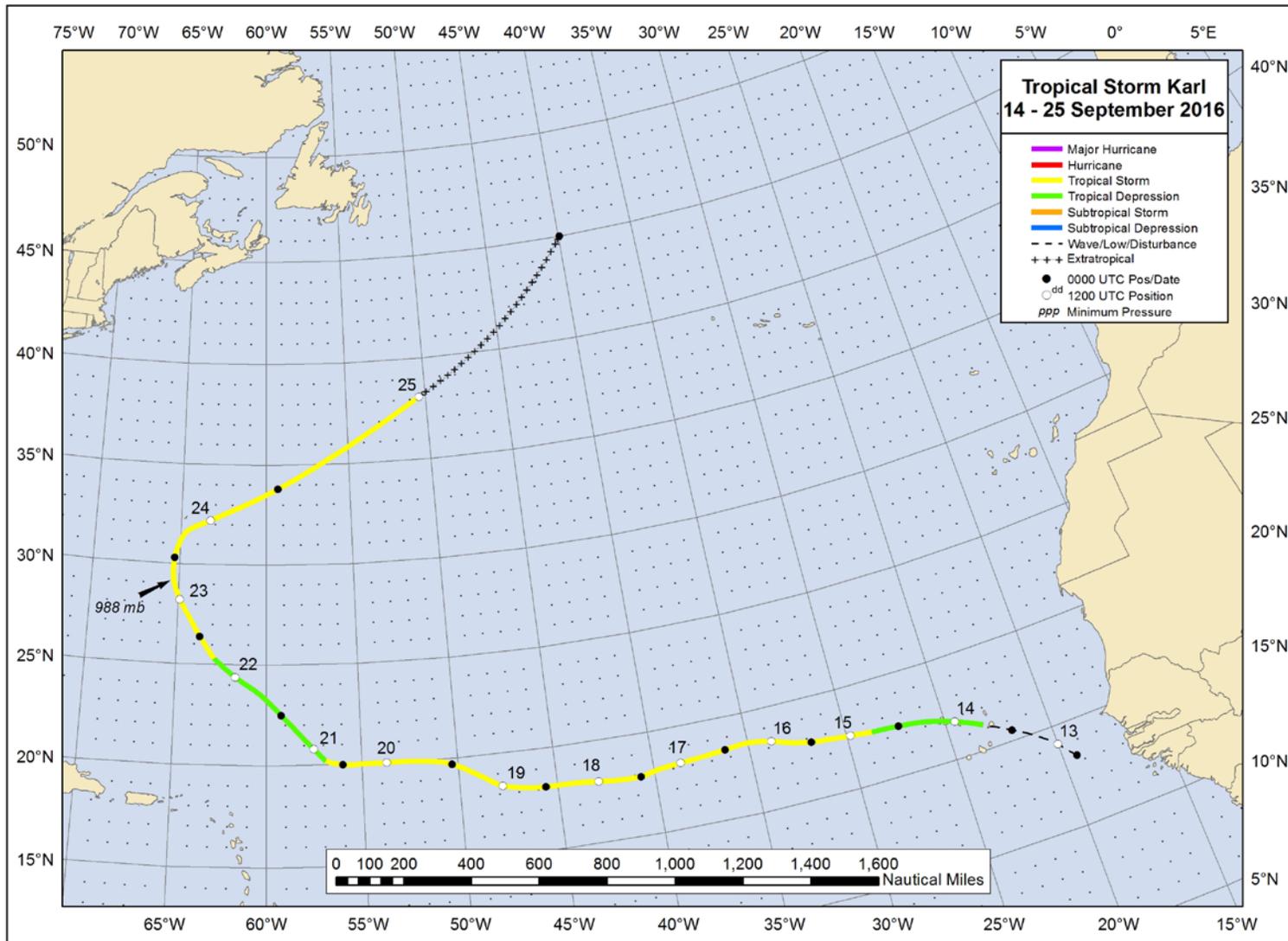


Figure 1. Best track positions for Tropical Storm Karl, 14-25 September 2016. Track during the extratropical stage is partially based on analyses from the NOAA Ocean Prediction Center.

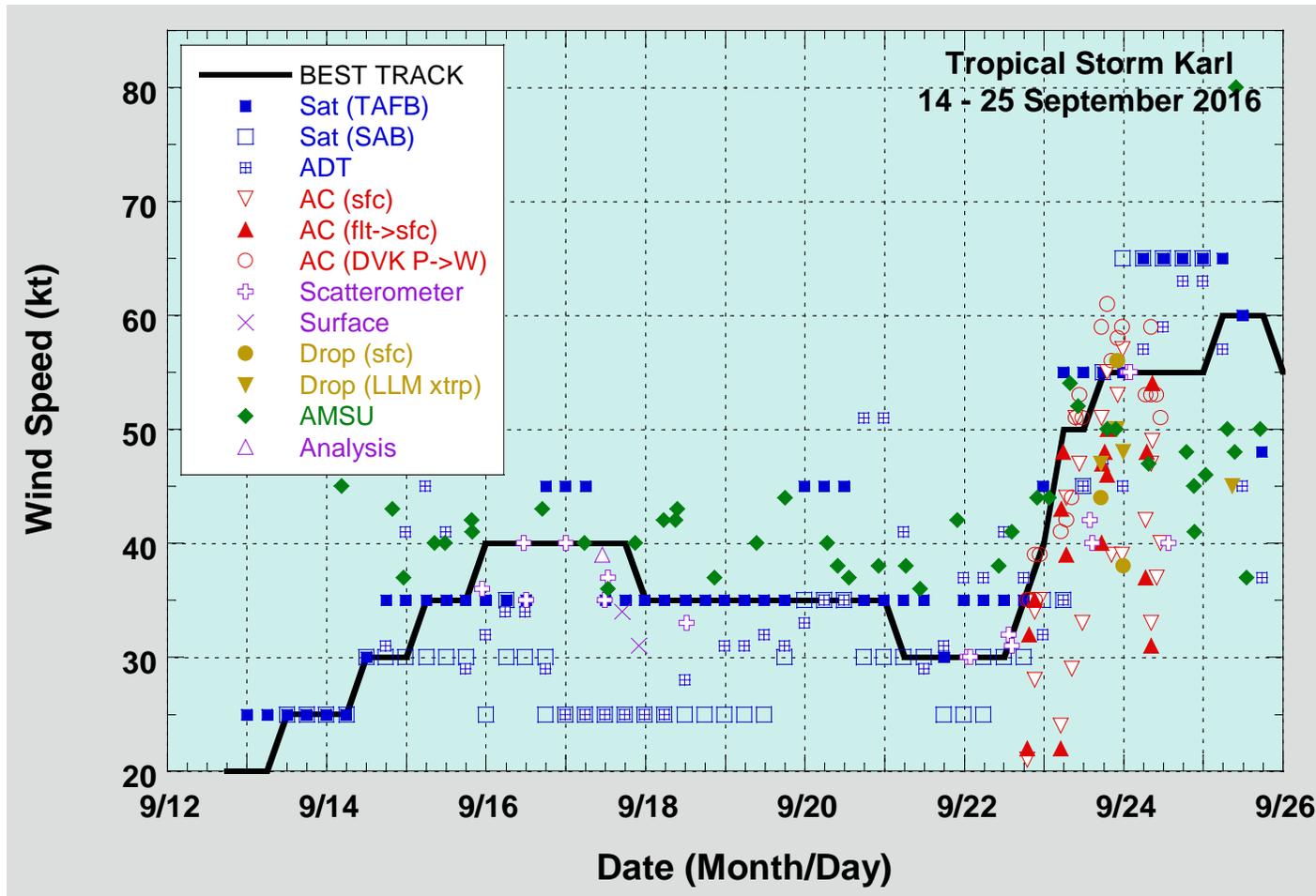


Figure 2. Selected wind observations and best track maximum sustained surface wind speed curve for Tropical Storm Karl, 14-25 September 2016. Aircraft observations have been adjusted for elevation using 90%, 80%, and 80% adjustment factors for observations from 700 mb, 850 mb, and 1500 ft, respectively. Dropwindsonde observations include actual 10 m winds (sfc), as well as surface estimates derived from the mean wind over the lowest 150 m of the wind sounding (LLM). Advanced Dvorak Technique estimates represent the Current Intensity at the nominal observation time. AMSU intensity estimates are from the Cooperative Institute for Meteorological Satellite Studies technique. Dashed vertical lines correspond to 0000 UTC.

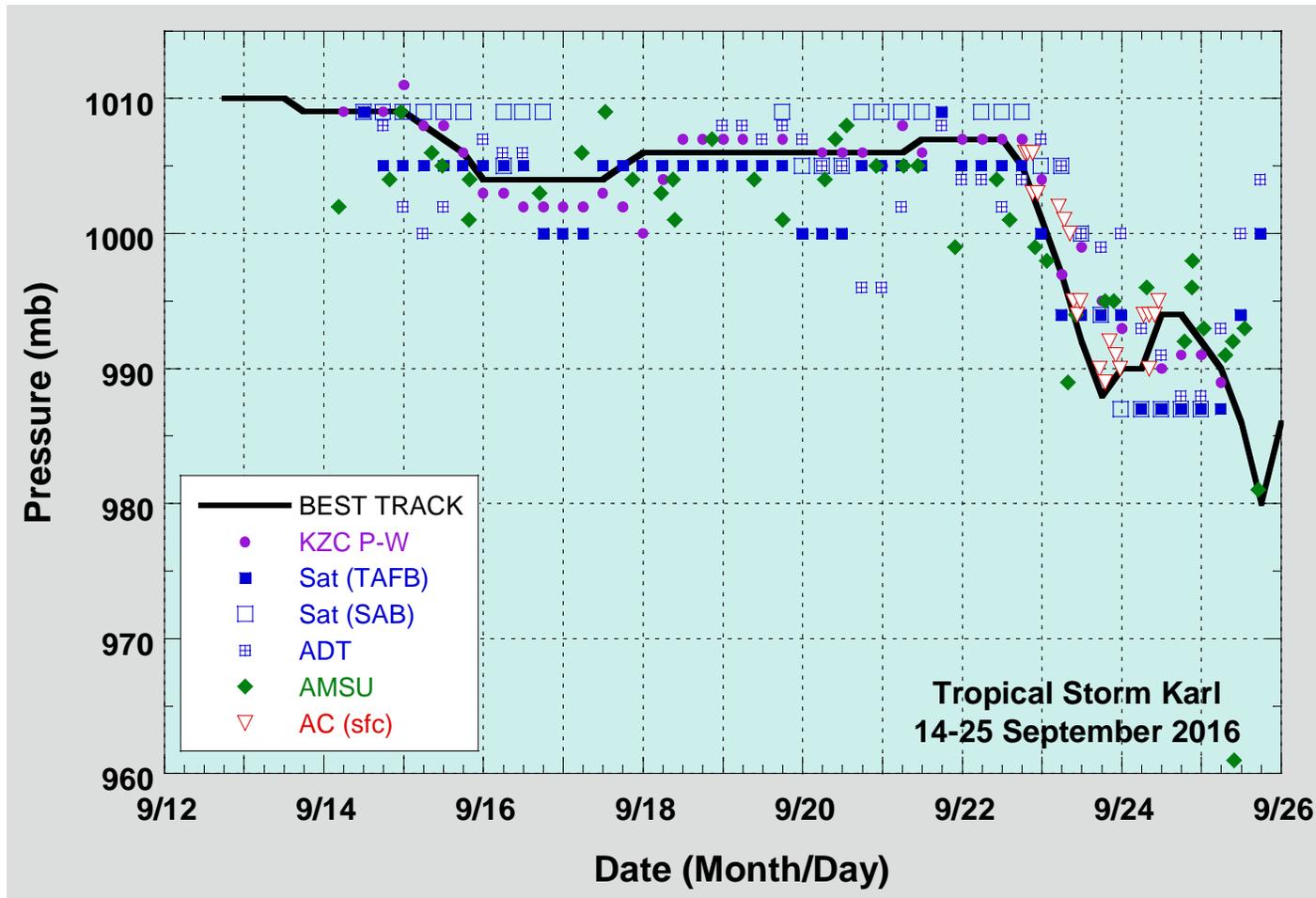


Figure 3. Selected pressure observations and best track minimum central pressure curve for Tropical Storm Karl, 14-25 September 2016. Advanced Dvorak Technique estimates represent the Current Intensity at the nominal observation time. AMSU intensity estimates are from the Cooperative Institute for Meteorological Satellite Studies technique. KZC P-W refers to pressure estimates derived using the Knaff-Zehr-Courtney pressure-wind relationship. Dashed vertical lines correspond to 0000 UTC.

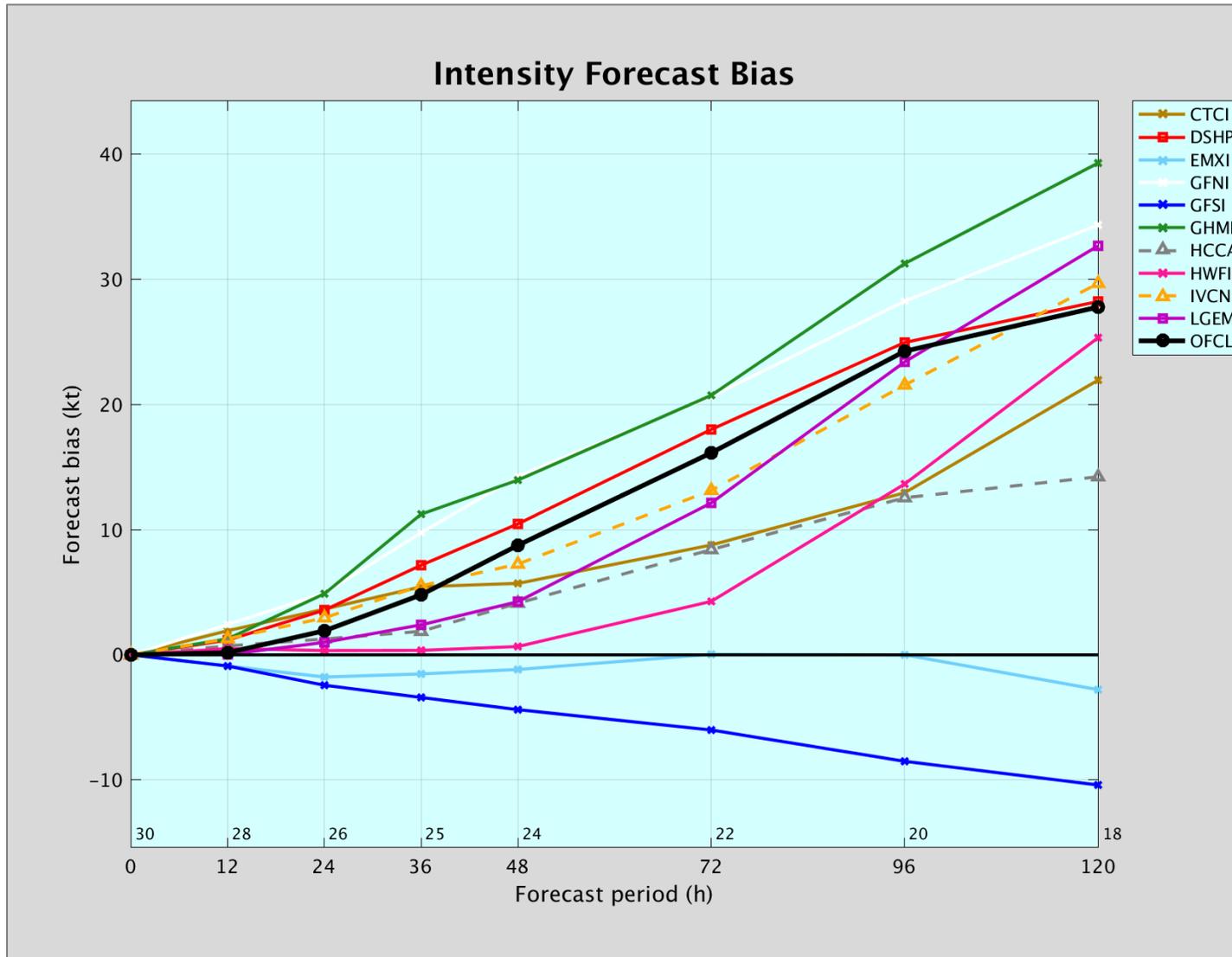


Figure 4. Intensity forecast bias for select guidance models and the NHC official forecast.