Tropical Cyclone Report
Hurricane Karen
12-15 October 2001

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Karen was a category 1 hurricane that originated from a baroclinic system. The cyclone passed just south of Bermuda as a powerful extratropical low and subtropical storm, and produced hurricane force wind gusts and widespread damage on the island. Karen later made landfall on Nova Scotia as a weak tropical storm.

a. Synoptic History

Karen originated from a cold frontal system that stalled a couple hundred miles southeast of Bermuda on 10 October. During the day, a strong negatively-tilted, difluent upper-level trough dug sharply southeastward off the east coast of the United States. The associated strong divergence and upward vertical motion fields east of the trough interacted with the cold front, increased the baroclinic characteristics of the boundary, and helped spin up a deep, extratropical low pressure system about 300 n mi southeast of Bermuda. Due to the strong baroclinic effects, the occluded low pressure system continued to deepen and tracked northward at 20 kt. By 1800 UTC 11 October, the mid- to upper-level circulations became vertically aligned with the low-level center as the system slowed down and tracked northwestward at 13 to 15 kt.

An upper-air observation at 2300 UTC from Bermuda indicated the presence of potentially cold, dry air in the mid- to upper-levels, which is not typical of the inner-core region of a tropical cyclone. However, the sounding data also showed that the powerful low pressure area was beginning to acquire some warm-core characteristics. The low- to mid-levels had become warmer than the surrounding environment (compared to the 1100 UTC sounding; data not shown) and the lapse rate was saturation adiabatic up to about 500 mb. The vertical wind profile was also more characteristic of a warm-core cyclone with the strongest winds occurring near the top of the boundary layer with decreasing wind speeds above that.

By 0000 UTC 12 October, the system had strengthened into a powerful 988 mb low and became Subtropical Storm One about 30 n mi south of Bermuda. The "best track" chart of the cyclone's path is given in Fig. 1, while the best track positions and intensities are listed in Table 1. Wind and pressure plots are shown in Figs. 2 and 3, respectively. The cyclone continued to acquire more tropical characteristics -- strong thunderstorms near the low-level center by around 1800 UTC. At that time, the low had also become cut off from the polar westerlies and had turned northward with a marked decrease in forward speed. The occluded frontal appearance in satellite imagery also became less distinct, which further indicated that the system was undergoing a transition from a subtropical low to a tropical cyclone. An investigative flight by an Air Force Reserve reconnaissance aircraft near that time confirmed that the cyclone had warm-core characteristics, at least in the lower levels of the troposphere where the entire mission took place.

Deep convection continued to develop and eventually encircled the low-level center giving the appearance of a banded-eye feature in satellite imagery. At 0600 UTC 13 October, Advanced Microwave Sounding Unit (AMSU) satellite-derived temperature data indicated the system had

acquired enough warm-core characteristics throughout the vertical column to make the transition to a tropical cyclone and it became Tropical Storm Karen about 170 n mi north of Bermuda. Karen then intensified very slowly and became a hurricane at 1800 UTC based on Dvorak satellite intensity estimates.

Karen moved in a general northward direction for the next two days and reached a peak intensity of 70 kt at 0600 UTC 14 October when it was located about 350 n mi south of Halifax, Nova Scotia. After peaking, Karen slowly weakened until the cyclone reached the southwest coast of Nova Scotia near Western Head as a 40-kt tropical storm at around 1200 UTC on the 15th. The cyclone then made a sharp turn to the northeast under the influence of strong mid-latitude westerlies and became an extratropical low pressure system again, losing all of its deep convection. The remnant low-level circulation eventually became absorbed by a larger extratropical low pressure system located to the west of Newfoundland over the Gulf of St. Lawrence.

b. Meteorological Statistics

Observations in Karen (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.

Sustained winds to near hurricane strength with wind gusts ranging from 78 to 85 kt were officially reported on Bermuda. A gust to 103 kt was reported by the cruise ship **Nordic Empress** anchored in a harbor on the west side of Bermuda at around 2317 UTC 11 October, when the low was near its closest approach to the island.

An Air Force Reserve reconnaissance aircraft made an investigative flight into Karen from 1600 UTC to 2100 UTC 12 October. The two center penetrations at 1725 UTC and 1910 UTC indicated 850 mb flight-level winds of 53 kt and 67 kt, respectively, which only equates to surface winds of approximately 42 kt and 54 kt, respectively, when using the standard 0.80 reduction factor. However, two dropwindsondes released northwest and southeast of the center indicated wind speeds of 60 to 63 kt in the boundary layer with a sharp decrease to less than 45 kt near the surface. Karen's peak intensity of 70 kt at 0600 UTC 14 October is based on an objective Dvorak satellite intensity estimate (ODT) of 70 kt.

It is important to note some of the inner-core thermodynamic and kinematic characteristics of Karen when the system passed close to Bermuda as an extratropical low. The 2300 UTC 11 October upper-air sounding (Fig. 4) indicates a vertical wind profile more characteristic of a warm-core tropical cyclone with the strongest winds (70 kt) present in the lowest layers with weakening and veering winds in the mid- and upper-levels. Temperatures at 700, 500, 400, and 300 mb also warmed 7.0^{O} , 7.0^{O}, 6.2^{O}, and 4.2^{O} C, respectively, during the previous 24 h, whereas temperatures at 250 and 200 mb remained steady or cooled slightly during the same period. While the vertical temperature and moisture profiles revealed a moist warm-core up to about 500 mb, this layer was overlaid by a deep layer of potentially colder and drier air. In fact, the lapse rate in the mid- and upper-levels were sharply cooler than the typical saturation adiabatic lapse rate of the inner-core region of tropical cyclones. This was most pronounced in the 500-400 mb layer where the lapse rate steepened to nearly dry adiabatic. While the sounding data indicates a thermodynamic structure more typical of a cold core, extratropical low pressure system above 500 mb, the vertical wind profile more closely resembles that of a warm-core tropical cyclone. Hence, the system is classified

as a subtropical storm immediately after the sounding time. However, there is presently no definitive criteria for determining when an extratropical low acquires enough warm-core characteristics to be classified as a subtropical low or when a subtropical low becomes a tropical cyclone. It is entirely possible that at 2300 UTC 11 October, Karen was already near tropical cyclone status.

Concerning the near-hurricane force sustained winds observed on Bermuda, the strong pressure difference between the central pressure (988 mb) and the higher than normal surrounding environmental pressures (1016-1020 mb) likely created a very tight pressure gradient across the island. While the Bermuda upper-air vertical wind profile (Fig 4) did not indicate any winds greater than 70 kt, the 103 kt wind gust observed by the **Nordic Empress** could have been caused by strong convective downdrafts emanating from low-topped convection. The downdrafts could have been created by the entrainment of the potentially cold (290-295 K theta-e) dry air that was present in the 400-300 mb layer (see Fig. 4).

Ship reports of tropical storm force winds associated with Karen are given in Table 2.

c. Casualty and Damage Statistics

The strong winds caused considerable tree and powerline damage on Bermuda. At one point, more than 23,000 people were without power. Three cruise ships weathered the storm in St. George Harbor without receiving any significant damage. However, the strong winds ripped out the bollard (a post for fastening mooring lines) from the wharf and snapped a three-inch mooring line, which resulted in the **Norwegian Majesty** cruise ship being set adrift in the harbor. One crew member suffered minor abrasions, but no passengers were injured. A dozen or so smaller vessels or boats broke loose from their moorings during the height of the storm and ran aground or were sunk. Fortunately, there were no lives lost. In addition to the strong winds, Bermuda received nearly three inches of rainfall which caused some minor street floods.

Some beneficial rainfall of 1.4 to 1.8 inches occurred across portions of drought-stricken Nova Scotia and New Brunswick. However, owing to the rapid forward speed and weakening trend at landfall, most areas of Nova Scotia, New Brunswick, and Prince Edward Island generally received less than one-half inch of rainfall. Wind gusts as high as 56 kt only caused minor tree damage on Nova Scotia. There were no reports of casualties.

d. Forecast and Warning Critique

No meaningful forecast verification statistics are available due to Karen's short life. However, the few cases that made up the 12-, 24-, 36-, and 48-h average errors of 56, 84, 112, and 199 n mi, respectively, were near or slightly above the 10-yr average.

No tropical cyclone watches or warnings were required for Hurricane Karen since it did not become a tropical system until after it passed northwest of Bermuda. However, the governments of Bermuda and Canada issued extratropical marine storm warnings at least 24 h in advance for Bermuda and Nova Scotia, respectively. The Marine Prediction Center and the TPC's Tropical Analysis and Forecast Branch also issued marine gale and storm warnings for their respective Atlantic High Seas Forecast areas of responsibility more than 24 h before the development of the powerful pre-Karen extratropical low.

Table 1. Best track for Hurricane Karen, 12-15 October 2001.

Date/Time (UTC)	Latitude (°N)	Longitude (°W)	Pressure (mb)	Wind Speed (kt)	Stage
11 / 0600	27.5	63.0	1009	30	extratropical low
11 / 1200	29.8	62.5	1003	35	"
11 / 1800	30.8	63.5	998	45	"
12 / 0000	31.8	64.7	991	60	subtropical storm
12 / 0600	32.2	65.8	988	60	"
12 / 1200	32.8	65.8	988	60	"
12 / 1800	33.5	66.3	988	60	"
13 / 0000	34.2	66.1	988	60	"
13 / 0600	34.9	65.3	988	60	tropical storm
13 / 1200	36.2	64.8	986	60	"
13 / 1800	37.3	64.6	985	65	hurricane
14 / 0000	37.9	64.0	985	65	"
14 / 0600	38.6	63.7	982	70	"
14 / 1200	39.3	63.9	988	60	tropical storm
14 / 1800	40.1	64.1	992	55	"
15 / 0000	40.9	64.4	995	50	"
15 / 0600	42.3	65.0	997	45	"
15 / 1200	44.2	64.8	998	40	"
15 / 1800	48.0	62.0	1002	40	extratropical low
16 / 0000					absorbed by larger extratropical low
14 / 0600	38.6	63.7	982	70	minimum pressure
15 / 1200	44.2	64.8	998	40	landfall near Western Head, NS

Table 2. Selected ship and buoy reports of winds ≥34 kt for Hurricane Karen, 12-15 October 2001.

Date/Time (UTC)	Ship call sign	Latitude (°N)	Longitude (°W)	Wind dir/speed (kt)	Pressure (mb)
11 / 2308	ELJV7[a,b]	32.3	64.8	111 / 70	
11 / 2310	ELJV7[a,b]	32.3	64.8	111 / 68	
11 / 2315	ELJV7[a,b]	32.3	64.8	111 / 65	
11 / 2317	ELJV7[a,b]	32.3	64.8	111 / 79G103	991.0
12 / 1500	ELOU5	34.8	71.3	030 / 38	1015.0
12 / 1800	ELOU5	35.3	72.2	030 / 38	1015.0
13 / 1800	LAQT4	37.5	66.9	060 / 35	
14 / 1200	GBRP	48.4	62.0	180 / 39	1027.7
15 / 0000	PDHW	38.2	61.5	210 / 37	1015.8
15 / 1800	GBRP	42.2	59.9	180 / 37	1017.9

[a] Anchored in port on west side of Bermuda

[b] Anemometer height 153 ft ASL

G = recorded wind gust

Table 3. Selected surface observations for Hurricane Karen, 12-15 October 2001.

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)			
Bermuda								
Bermuda IAP (TXKF)	12/0030	992.0 [e]						
Bermuda IAP (TXKF)	12/0055	992.7	12/0135	58	78			
Bermuda IAP (TXKF)			12/0230		70			
Bermuda IAP (TXKF)			12/0310		78			
Bermuda IAP (TXKF)			12/1200					2.70
Devonshire [g]			12/0142		87			
Fort George [h]			11/2229	64	83			
Fort George [h]			11/2239	65	84			
Fort George [h]			11/2249	64	85			
Fort George [h]			11/2329	66	79			
Fort George [h]			12/0019	66	82			
Fort George [h]			12/0039	63	84			
North Rock [i]			11/2330		76			

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)			
Canada								
Baccaro Pt, NS (WCP)			15/0730	32	41			
Beaver Island, NS (WBV)			15/1545	39	47			
Cape George, NS (WGU)			15/1630	41	56			
Caribou Pt, NS (WBK)			15/1545	31	39			
Charlottetown, PEI (CYYG)			15/1845	23	34			
Grand Etang, NS (WZQ)			15/1000	36	47			
Grindstone Is, QB (CYGR)			15/2000	27	40			
Halifax IAP, NS (CYHZ)			15/1400	30	39			
Hart Island, NS (WRN)			15/1745	31	42			
McNabs Island, NS (XMI)			15/1330	38	56			
Saint John, NB (CYSJ)								1.40
Shearwater, NS (CYAW)			15/1330	30	39			
Sydney, NS (CYQY)			15/1900	24	34			
Yarmouth, NS (CYQI)								1.80
Western Head, NS (WWE)			15/1400	20	37			
44142 [f] (42.5N 64.0W)			15/0800	34	40			
44258 [f] (44.5N 63.3W)			15/1500	29	34			

[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] estimated.
[f] 10-min average; moored buoys.
[g] Devonshire, Cable and Wireless Mast anemometer, 300 ft ASL, 5 n mi southwest of TXKF.
[h] Fort George (Harbour Radio) anemometer, 230 ft ASL, 1.25 n mi north of TXKF.
[i] North Rock (northern reef) anemometer, 80 ft ASL, approx. 10 n mi north of TXKF.

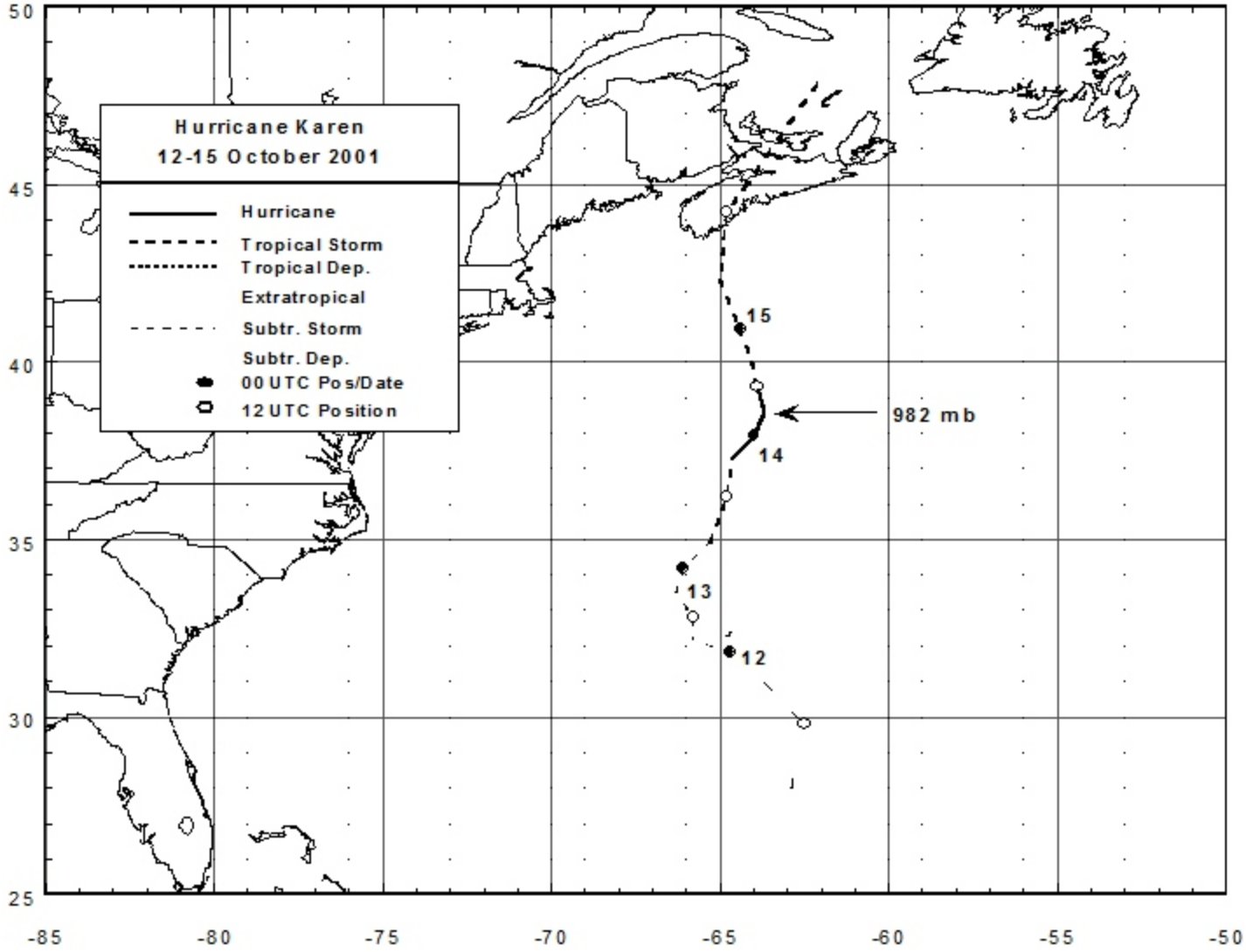

Figure 1. Best track positions for Hurricane Karen, 12-15 October 2001.

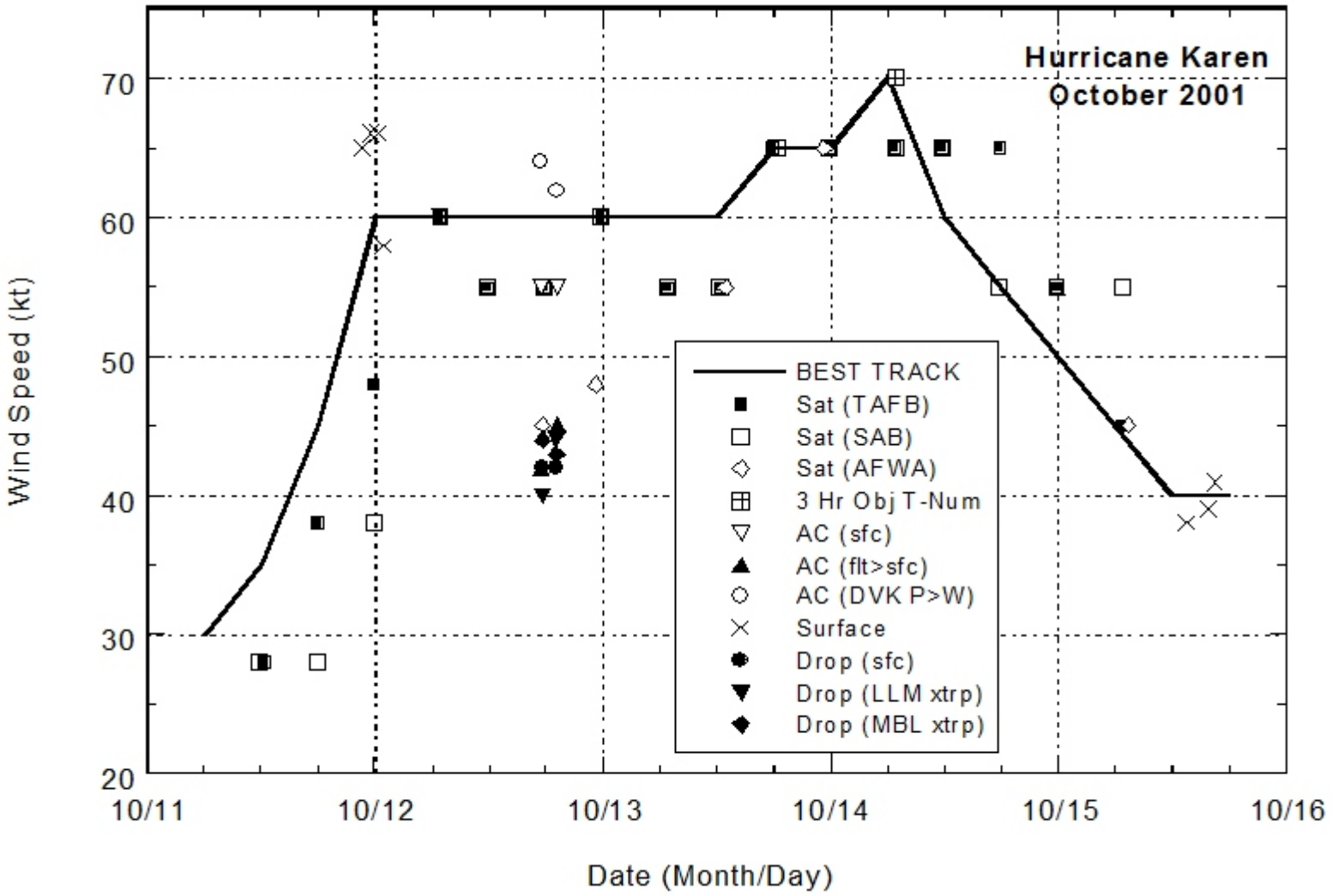

Figure 2. Best track maximum sustained surface wind speed curve for Hurricane Karen, 12-15 October 2001, and the observations on which the best track curve is based. Aircraft observations have been adjusted for elevation using 90%, 80%, and 80% reduction factors for observations from 700 mb, 850 mb, and 1500 ft, respectively. 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), and from the sounding boundary layer mean (MBL).

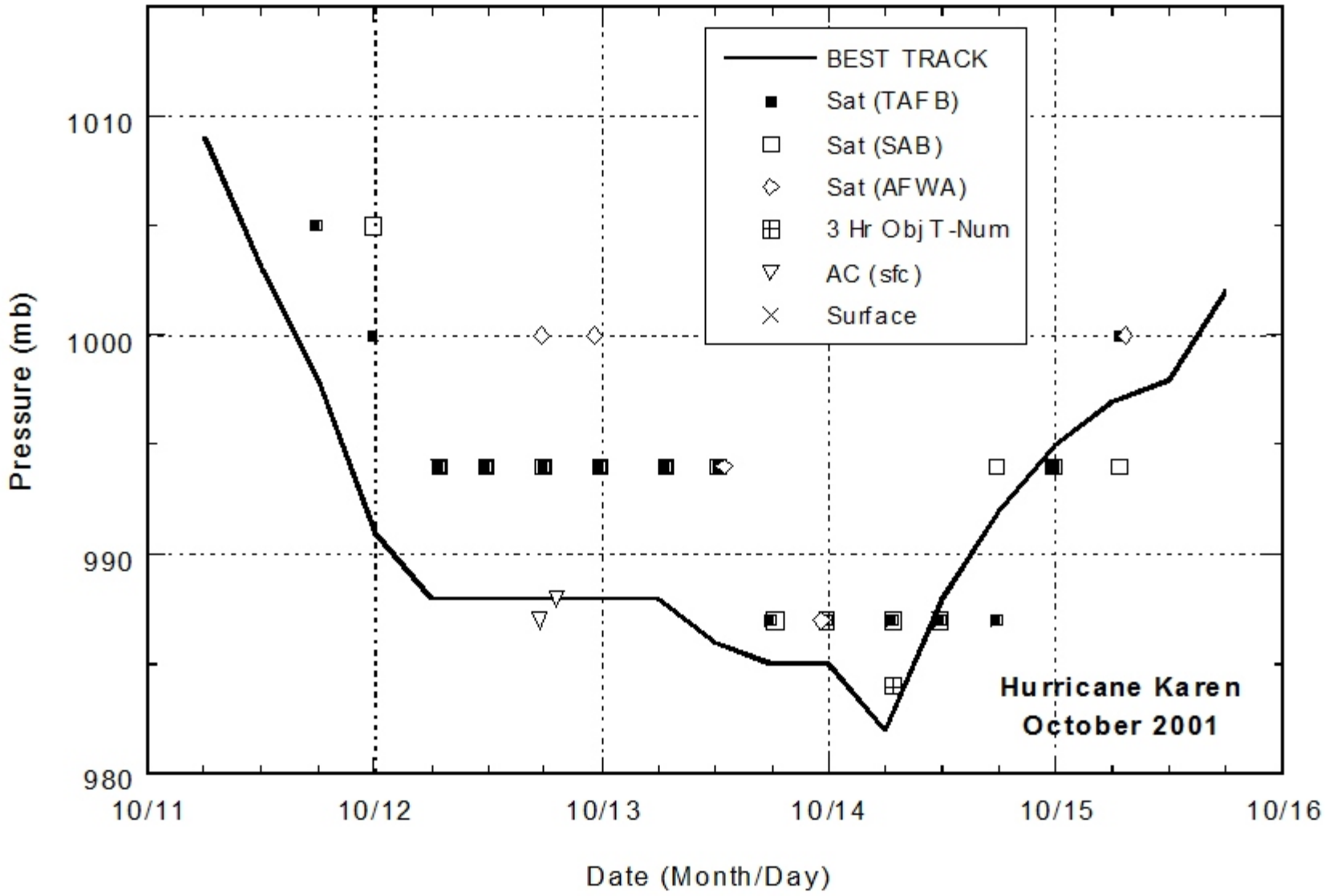

Figure 3. Best track minimum central pressure curve for Hurricane Karen, 12-15 October 2001, and the observations on which the best track curve is based.

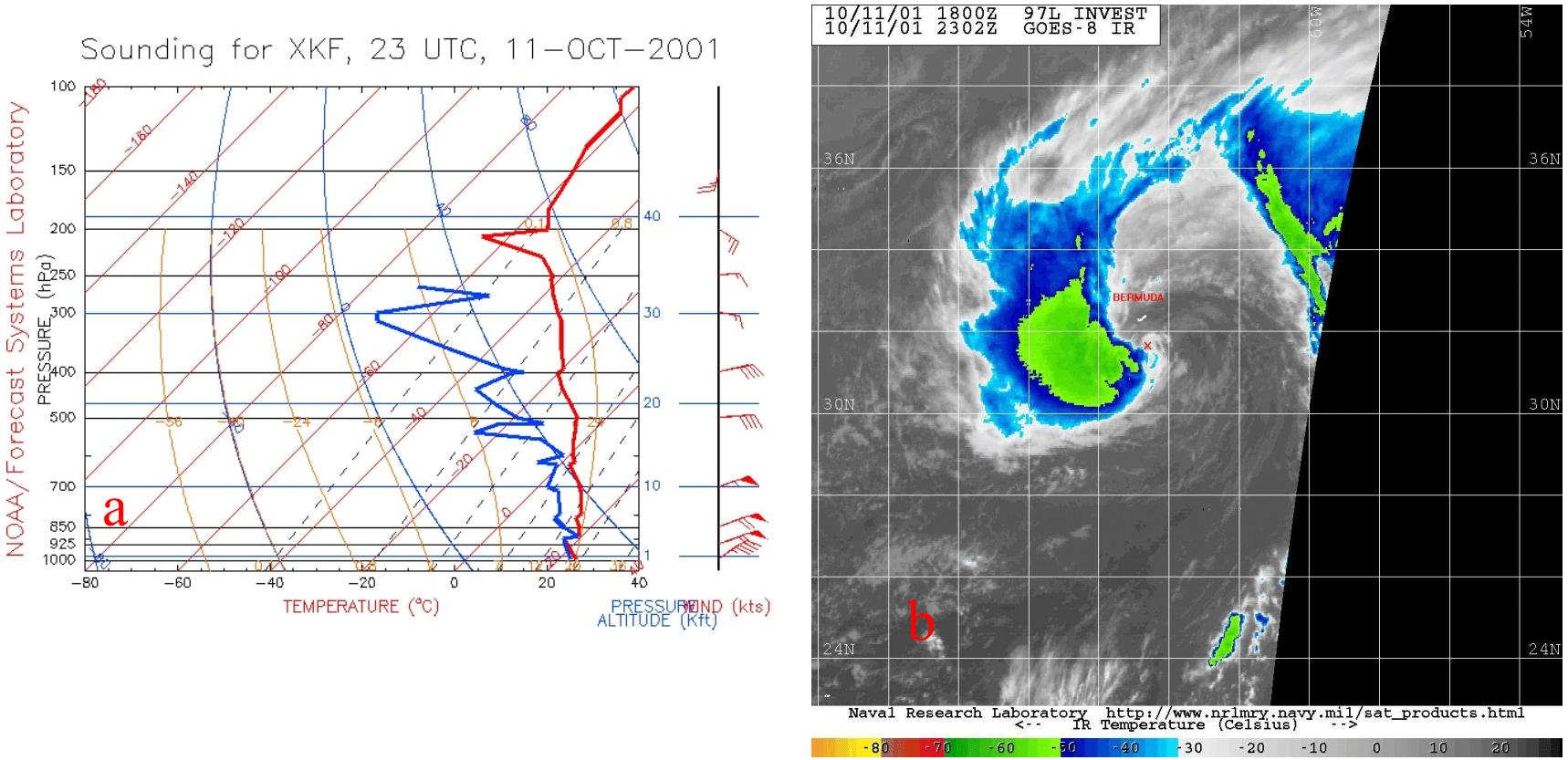

Figure 4. (a) Sounding from Bermuda (XKF) at 2300 UTC 11 October 2001; (b) Infrared satellite image at 2302 UTC 11 October at approximately the same time as the sounding data when the center of the pre-Karen extratropical low was located ("X") about 30 n mi south of the island. The decreasing vertical wind profile above the 850 mb-level is characteristic of a warm-core low pressure system. However, note the presence of cool, dry air and the steeper than saturation-adiabatic lapse rate in the mid- and upper-levels (i.e., above 500 mb level) of the sounding plot (note: temperature spike at 210 mb is due to a program plotting error). Wind gusts above hurricane force, with some as high as 103 kt, occurred on Bermuda within the next 2 hours. The sounding plot is courtesy of the NOAA Forecast Systems Laboratory and the NOAA National Climatic Data Center. The satellite image is courtesy of the Naval Research Laboratory .