NATIONAL HURRICANE CENTER
TROPICAL CYCLONE REPORT

HURRICANE RAFAEL

(AL182024)

4–10 November 2024

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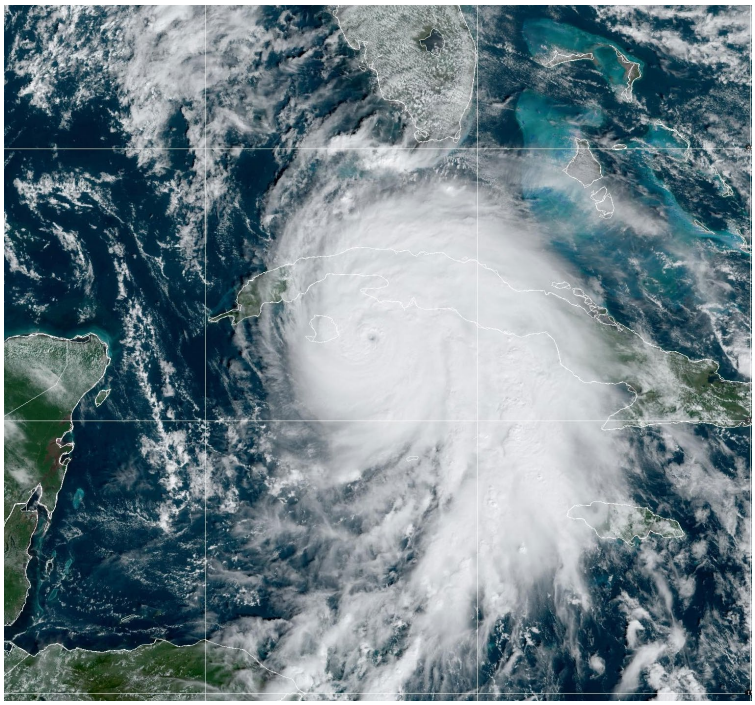

GOES-EAST GEOCOLOR SATELLITE IMAGE OF HURRICANE RAFAEL APPROACHING WESTERN CUBA AT 1520 UTC 6 NOVEMBER 2024. IMAGE COURTESY NOAA.

Rafael was a late-season category 3 hurricane (on the Saffir-Simpson Hurricane Wind Scale) that formed over the central Caribbean Sea and made landfall in western Cuba. The hurricane eventually dissipated a few days later over the central Gulf of America due to very dry air and strong wind shear. Rafael produced devastating wind and flooding across western Cuba, and was responsible for 2 deaths in Jamaica, and caused over $1 billion (USD) in damage across countries of the Caribbean.

Hurricane Rafael

4–10 NOVEMBER 2024

SYNOPTIC HISTORY

The origin of Rafael was related to a Central American Gyre (CAG)[1] that set up over the southwestern Caribbean Sea in early November. Originally the gyre manifested as a significant eastward displacement of the typical late-season eastern Pacific monsoon trough, but by 1 November the broad circulation was becoming rounder, with a large radius-of-maximum winds and disorganized convection (all typical of CAGs). Notably, the associated large-scale monsoonal flow brought heavy rains to portions of Costa Rica, Panama and Colombia as the gyre moved slowly eastward. Convection increased in coverage on 2 November on the eastern side of the gyre, and by early on 3 November, the convective area was more concentrated with a mid-level circulation noted, albeit associated with only an elongated surface circulation. The National Hurricane Center (NHC) initiated potential tropical cyclone advisories at 2100 UTC that day since the system was expected to become a tropical cyclone and bring tropical storm or hurricane conditions to land areas within the next couple of days. Thunderstorm activity formed near the mid-level center early on 4 November, causing the surface circulation to become better defined, and an Air Force Reserve reconnaissance aircraft confirmed the formation of a tropical depression by 1200 UTC 4 November, about 180 n mi southwest of Kingston, Jamaica. 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[2].

The depression became a tropical storm 6 h after formation and moved northwestward, steered by building mid-level high pressure ridging over Florida and the western Atlantic. Steady strengthening occurred late on 4 November and early on 5 November as the initially broad tropical cyclone gradually developed a smaller radius-of-maximum winds with ample deep convection while passing southwest of Jamaica. Rapid intensification began later on 5 November after the storm formed a small inner-core while moving over the very warm and deep waters of the northwestern Caribbean Sea within light vertical wind shear. Rafael became a hurricane by 0000 UTC 6 November just south of Little Cayman and passed just west of that island. The hurricane continued to rapidly intensify, with a distinct visible eye on the morning of 6 November (cover), and became a major hurricane with 100-kt winds by 1800 UTC while it approached western Cuba. A few hours later, Rafael made landfall just east of Playa Majana in Artemisa province at 2115 UTC 6 November, maintaining its 100-kt intensity with an estimated landfall pressure of 955 mb.

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[1] A Central American gyre (CAG) is a broad lower-tropospheric cyclonic circulation occurring near Central America. For more information please refer to Papin, P., L. F. Bosart, R. D. Torn, 2017: A Climatology of Central American Gyres. Mon. Wea. Rev., 145, 1983-2000.

[2] 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.

Rafael weakened somewhat due to the land interaction with western Cuba, emerging as a category 2 hurricane over the southeastern Gulf of America just before 0000 UTC 7 November. Little change in intensity occurred that day while the track gradually bent westward over the warm Gulf waters, despite some increase in shear. Early on 8 November, satellite images showed a distinct eye had re-formed with the hurricane, and it is estimated that Rafael reached a peak intensity of 105 kt near 0600 UTC 8 November while located a couple of hundred miles north of the north coast of the Yucatan Peninsula. However, rapid weakening then occurred due to a sharp increase in shear facilitating dry air entrainment into the central core along with cooler central Gulf waters west of the Loop Current. Rafael weakened to a 55-kt tropical storm just 24 h after peak intensity and degraded further in the unfavorable environment. The storm slowed down as it reached the western end of the ridge, turning northwestward and northward on 9 and 10 November. Vertical wind shear increased markedly on 9 November, causing all of the tropical cyclone's deep convection to be displaced well northeast of the exposed low-level center. Rafael continued to weaken, and by 1200 UTC 10 November, it no longer had enough organized convection to be considered a tropical cyclone, sitting a couple of hundred miles south of the Louisiana coast. The remnants of Rafael quickly became quite stretched north-to-south, and the system decayed into a trough of low pressure by 1800 UTC that day.

METEOROLOGICAL STATISTICS

Observations in Rafael (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), objective Advanced Dvorak Technique (ADT) estimates and Satellite Consensus (SATCON) 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 21 aircraft missions into Rafael and its precursor disturbance from 3–9 November (Fig. 4). This includes 17 flights of the U.S. Air Force Reserve Command's 53rd Weather Reconnaissance Squadron's WC-130 aircraft, 3 flights of the NOAA WP-3D Orion aircraft and 1 flight of the NOAA G-IV synoptic surveillance aircraft. These missions provided a total of 45 center fixes for Rafael. 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), the Defense Meteorological Satellite Program (DMSP) satellites, and the Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) satellites, among others, were also useful in constructing the best track of Rafael.

Ship reports of winds of tropical storm force associated with Rafael are given in Table 2, and selected surface observations from land stations and data buoys are given in Table 3.

Winds and Pressure

The 105-kt peak intensity of Rafael on 8 November is primarily based on satellite data and backward/forward extrapolation of available aircraft data. While there was no aircraft in the hurricane when the satellite estimates were highest, most of the satellite estimates were biased too high while Rafael was in the Gulf of America, and 105 kt was chosen as the peak, near the low end of the satellite data. It is worth mentioning that Rafael is tied for the strongest November hurricane on record in the Gulf of America (with Kate 1985).

It is estimated that Rafael made landfall as a 100-kt major hurricane at 2115 UTC 6 November, although this intensity estimate is somewhat uncertain given the remote location in Cuba where Rafael moved ashore and the lack of aircraft reconnaissance for the 3 hours prior to landfall. The 100-kt intensity is based on the last mission, which showed peak 700-mb flight-level winds of 104 kt around 1800 UTC and extrapolated pressures around 955 mb. Note that no central dropsondes were available, and the aircraft was unable to sample the northeastern quadrant where typically the maximum winds would be located for a system moving northwestward. Additionally, Mariel near the north coast of Cuba reported peak 10-min sustained winds of 87 kt, which suggest maximum winds of at least 95 kt for a 1-min average, and that was about an hour after landfall. Satellite estimates suggested that Rafael likely maintained its intensity as it reached the coast, though there is more uncertainty regarding the cyclone's intensity than average for a typical landfalling major hurricane.

The estimated minimum central pressure of 954 mb over the central Gulf of America is based on the Knaff-Zehr-Courtney pressure-wind relationship for the given 105-kt peak sustained winds.

Cuba

Hurricane conditions occurred over portions of west-central Cuba, including the provinces of Artemisa, Mayabeque and La Habana. Tropical storm conditions occurred across portions of Pinar del Rio. The peak 10-min sustained winds were 87 kt in Mariel, Artemisa, with gusts to 100 kt, before the station stopped recording data (see Table 3 for more reports).

Cayman Islands

No strong winds or low pressures were measured in the Cayman Islands. Grand Cayman reported a minimum pressure of 1004.8 mb at 0300 UTC 6 November, with a peak gust of 25 kt.

Florida

While the core of Rafael moved far southwest of the Florida Keys, one land-based site (Key West Naval Air Station) did record sustained tropical-storm-force winds (34 kt), with a gust to 46 kt late on 6 November.

Storm Surge[3]

No in situ water level measurements were available in western Cuba, though the Cuban Meteorological Service reported high surge on the north coast of Cuba west of where Rafael emerged into the Straits of Florida. The peak inundation observed in the Florida Keys was less than 1.2 ft above Mean Higher High Water (MHHW).

Rainfall

In Cuba, heavy rainfall of 4–8 inches (100–200 mm) was common over western and west-central portions of the country. The peak rainfall total reported was 8.56 inches (218 mm) over Bauta in Artemisa province.

In the Cayman Islands, about 11 inches (~280 mm) was reported over Cayman Brac as a storm total rainfall. Grand Cayman had much less rainfall west of Rafael's track, with 1.3 inches (33 mm) recorded.

In the Florida Keys, rainfall was generally light, with 1–3 inches recorded over portions of the Lower Florida Keys, and the heaviest total was 3.43 inches on Cudjoe Key.

While Jamaica received very heavy rainfall from Rafael, no totals were available.

Tornadoes

No tornadoes were reported in association with Rafael.

CASUALTY AND DAMAGE STATISTICS

Rafael is responsible for at least 2 direct[4] fatalities during its time as a tropical cyclone. Two people in Jamaica whose truck washed away from flooding perished. Before Rafael became

[3] Several terms are used to describe water levels due to a storm. **Storm surge** is defined as the abnormal rise of water generated by a storm, over and above the predicted astronomical tide, and is expressed in terms of height above normal tide levels. Because storm surge represents the deviation from normal water levels, it is not referenced to a vertical datum. **Storm tide** is defined as the water level due to the combination of storm surge and the astronomical tide, and is expressed in terms of height above a vertical datum, i.e. the North American Vertical Datum of 1988 (NAVD88) or Mean Lower Low Water (MLLW). **Inundation** is the total water level that occurs on normally dry ground as a result of the storm tide, and is expressed in terms of height above ground level. At the coast, normally dry land is roughly defined as areas higher than the normal high tide line, or Mean Higher High Water (MHHW).

[4] Deaths occurring as a direct result of the forces of the tropical cyclone are referred to as "direct" deaths. These would include those persons who drowned in storm surge, rough seas, rip currents, and freshwater floods. Direct deaths also include casualties resulting from lightning and wind-related events (e.g., collapsing structures). Deaths occurring from such factors as heart attacks, house fires, electrocutions from downed power lines, vehicle accidents on wet roads, etc., are considered "indirect" deaths.

a tropical cyclone, the large CAG circulation caused torrential rain in Panama and Colombia, with media reports suggesting 5 flooding-related fatalities in Panama and 1 in Colombia.

While there were no reports of injuries or deaths in Cuba associated with Rafael, the hurricane was quite destructive there. Media reports indicate over 3000 homes were damaged in Artemisa and Mayabeque provinces, including fortified buildings like hospitals and schools, with extreme crop damage across tens of thousands of acres. The entire electrical grid of Cuba was knocked offline after the hurricane, and over half of the cell phones were without service in western Cuba (along with over 53,000 landlines). Preliminary damage estimates were around 1 billion USD from Cuban economists.

Heavy rainfall caused flash floods and mud slides over Jamaica, with an estimated 8 million USD in damage recorded across the island according to news reports sourcing the government of Jamaica.

In the Cayman Islands, the worst damage was located in Cayman Brac. Many trees and powerlines were downed, and some structures received damage as seen in media photos. No monetary estimates were available.

FORECAST AND WARNING CRITIQUE

Genesis

The genesis of Rafael was well forecast overall (Table 4). The disturbance from which Rafael developed was introduced in the Tropical Weather Outlook (TWO) over 8 days (204 h) prior to genesis and raised to the medium category over 7 days (186 h) before formation. A low 2-day chance of formation was introduced into the outlook 90 h before genesis, and the near-term probabilities were raised to the medium and high categories 60 h and 36 h before genesis, respectively. The forecasts for the cyclone's genesis location were accurate and had a 100% hit rate, lying within every genesis area depicted in NHC's Graphical TWO (Fig. 5).

Track

A verification of NHC official track forecasts (OFCL) for Rafael is given in Table 5a. Official track forecast errors were much lower than the mean official errors for the previous 5-yr period at all forecast times, with an exceptionally low average 48-h error of only 23.9 n mi. A homogeneous comparison of the official track errors with selected guidance models is given in Table 5b and illustrated in Fig. 6. The NHC track forecasts verified extremely well and were quite skillful, outperforming almost all of the available track model guidance except the consensus aids. The ECMWF (EMXI) did very well at long range for Rafael, and the GFS and HAFS models struggled with Rafael especially at longer ranges. The initial track forecast for Rafael showed the system ending up closer to the Louisiana coast than what occurred (Fig. 7), and later on the tropical cyclone dissipated more quickly than anticipated over the central Gulf of America, rather than turn southwestward. These forecasts aren't well represented in the verification since NHC verification rules require a system to exist to verify any forecasts (i.e. any systems that dissipate faster than anticipated would not show up).

Intensity

A verification of NHC official intensity forecasts (OFCL) for Rafael is given in Table 6a. Official intensity forecast errors were above the mean official errors for the previous 5-yr period through 72 h and then below the mean at 96-120 h. A homogeneous comparison of the official intensity errors with selected guidance models is given in Table 6b and illustrated in Fig. 8. While the NHC forecast did reasonably well compared to most of the guidance, NHC initially showed a lower peak intensity than what occurred near Cuba and then maintained the hurricane for too long over the Gulf of America (Fig. 9a). The best performing deterministic models were the HWRF and HMON (Fig. 9b) models, which showed the rapid intensification and weakening episodes fairly well, and the HCCA model (Fig. 9c) was also a top performer. The HAFS guidance (especially HAFS-B, Fig. 9d) really struggled with Rafael, with errors at times twice the average of the official forecast and very inconsistent forecasts from cycle to cycle.

Wind Watches and Warnings

Coastal watches and warnings associated with Rafael are given in Table 7. For the United States, a Tropical Storm Watch was first issued at 2100 UTC 4 November for the Lower and Middle Florida Keys, with a Tropical Storm Warning issued at 1500 UTC 5 November. Tropical-storm-force winds first affected the Lower Keys around 0000 UTC 7 November, resulting in a lead time of about 51 hours for the watch and 39 hours for the warning.

IMPACT-BASED DECISION SUPPORT SERVICES (IDSS) AND PUBLIC COMMUNICATION

The NHC began communication with emergency managers on November 4 as Rafael was developing in the central Caribbean Sea. Five decision support briefings were provided to emergency managers and coordinated through the FEMA Hurricane Liaison Team embedded at the NHC. These briefings included video-teleconferences with FEMA HQ, FEMA Region 4, and FEMA Region 6. Briefing support continued through November 8 as Rafael moved southwest of the Florida Keys and into the Gulf of America.

The NHC conducted 10 live stream broadcasts from 3–9 November that were promoted on NHC Facebook, Instagram, YouTube and X accounts. NHC provided a total of 9 virtual interviews during the event to national networks and local affiliates.

Beginning on 3 November, TAFB provided seven live briefings to US Coast Guard District 7 and five live briefings to US Coast Guard District 8 in support of their life-saving mission.

ACKNOWLEDGEMENTS

Data in Table 3 and damage summaries were compiled from the Post Tropical Cyclone Report issued by WFO Key West and from the Cuban Meteorological Service (INSMET). Data from the National Data Buoy Center and NOS Center for Operational Oceanographic Products and Services were also used in this report. Lisa Bucci (NHC) created the aircraft reconnaissance summary graphic (Fig. 4) and the NHC track and intensity plots (Figs. 7 and 9). Philippe Papin (NHC) created the graphical TWO verification image (Fig.5). Matthew Green (FEMA), Maria Torres (NHC Public Affairs) and Chris Landsea (NHC TAFB) contributed to the IDSS and Public Communication section.

Table 1. Best track for Hurricane Rafael, 4–10 November 2024.

Date/Time (UTC)	Latitude (°N)	Longitude (°W)	Pressure (mb)	Wind Speed (kt)	Stage
03 / 1800	12.7	77.0	1004	30	disturbance
04 / 0000	13.5	76.8	1004	30	"
04 / 0600	14.2	76.7	1004	30	"
04 / 1200	14.8	76.6	1003	30	tropical depression
04 / 1800	15.1	76.4	1001	35	tropical storm
05 / 0000	15.8	76.9	999	40	"
05 / 0600	16.6	77.6	994	45	"
05 / 1200	17.5	78.3	993	50	"
05 / 1800	18.5	79.1	990	60	"
06 / 0000	19.4	80.0	985	70	hurricane
06 / 0600	20.1	80.9	975	80	"
06 / 1200	21.0	81.6	964	90	"
06 / 1800	22.0	82.3	955	100	"
06 / 2115	22.7	82.7	955	100	"
07 / 0000	23.1	83.2	968	95	"
07 / 0600	23.8	84.1	970	90	"
07 / 1200	24.3	84.9	969	90	"
07 / 1800	24.6	85.7	968	90	"
08 / 0000	24.6	86.6	966	90	"
08 / 0600	24.4	87.6	954	105	"
08 / 1200	24.4	88.4	962	95	"
08 / 1800	24.6	89.1	973	80	"

Date/Time (UTC)	Latitude (°N)	Longitude (°W)	Pressure (mb)	Wind Speed (kt)	Stage
09 / 0000	24.7	89.7	986	65	"
09 / 0600	24.8	90.5	992	55	tropical storm
09 / 1200	25.0	91.2	998	50	"
09 / 1800	25.3	91.5	1000	45	"
10 / 0000	25.6	91.7	1001	40	"
10 / 0600	25.9	91.9	1003	35	"
10 / 1200	26.1	91.9	1003	35	low
10 / 1800					dissipated
08 / 0600	24.4	87.6	954	105	minimum pressure and maximum winds
06 / 2115	22.7	82.7	955	100	landfall just east of Playa Majana, Artemisa, Cuba

Table 2. Selected ship reports with winds of at least 34 kt for Hurricane Rafael, 4–10 November 2024.

Date/Time (UTC)	Ship call sign	Latitude (°N)	Longitude (°W)	Wind dir/ speed (kt)	Pressure (mb)
07 / 0800	WDBH	24.1	83.0	100 / 49	1005.6
07 / 0900	WDBH	24.2	83.2	110 / 55	1005.4
07 / 1100	WDBH	24.5	83.5	110 / 45	1004.4
08 / 1400	C6GY5	23.7	90.4	320 / 36	1005.6
08 / 1800	9V7200	27.7	87.1	090 / 35	1017.0
08 / 2300	WLZ9WH	26.7	87.4	090 / 45	1008.3
09 / 0500	WLZ9WH	25.5	86.6	080 / 40	1012.6
10 / 0800	WGAH	27.0	90.1	090 / 36	1008.9

Table 3. Selected surface observations for Hurricane Rafael, 4–10 November 2024.

Location	Minimum Sea Level Pressure		Maximum Surface Wind Speed			Storm surge (ft)	Storm tide (ft)	Estimated Inundation (ft)[c]	Total rain (in)
	Date/ time (UTC)	Press. (mb)	Date/ time (UTC)[a]	Sustained (kt)[b]	Gust (kt)				
Buoys									
42001 Mid Gulf (25.93N 89.66W) (3.7 m)	08/2050	1001.3	09/0751	38 (1-min)	48				
42058 Central Caribbean (14.51N 75.15W) (3.7 m)	04/0920	1005.2	05/0659	32 (1-min)	35				
Cuba									
International Civil Aviation Organization (ICAO) Sites									
Santa Lucia (WMO 78312)	07/0230	1001.6	06/2110	19	35				0.79
Isabel Rubio (WMO 78313)									5.44
La Palma (WMO 78316)	07/0040	998.2	07/0152	26	44				1.37
Paso Real de San Diego (WMO 78317)	06/2035	997.4	07/0040	27	40				0.76
Bahía Honda (WMO 78318)	06/2300	972.2	06/2210	76	94				1.85
Güira de Melena (WMO 78320)	06/2110	981.8	06/2110	81	97[i]				7.01
Bauta (WMO 78376)	06/2150	985	06/2210	55	70				8.56
Mariel, Artemisa	06/2222	976.4	06/2210	83	100[i]				4.41
Güines (WMO 78323)	06/1900	991.1	06/1800	38	52				6.26
Batabanó (WMO 78322)	06/2100	992.5	06/1610	76	89				7.57
Bainoa (WMO 78340)	06/1300	994.2	06/1745	32	40				
Casablanca (WMO 78325)	06/1900	998.1	06/1845	49	64				
Santiago de las Vegas (WMO 78373)			06/1626	43	53				
United States- Florida									
International Civil Aviation Organization (ICAO) Sites									
Key West (KEYW) (24.56N 81.76W)	06/2153	1009.8	07/0206	31	41				2.42
Marathon (KMTH) (24.73N 81.05W)	06/2153	1010.1	07/0159	23	36				
Key West NAS (KNQX) (24.58N 81.68W)	06/2153	1009.1	07/0201	34	46				2.58
Coastal-Marine Automated Network (C-MAN) Sites									
Long Key (LONF1) (24.84N 80.86W) (6.3m)	06/2130	1009.2	06/0900	25	36				
Sand Key (SANF1) (24.46N 81.88W) (15m)	06/2140	1007.8	06/2316	47	57				

Location	Minimum Sea Level Pressure		Maximum Surface Wind Speed			Storm surge (ft)	Storm tide (ft)	Estimated Inundation (ft)[c]	Total rain (in)
	Date/ time (UTC)	Press. (mb)	Date/ time (UTC)[a]	Sustained (kt)[b]	Gust (kt)				
National Ocean Service (NOS) Sites									
Key West (KYWF1) (24.56N 81.81W) (15m)	06/2130	1009.6	07/0948	24	38			1.19	
WeatherFlow									
Alligator Reef (XALG) (24.85N 80.62W) (7.5m)	06/0858	1009.5	07/0023	28	36				
Key West CG (XKYW) (24.57N 81.90W) (10m)			06/2335	23	35				
WeatherSTEM/FSWN									
Key West HS (0470W) (24.55N 81.78W) (10m)			06/2213		36				
Duck Key (1846W) (24.77N 80.91W) (15m)			06/2211		36				
Keys Energy Sites									
Big Coppitt Key (KEYS13149) (24.60N 81.65W) (18m)			07/0207	31	42				
Key West (KEYS4149) (24.56N 81.80W) (11m)			07/0213	22	35				
Cudjoe Key (KEYSCKS) (24.66N 81.48W) (10m)			07/0709	23	34				
CoCoRAHS sites									
Cudjoe Key (FL-MN-52) (24.66N 81.49W)									3.43

[a] Date/time is for sustained wind when both sustained and gust are listed.
[b] Sustained wind averaging periods- Cuba 10 min, for C-MAN and land-based reports 2 min except WeathefFlow 5 min; buoy averaging periods 8 min
[c] Estimated inundation is the maximum height of water above ground. For NOS tide gauges, the height of the water above Mean Higher High Water (MHHW) is used as a proxy for inundation.
[i] Incomplete

Table 4. Number of hours in advance of formation of Rafael 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	**168-Hour Outlook**
Low (<40%)	90	204
Medium (40%-60%)	60	186
High (>60%)	36	72

Table 5a. NHC official (OFCL) and climatology-persistence skill baseline (OCD5) track forecast errors (n mi) for Rafael. 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	60	72	96	120
OFCL	**15.2**	**16.1**	**16.0**	**23.9**	**42.7**	**62.7**	**116.8**	**151.4**
OCD5	38.4	94.6	183.8	299.9	423.6	538.3	703.9	800.5
Forecasts	22	20	18	16	14	12	8	4
OFCL (2019-23)	23.9	36.5	49.3	63.4	79.2	93.4	132.9	190.4
OCD5 (2019-23)	45.7	97.1	153.0	205.4	254.9	297.8	372.7	439.1

Table 5b. Homogeneous comparison of selected track forecast guidance models (in n mi) for Rafael. 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	60	72	96	120
OFCL	13.1	13.9	14.0	21.4	42.7	66.5	117.0	145.0
OCD5	39.3	94.1	182.4	299.6	424.1	539.2	703.5	792.3
GFSI	13.3	21.3	30.1	36.2	55.4	91.3	210.5	579.5
HWFI	15.7	21.9	26.9	38.6	65.7	91.2	**115.2**	174.9
HMNI	14.2	21.0	23.6	32.6	59.9	104.7	156.5	176.5
HFAI	17.8	29.8	37.0	46.3	67.3	104.3	191.3	615.6
HFBI	17.3	26.7	34.2	44.6	56.3	85.9	163.1	575.1
EMXI	13.5	16.0	23.1	32.5	54.4	70.4	**75.5**	**114.1**
NVGI	23.8	42.4	77.4	114.6	152.0	205.3	305.1	327.3
CMCI	19.3	35.5	49.6	63.5	91.2	140.8	317.4	558.9
CTCI	16.7	27.7	38.7	59.1	89.5	114.3	257.4	493.0
TVCA	**12.2**	16.0	16.4	**19.7**	**36.9**	**60.5**	**104.1**	270.4
TVCX	**12.3**	15.7	16.4	**19.1**	**37.6**	**61.3**	**97.6**	239.4
GFEX	**11.5**	14.8	18.2	**20.5**	**32.7**	**54.4**	**96.6**	236.9
TVDG	**12.3**	15.4	16.4	**17.9**	**35.8**	**58.1**	**97.0**	239.2
HCCA	13.3	17.2	16.2	24.5	46.4	73.2	**68.6**	206.0
FSSE	**12.9**	16.9	20.1	21.8	43.4	**56.7**	**81.6**	**124.4**
AEMI	13.2	20.6	26.3	37.9	59.0	89.2	230.1	420.1
TABS	38.3	76.2	116.6	155.0	184.2	195.9	271.8	675.2
TABM	24.7	43.5	65.8	96.8	137.3	179.5	370.5	857.4
TABD	28.8	63.9	98.5	139.4	193.3	256.7	470.4	891.3
Forecasts	21	19	17	15	13	11	7	3

Table 6a. NHC official (OFCL) and climatology-persistence skill baseline (OCD5) intensity forecast errors (kt) for Rafael. 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	60	72	96	120
OFCL	6.1	10.8	11.4	14.7	17.1	19.2	**11.9**	**6.2**
OCD5	10.4	19.2	27.2	31.5	35.9	32.6	26.2	5.2
Forecasts	22	20	18	16	14	12	8	4
OFCL (2019-23)	5.0	7.3	8.5	9.7	10.4	10.9	12.9	15.5
OCD5 (2019-23)	6.6	10.2	13.1	15.6	17.2	18.6	21.8	22.6

Table 6b. Homogeneous comparison of selected intensity forecast guidance models (in kt) for Rafael. 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 6a due to the homogeneity requirement.

Model ID	Forecast Period (h)							
	12	24	36	48	60	72	96	120
OFCL	6.2	11.1	11.5	14.3	16.5	19.1	9.3	6.7
OCD5	10.5	19.6	26.9	30.3	33.9	30.1	21.1	**5.3**
HWFI	10.0	11.9	11.5	**11.8**	**11.8**	**14.6**	**5.7**	16.0
HMNI	6.9	**8.2**	**10.9**	**14.1**	**12.4**	**12.9**	12.3	8.3
HFAI	7.2	11.2	14.2	19.9	29.0	38.4	19.7	15.7
HFBI	8.8	**9.2**	12.1	21.6	36.4	45.9	16.7	13.0
DSHP	9.8	14.2	16.9	16.7	**15.8**	19.5	9.7	**3.0**
LGEM	9.4	13.7	16.6	16.7	17.2	21.1	13.4	9.7
ICON	8.5	11.3	12.0	**12.5**	**13.2**	**16.0**	**7.1**	**6.3**
IVCN	8.0	**10.1**	**11.2**	**13.9**	17.3	23.1	9.9	**5.0**
IVDR	8.0	**10.0**	**10.5**	**13.7**	17.6	23.5	10.9	7.3
CTCI	10.0	14.9	15.6	15.6	16.8	21.6	17.9	18.7
GFSI	10.0	14.3	16.2	15.9	20.0	23.6	13.9	20.0
EMXI	10.9	16.8	21.1	24.0	26.8	31.5	16.4	**5.3**
HCCA	8.4	**9.1**	**8.6**	**13.3**	17.4	20.7	10.6	**5.3**
FSSE	7.3	**7.6**	**7.2**	**8.3**	**11.2**	**16.5**	**7.9**	**6.3**
Forecasts	21	19	17	15	13	11	7	3

Table 7. Watch and warning summary for Hurricane Rafael, including those issued with potential tropical cyclone advisories before Rafael formed.

Date/Time (UTC)	Action	Location
3 / 2100	Tropical Storm Warning issued	Jamaica
3 / 2100	Hurricane Watch issued	Cayman Islands
4 / 1200	Hurricane Watch changed to Hurricane Warning	Cayman Islands
4 / 1500	Tropical Storm Watch issued	Villa Clara to Las Tunas
4 / 1500	Tropical Storm Watch issued	Cienfuegos
4 / 1500	Hurricane Watch issued	Pinar del Rio to Matanzas
4 / 1500	Hurricane Watch issued	Isle of Youth
4 / 2100	Tropical Storm Watch issued	Dry Tortugas to Channel 5 Bridge
5 / 0300	Tropical Storm Watch changed to Tropical Storm Warning	Cienfuegos
5 / 0300	Hurricane Watch changed to Hurricane Warning	Pinar del Rio to Matanzas
5 / 0300	Hurricane Watch changed to Hurricane Warning	Isle of Youth
5 / 0300	Tropical Storm Watch modified to	Camaguey to Las Tunas
5 / 0300	Tropical Storm Warning issued	Villa Clara to Ciego de Avila
5 / 1500	Tropical Storm Watch changed to Tropical Storm Warning	Dry Tortugas to Channel 5 Bridge
5 / 1500	Tropical Storm Watch discontinued	All
5 / 2100	Tropical Storm Watch issued	Camaguey to Las Tunas
5 / 2100	Tropical Storm Warning discontinued	Jamaica
6 / 1200	Tropical Storm Watch discontinued	All
6 / 1200	Hurricane Warning discontinued	Grand Cayman
6 / 1500	Hurricane Warning discontinued	Little Cayman to Cayman Brac
7 / 0300	Tropical Storm Warning discontinued	Villa Clara
7 / 0300	Tropical Storm Warning discontinued	Cienfuegos

Date/Time (UTC)	Action	Location
7 / 0300	Hurricane Warning modified to	Pinar del Rio to Mayabeque
7 / 0300	Hurricane Warning discontinued	Isle of Youth
7 / 0900	Hurricane Warning discontinued	All
7 / 1200	Tropical Storm Warning discontinued	All

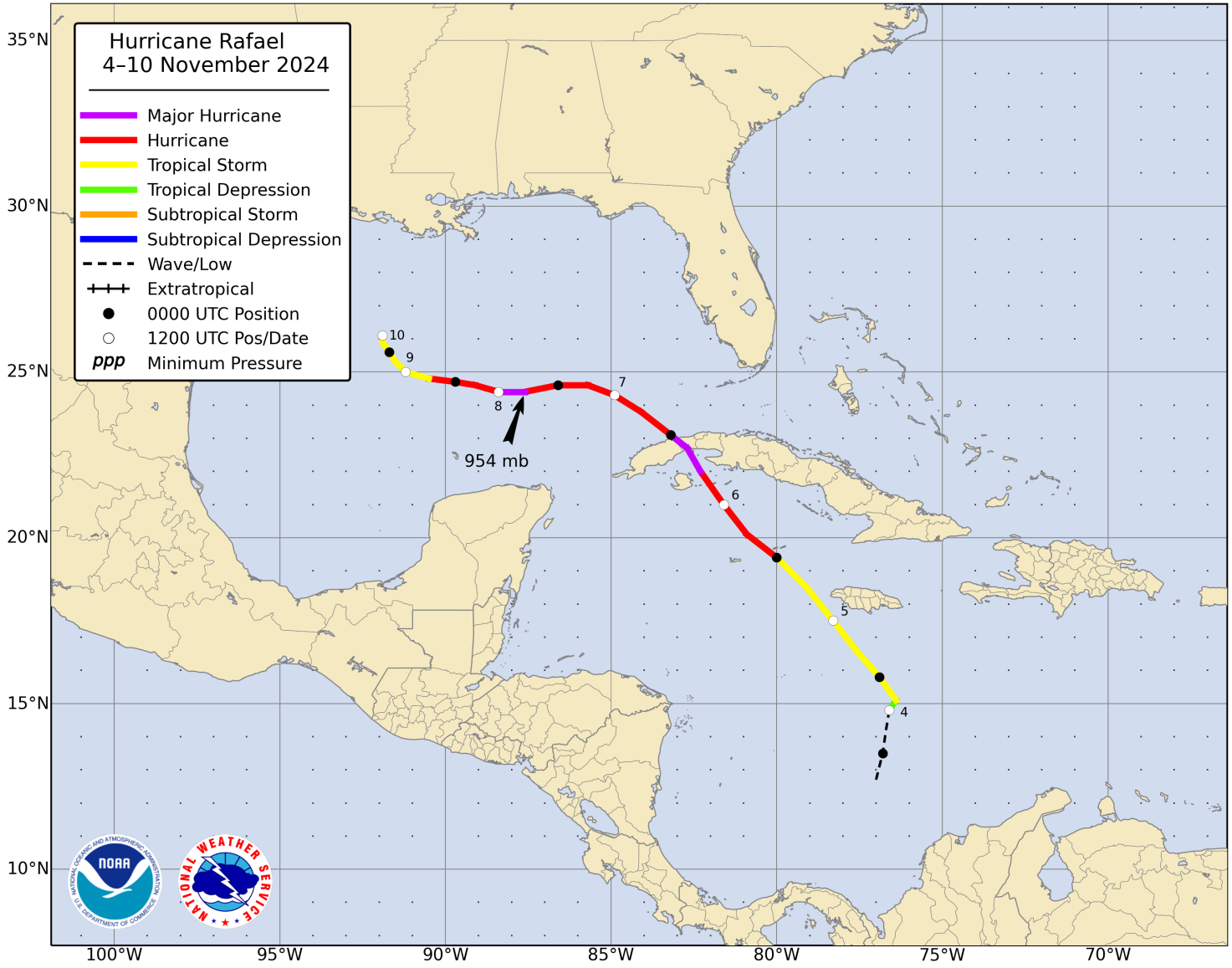

Figure 1. Best track positions for Hurricane Rafael, 4–10 November 2024.

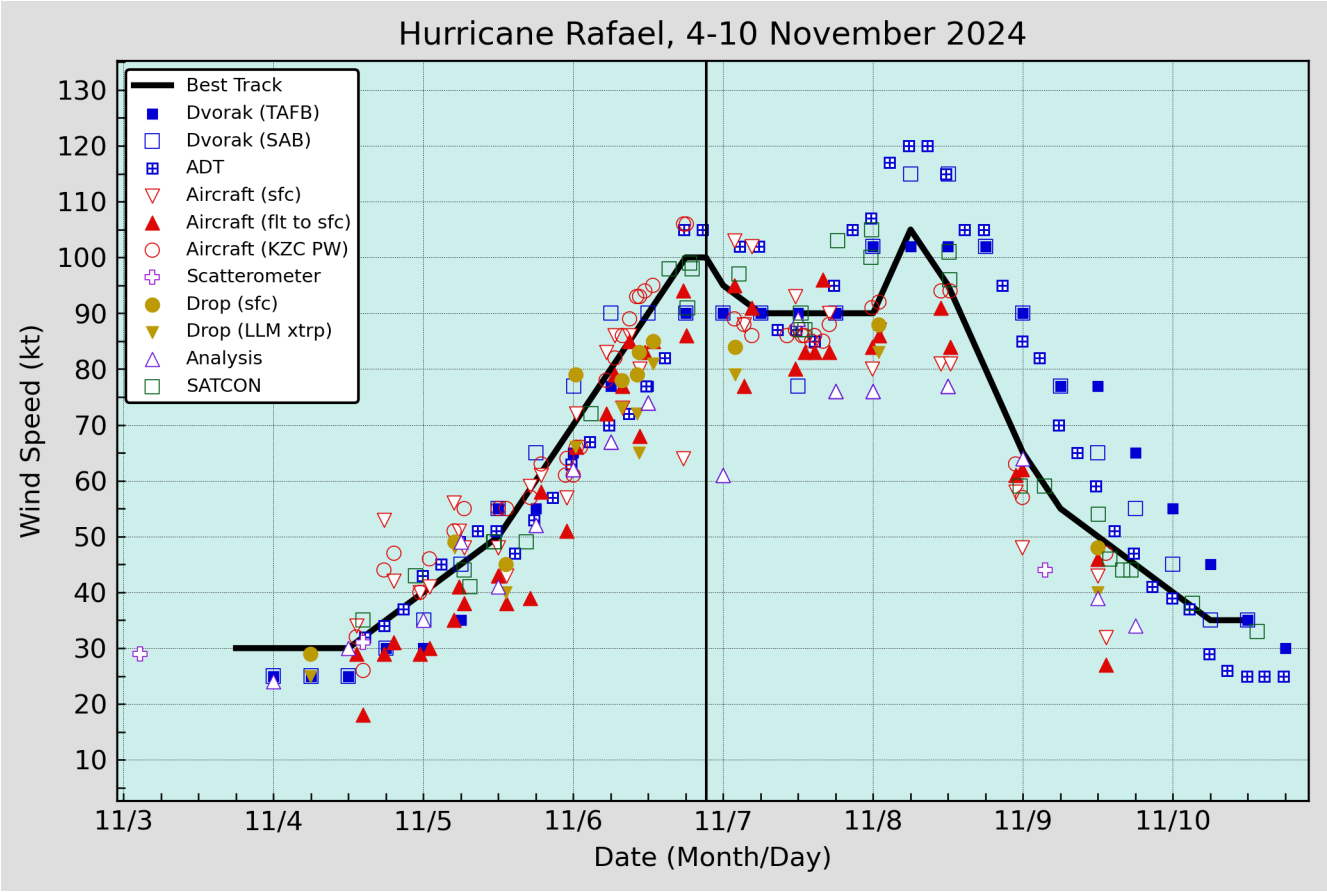

Figure 2. Selected wind observations and best track maximum sustained surface wind speed curve for Hurricane Rafael, 4–10 November 2024. Aircraft observations have been adjusted for elevation using 90%, 80%, and 75% adjustment factors for observations from 700 mb, 850 mb, and 925 mb, respectively. Dropwindsonde 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. SATCON intensity estimates are from the Cooperative Institute for Meteorological Satellite Studies. Dashed vertical lines correspond to 0000 UTC, and the solid vertical line corresponds to landfall.

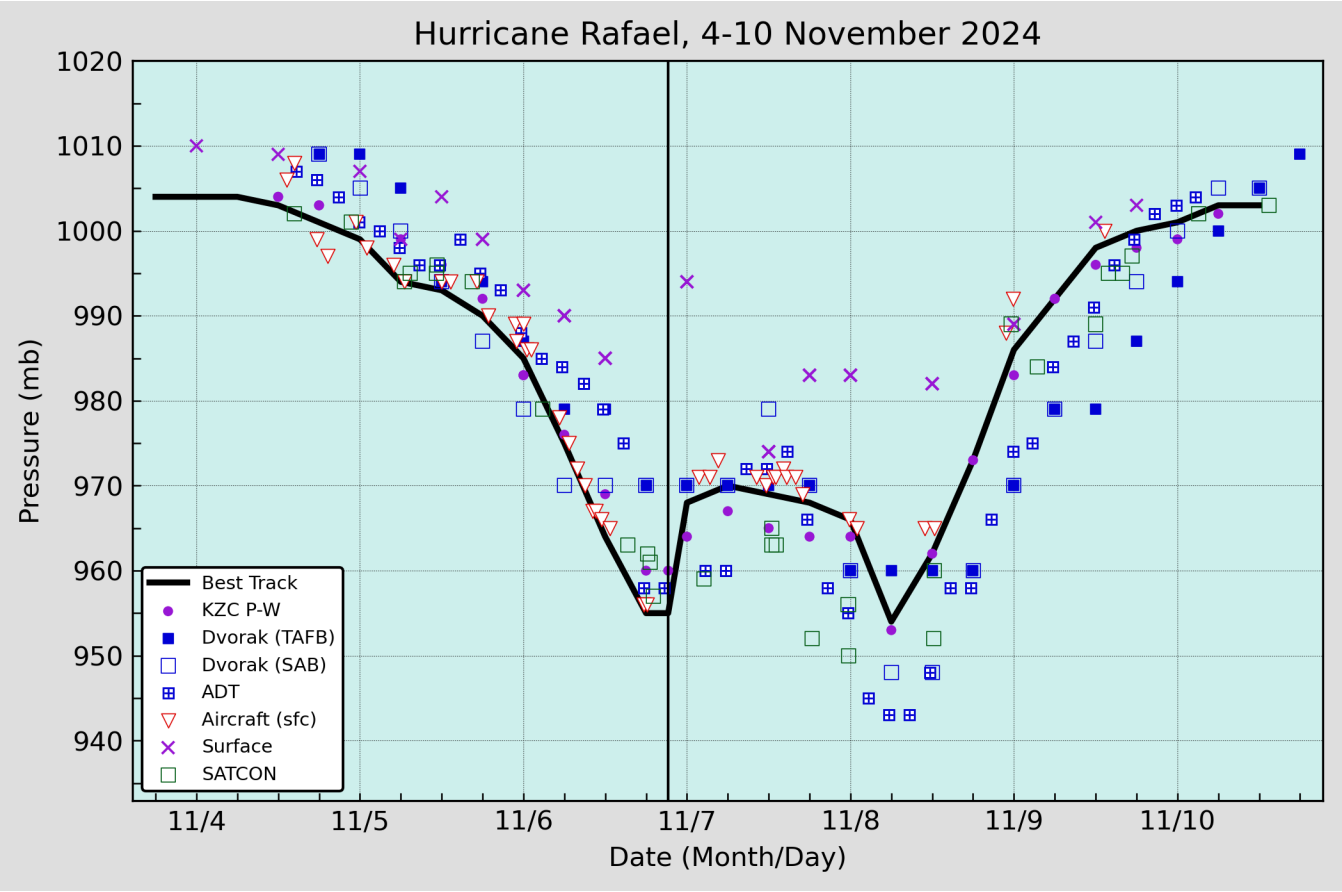

Figure 3. Selected pressure observations and best track minimum central pressure curve for Hurricane Rafael, 4–10 November 2024. Advanced Dvorak Technique estimates represent the Current Intensity at the nominal observation time. SATCON intensity estimates are from the Cooperative Institute for Meteorological Satellite Studies. KZC P-W refers to pressure estimates derived using the Knaff-Zehr-Courtney pressure-wind relationship. Dashed vertical lines correspond to 0000 UTC, and the solid vertical lines corresponds to landfall.

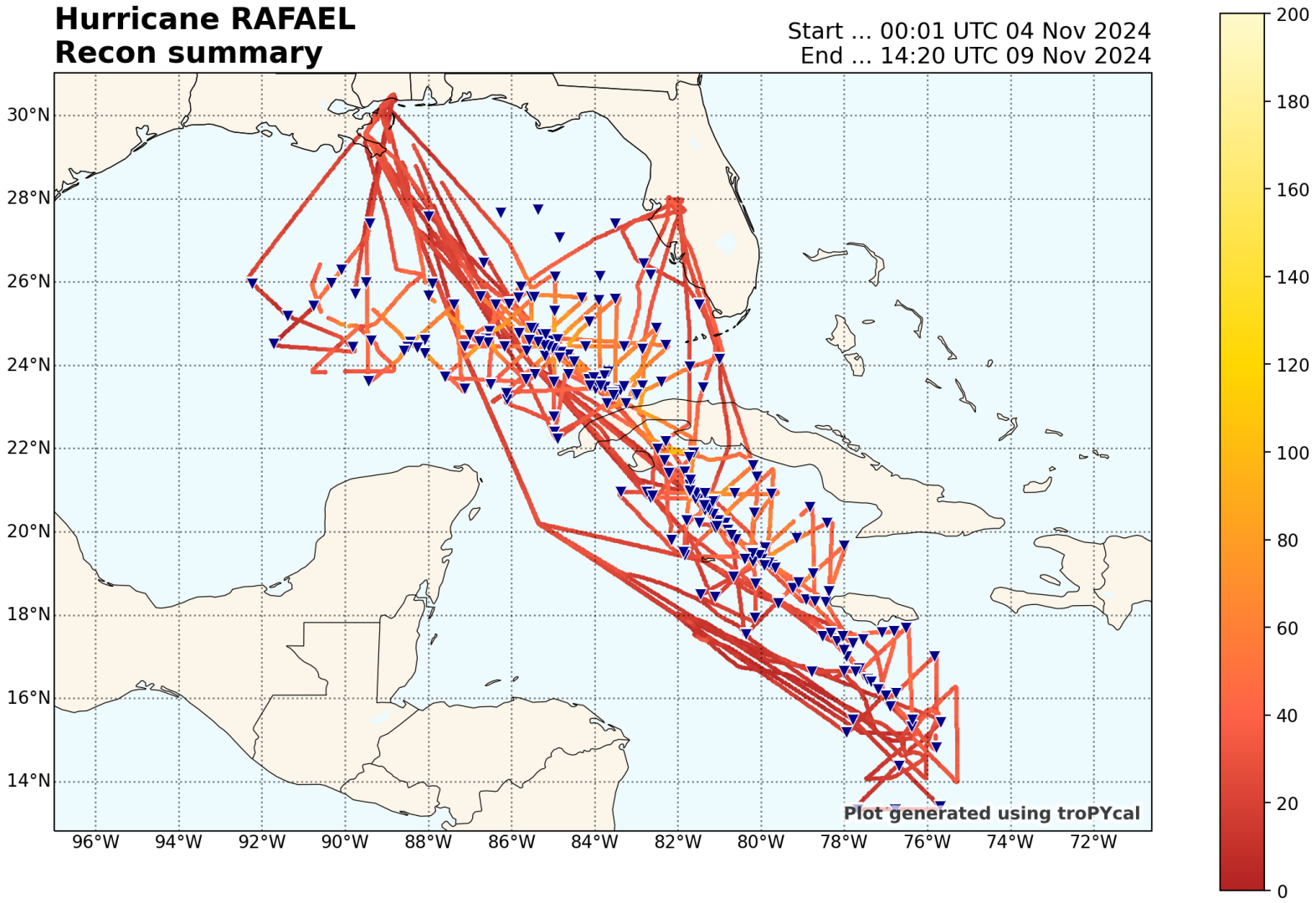

Figure 4. Air Force Reserve and NOAA Hurricane Hunter aircraft flight tracks (colored lines) from reconnaissance missions into Rafael from 4–9 November 2024. The blue triangles indicate dropsonde locations. The color of the flight track represents the observed flight-level wind speed in knots at that location (see legend). Dropsondes with no flight tracks are from the NOAA G-IV aircraft.

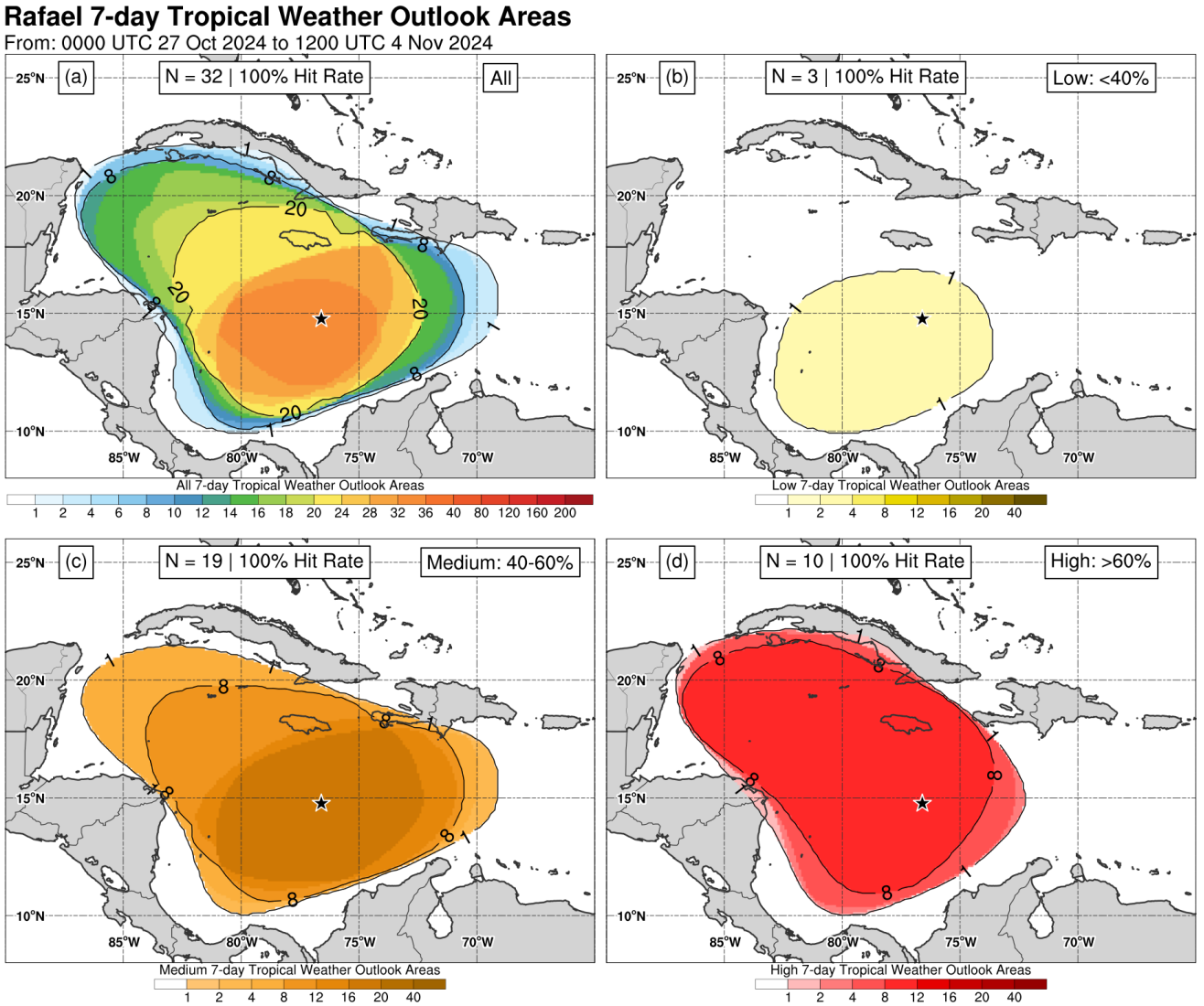

Figure 5. Composites of 7-day tropical cyclone genesis areas depicted in NHC's Tropical Weather Outlooks prior to the formation of Rafael for (a) all probabilistic genesis categories, (b) the low (<40%) category, (c) medium (40–60%) category, and (d) high (>60%) category. The location of genesis is indicated by the black star.

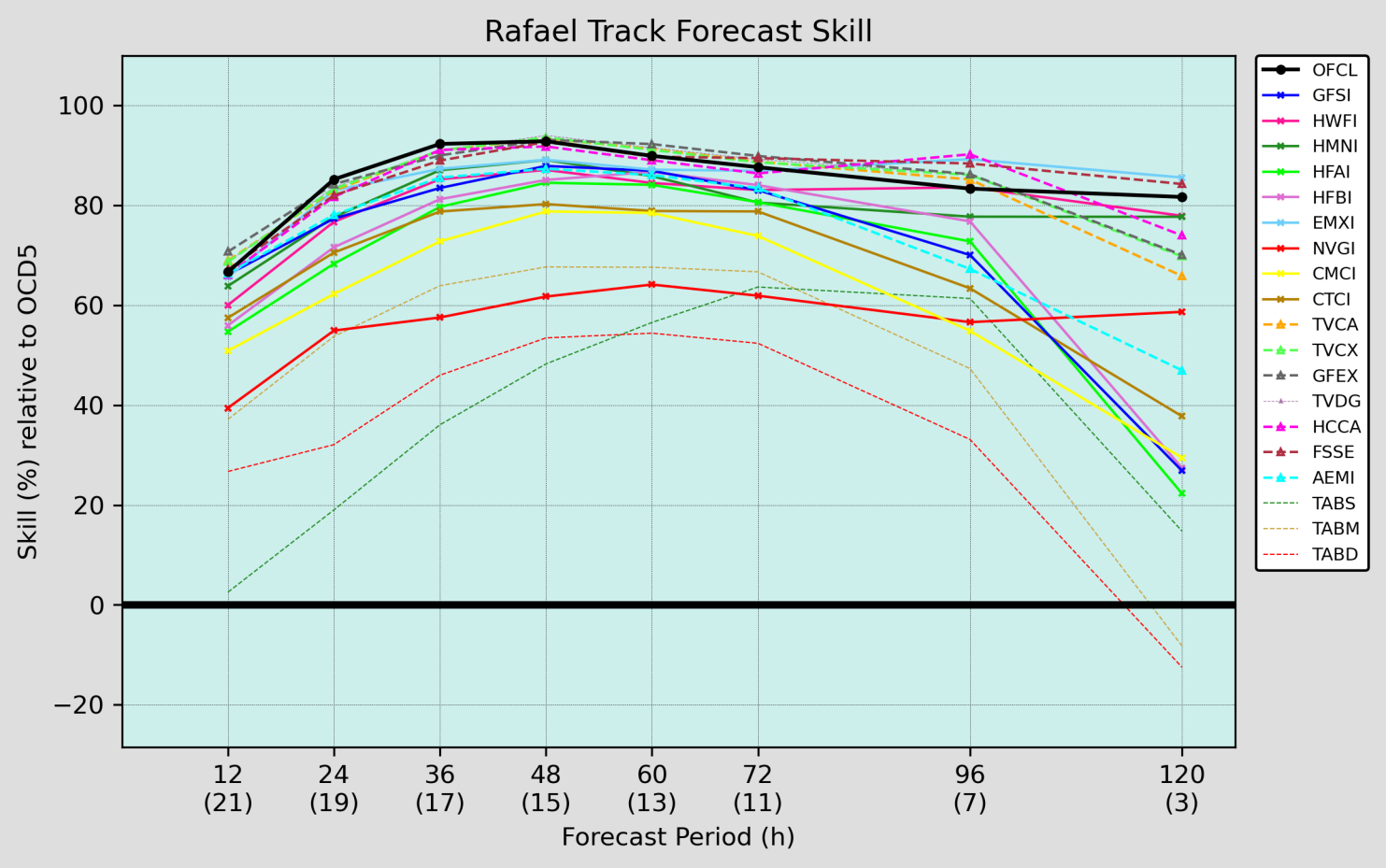

Figure 6. NHC official forecast and selected model forecast track skill (relative to climatology-persistence, OCD5) for Hurricane Rafael, 4–10 November 2024.

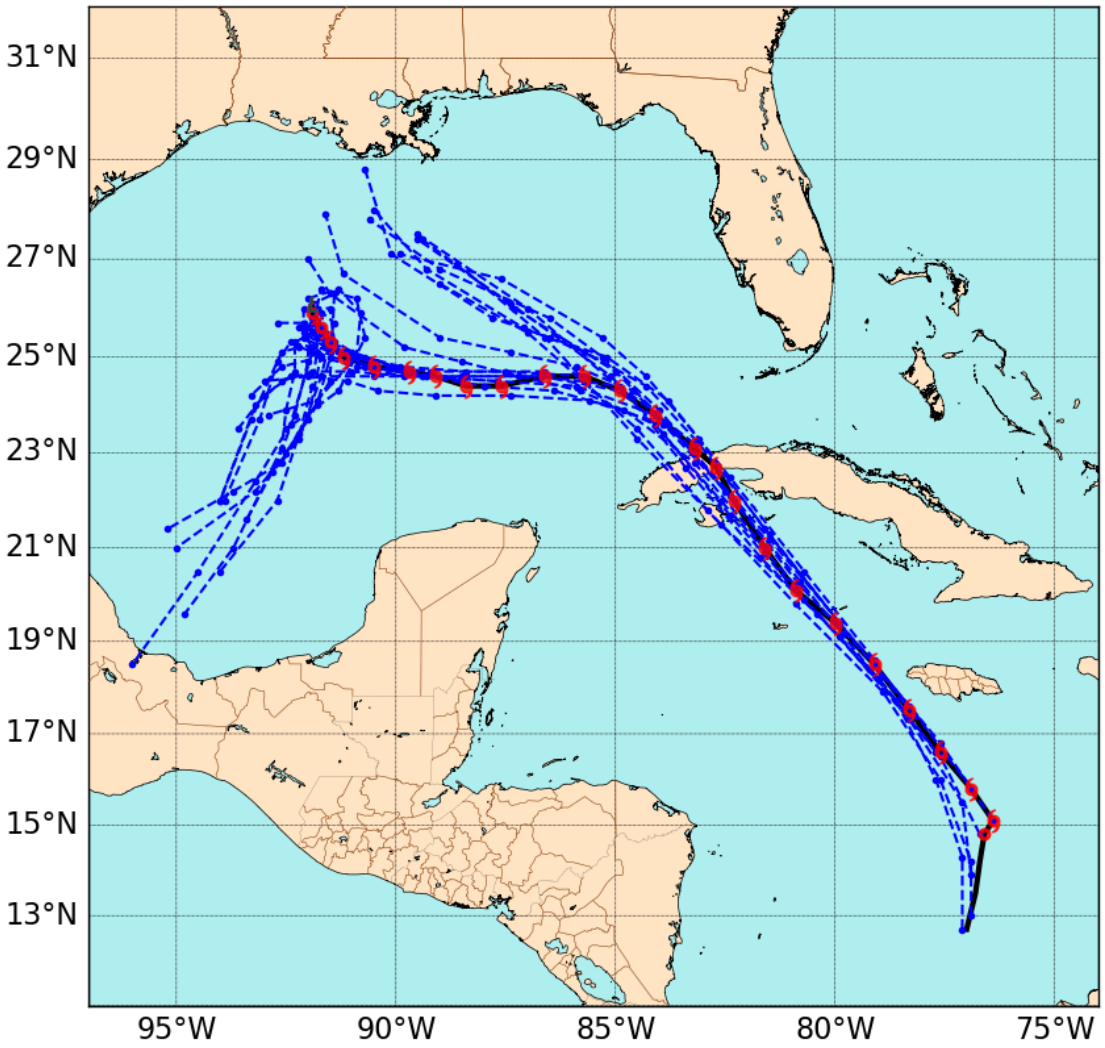

Figure 7. NHC official track forecasts (blue lines, with 0, 12, 24, 36, 48, 60, 72, 96, and 120 h positions indicated) for Rafael from 1800 UTC 3 November to 0000 UTC 9 November. The best track is given by the red line with positions at 6-h intervals.

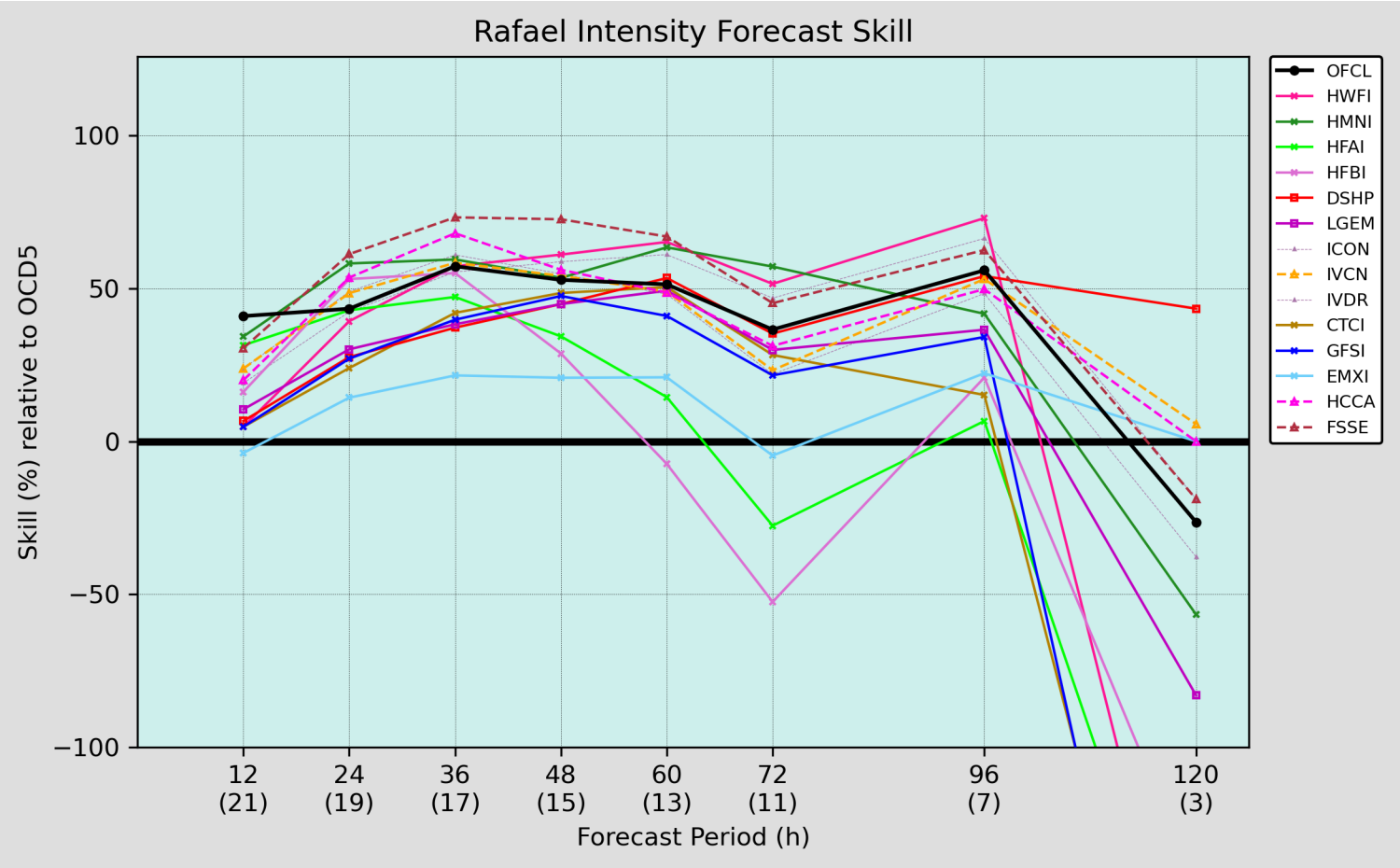

Figure 8. NHC official forecast and selected model forecast intensity skill (relative to climatology-persistence, OCD5) for Hurricane Rafael, 4–10 November 2024

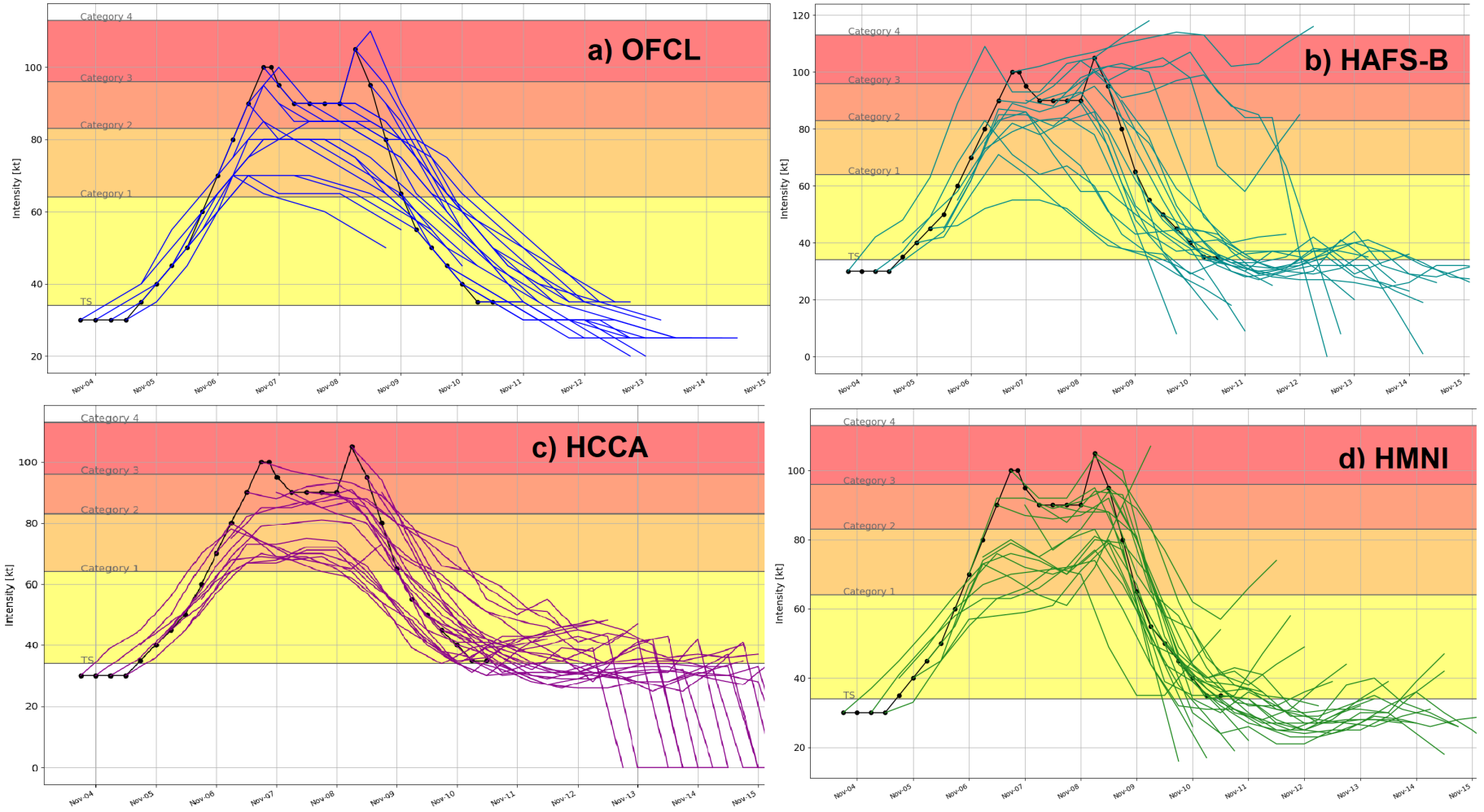

Figure 9. Intensity forecasts for the NHC forecast and various models for Rafael during 3-10 November with the verifying values in red. a) OFCL, b) HAFS-B c) HCCA d) HMNI