NATIONAL HURRICANE CENTER TROPICAL CYCLONE REPORT

HURRICANE EARL

(AL062022)

2–10 September 2022

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National Hurricane Center
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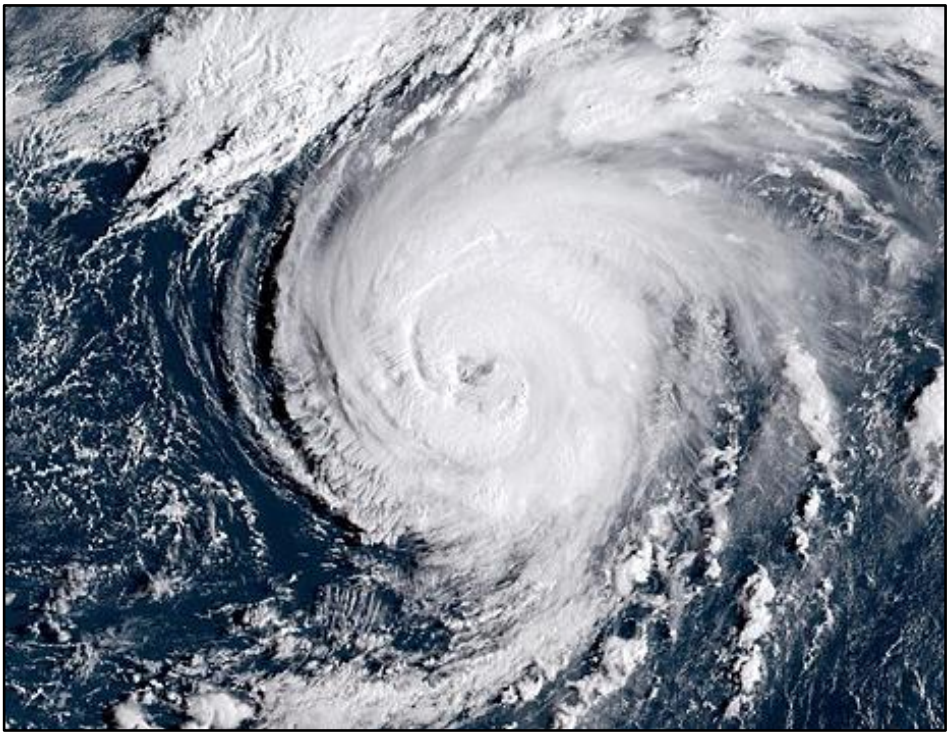

GOES-16 GEOCOLOR IMAGE OF EARL AT 1200 UTC 9 SEPTEMBER 2022 PASSING EAST OF BERMUDA. IMAGE COURTESY OF NOAA/NESDIS/STAR

Earl was a typical September hurricane that formed northeast of the Lesser Antilles and turned northward away from those islands, becoming a large category 2 hurricane over the southwestern Atlantic before passing east of Bermuda over the open central Atlantic Ocean. Two people died from a lightning strike in Puerto Rico coastal waters, and while the post-tropical cyclone moved offshore of Canada, heavy rain flooded portions of southeastern Newfoundland.

Hurricane Earl

2–10 SEPTEMBER 2022

SYNOPTIC HISTORY

Earl formed from a westward-moving tropical wave that left the coast of west Africa early on 25 August. Thunderstorm activity was not very persistent or organized near the wave axis for the next several days due to a dry mid-level environment and easterly wind shear. A broad area of elongated low pressure formed by 30 August over the central Atlantic, and thunderstorms increased in coverage. However, a continuation of the shear and dry mid-level environment allowed only a slow increase in overall organization while the low moved west-northwestward. As the system moved over the warmer water east of the Lesser Antilles on 1 September, deep convection finally became more organized and a mid-level circulation developed, but the system still lacked a well-defined surface center according to NOAA and Air Force Reserve Hurricane Hunter aircraft data. Late the next day, satellite and aircraft data indicated that a well-defined low-level center had formed and the winds had increased, so the system became a tropical storm at 1800 UTC 2 September a few hundred miles east of the northern Leeward Islands. The "best track" chart of Earl'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[1].

After formation, moderate southwesterly shear caused Earl to only slowly intensify, despite being over very warm waters, while the storm moved more slowly to the west-northwest. Earl passed about 65 n mi north of the northern Leeward Islands on 3-4 September, but none of the strong winds were located south of the center due to the shear. The storm reached its first peak intensity of 60 kt on 5 September while turning northward into a break in the central Atlantic subtropical ridge. This motion continued for the next several days between the central Atlantic ridge and a distant trough over North America. Although the cyclone was experiencing moderate-to-strong westerly shear during that time, aircraft data indicated that Earl slowly strengthened after 5 September, perhaps aided by a diffluent environment aloft and conducive thermodynamic conditions. The storm became a hurricane near 1800 UTC 6 September, several hundred miles south of Bermuda, and reached a second peak intensity of 90 kt near 0000 UTC 8 September. After the second peak intensity, despite the central pressure still falling and the shear becoming low, aircraft data indicated that the maximum winds of Earl gradually decreased on 8 September, perhaps due to dry air entrainment. The eye had increased to about 55 n mi wide by that point, and there were some indications from the data that instead of contributing to the maximum winds, the falling central pressure was instead leading to Earl becoming larger in size.

[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.

The large hurricane accelerated to the north and north-northeast on 8-9 September ahead of a mid-latitude trough, and strengthening resumed early on 9 September. The final peak intensity of Earl, 95 kt, was reached at about 0000 UTC 10 September several hundred miles southeast of Nova Scotia, Canada. Extratropical transition started shortly thereafter due to interaction with the aforementioned trough, and Earl became a large and strong post-tropical cyclone by 1800 UTC 10 September, a few hundred miles south of the Avalon Peninsula of Newfoundland. The system merged with the extratropical trough and moved slowly northeastward or eastward on 11 and 12 September. The gradually weakening post-tropical cyclone then moved faster to the east-northeast and northeast before becoming absorbed by another mid-latitude low late on 15 September about 700 n mi east of St. John's, Newfoundland.

METEOROLOGICAL STATISTICS

Observations in Earl (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 nine flights of the 53rd Weather Reconnaissance Squadron of the U.S. Air Force Reserve Command and fourteen flights from the NOAA Aircraft Operations Center (AOC). 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 Earl.

Selected surface observations from land stations are given in Table 2. There were no ship reports of tropical-storm-force winds while Earl was a tropical cyclone.

Winds and Pressure

The 95-kt peak intensity of Earl was based on a blend of 100-110 kt objective Dvorak and SATCON estimates with 90-kt subjective estimates from TAFB and SAB, with a corresponding minimum pressure of 948 mb obtained from the Knaff-Zehr-Courtney (KZC) pressure-wind relationship. The peak intensity of Earl occurred after a 12-day series of reconnaissance flights from AOC and the Air Force Reserve, from before genesis on 28 August to early on 9 September.

Earl made its closest approach to Bermuda on 9 September. Sustained tropical-storm-force winds were reported at a few, mostly elevated, sites on the island (Table 2). A wind gust to 46 kt was reported at the L.F. Wade International Airport, and a gust to 49 kt was reported at the Crescent offshore navigation aid. Buoy 41049, about 300 n mi south of Bermuda, reported a peak sustained wind of 35 kt at 1100 UTC 8 September.

Rainfall and Flooding

Outer rain bands from Earl caused heavy rain on Puerto Rico (Fig. 4). While 3 to 5 inches were generally reported in eastern Puerto Rico, a peak spot value of 7.70 inches was measured near Finca La Loma. There were isolated flooding reports, but no significant impacts were noted from this rainfall. A full listing of rainfall reports can be found in a supplementary data file at: https://www.nhc.noaa.gov/data/tcr/supplemental/earl_rain.xlsx.

As post-tropical Earl stalled offshore of Newfoundland, very heavy rains impacted the southeastern portion of the island, especially on the Avalon Peninsula (Fig. 5). The peak measured amount was 8.18 inches (208 mm) in Paradise.

CASUALTY AND DAMAGE STATISTICS

There were 2 casualties[2] associated with Earl while it was a tropical cyclone. A man and a woman were killed on a jet ski due to lightning in Cayo Matias near Salinas, in Puerto Rican coastal waters, from an outer band of the cyclone. Note there were two rip current deaths in the United States on 6 and 8 September near Ocean City, Maryland, and Ocean City, New Jersey, respectively, but these were due to swell behind a cold front, not from Earl.

No significant damage occurred over land while Earl was a tropical cyclone. Minor damage occurred near Trepassey, Canada, when a retaining wall gave out, but no damage figures are available. Heavy rainfall also led to urban flooding from the Waterford River, with stranded cars and water noted in a few dwellings. No damage figures are available, but it was thought to be minor.

FORECAST AND WARNING CRITIQUE

The genesis of Earl was anticipated well in advance, but the timing of genesis was a serious challenge, with formation eventually occurring much later than first expected. The system was introduced in the Tropical Weather Outlook at 1200 UTC 23 August with a low chance (<40%) of development over the next 5 days, about 10 days before genesis occurred (Table 3). The system was assessed a 5-day medium (40-60%) chance of formation 144 h before development, and it reached the high category (>60%) 126 h before tropical cyclone formation took place. Similarly, the 2-day chance of formation also anticipated that the system would form much quicker. The 2-day probability of development reached the low and medium categories 204 and 120 h before formation, respectively. The high category was not reached in the 2-day genesis forecasts, a reflection of the timing uncertainty. While initial graphical 5-day genesis forecasts did

[2] 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.

not include the area in which Earl actually formed (Fig. 6a), outlooks made in the high category (5+ days lead time) completely covered the area where Earl finally formed (Fig. 6d).

A verification of NHC official track forecasts for Earl is given in Table 4a. Official track forecast errors (OFCL) were lower than the mean official errors for the previous 5-year period at all times but 120 h. A homogeneous comparison of the official track errors with selected guidance models is given in Table 4b. The consensus models had the lowest errors for Earl, below almost any deterministic model or the OFCL track forecast average. The HMON model had a good performance for this hurricane, while the ECMWF and UKMET models had higher errors than the GFS model at longer-time ranges.

A verification of NHC official intensity forecasts for Earl is given in Table 5a. Official intensity errors were above or near the mean official errors for the previous 5-year period at all forecast times. However, the OCD5 (climatology/persistence) errors were generally lower than their respective 5-year means, suggesting that Earl's intensity was actually more predictable than for a typical Atlantic tropical cyclone over the past 5 years. A homogeneous comparison of the official intensity errors with selected guidance models is given in Table 5b. The NHC official intensity forecasts were outperformed by much of the guidance, especially the consensus aids, and the HWRF model had a good performance for this hurricane. It is interesting to note that the corrected-consensus aids HCCA and FSSE were worse than the simple consensus aids during Earl, the former of which NHC forecasters leaned toward in a subjective review of the Tropical Cyclone Discussions. The first several NHC forecasts exhibited a low bias, showing little significant intensification, while later forecasts showed Earl as a category 4 hurricane when it eventually peaked as a large category 2.

Coastal watches and warnings issued in association with Earl are shown in Table 6.

Table 1. Best track for Hurricane Earl, 2-10 September 2022.

Date/Time (UTC)	Latitude (°N)	Longitude (°W)	Pressure (mb)	Wind Speed (kt)	Stage
02 / 1800	17.9	58.6	1006	35	tropical storm
03 / 0000	18.3	59.8	1005	40	"
03 / 0600	18.6	60.9	1004	40	"
03 / 1200	18.9	61.9	1002	40	"
03 / 1800	19.2	62.9	999	45	"
04 / 0000	19.4	63.6	999	45	"
04 / 0600	19.5	64.1	999	45	"
04 / 1200	19.8	64.6	999	45	"
04 / 1800	20.0	65.0	998	50	"
05 / 0000	20.3	65.3	998	50	"
05 / 0600	20.8	65.4	998	55	"
05 / 1200	21.5	65.2	998	55	"
05 / 1800	22.0	65.2	997	60	"
06 / 0000	22.5	65.2	991	60	"
06 / 0600	23.1	65.3	995	55	"
06 / 1200	23.5	65.7	996	55	"
06 / 1800	23.9	65.7	994	65	hurricane
07 / 0000	24.5	65.8	985	70	"
07 / 0600	25.0	65.9	982	75	"
07 / 1200	25.4	65.8	978	75	"
07 / 1800	26.1	65.6	974	80	"
08 / 0000	26.8	65.5	970	90	"
08 / 0600	27.7	65.5	969	90	"
08 / 1200	28.7	65.3	962	85	"
08 / 1800	29.7	64.8	962	80	"
09 / 0000	30.6	64.3	964	80	"
09 / 0600	31.9	63.2	963	80	"

Date/Time (UTC)	Latitude (°N)	Longitude (°W)	Pressure (mb)	Wind Speed (kt)	Stage
09 / 1200	33.4	61.9	961	85	"
09 / 1800	34.9	59.8	954	90	"
10 / 0000	37.1	56.8	948	95	"
10 / 0600	40.0	54.3	955	90	"
10 / 1200	42.4	53.3	964	80	"
10 / 1800	43.3	52.8	967	70	extratropical
11 / 0000	43.3	52.6	968	60	"
11 / 0600	43.8	52.2	970	55	"
11 / 1200	44.2	52.0	974	50	"
11 / 1800	44.3	51.9	974	45	"
12 / 0000	44.2	51.9	974	45	"
12 / 0600	44.3	52.1	978	40	"
12 / 1200	43.9	51.9	978	40	"
12 / 1800	43.2	51.2	981	35	"
13 / 0000	42.9	48.3	981	35	"
13 / 0600	43.0	46.8	985	35	"
13 / 1200	43.4	45.2	989	35	"
13 / 1800	44.3	43.7	989	35	"
14 / 0000	45.0	42.4	990	35	"
14 / 0600	45.4	41.6	990	35	"
14 / 1200	45.5	40.9	990	35	"
14 / 1800	45.3	40.5	992	30	"
15 / 0000	45.2	39.4	994	30	"
15 / 0600	45.2	37.7	995	30	"
15 / 1200	45.6	36.1	996	30	"
15 / 1800	-	-	-	-	dissipated
10 / 0000	37.1	56.8	948	95	minimum pressure and maximum winds

Table 2. Selected surface observations for Hurricane Earl, 2–10 September 2022.

Location	Minimum Sea Level Pressure		Maximum Surface Wind Speed			Storm surge (ft)[c]	Storm tide (ft)[d]	Estimated Inundation (ft)[e]	Total rain (in)
	Date/ time (UTC)	Press. (mb)	Date/ time (UTC)[a]	Sustained (kt)[b]	Gust (kt)				
Bermuda									
L.F. Wade Intl. AP AWOS (AviMet 12) (32.366N 64.694W)	09/0405	992.1	09/0143	35 (10 m, 2 min)	43				
L.F. Wade Intl. AP AWOS (AviMet 30) (32.361N 64.668W)	09/0446	992.0	09/0046	37 (10 m, 2 min)	46				
L.F. Wade Intl. AP Heliport (32.36N 64.70W)	09/0405	992.6		33 (12 m, 1 min)	46				
National Museum of Bermuda AWOS (32.33N 64.83W)				51 (44 m, 2 min)	58				
Marine Ops Centre MAROPS (32.38N 64.68W)			09/0744	48 (88 m, 10 min)	53				
The Crescent (32.41N 64.82W)			09/0145	42 (6 m, 10 min)	49				

[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 reports are 2 min; buoy averaging periods are 8 min.
[c] Storm surge is water height above normal astronomical tide level.
[d] For most locations, storm tide is water height above the North American Vertical Datum of 1988 (NAVD88).
[e] Estimated inundation is the maximum height of water above ground. For NOS storm tide gauges, the height of the water above Mean Higher High Water (MHHW) is used as a proxy for inundation.

Table 3. 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%)	204	246
Medium (40%-60%)	120	144
High (>60%)	-	126

Table 4a. NHC official (OFCL) and climatology-persistence skill baseline (OCD5) track forecast errors (n mi) for Hurricane Earl, 2–10 September 2022. 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	**21.8**	**27.8**	**34.0**	**41.4**	**49.6**	**57.0**	**105.9**	252.7
OCD5	40.6	86.9	137.0	186.1	221.5	250.7	332.8	479.1
Forecasts	29	27	25	23	21	19	15	11
OFCL (2017-21)	23.6	35.5	47.6	61.4	78.2	91.3	125.6	172.1
OCD5 (2017-21)	45.5	98.3	156.7	213.7	252.4	316.9	403.6	484.6

Table 4b. Homogeneous comparison of selected track forecast guidance models (in n mi) for Hurricane Earl, 2–10 September 2022. 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	60	72	96	120
OFCL	22.4	28.7	33.3	39.8	46.5	52.3	103.9	263.0
OCD5	41.2	88.0	137.8	186.8	222.6	250.9	337.4	498.4
GFSI	24.1	30.1	42.1	53.1	58.0	73.8	122.9	229.2
EMXI	22.9	32.1	42.8	49.7	63.8	70.7	135.0	368.2
EGRI	22.7	32.3	41.1	56.5	69.0	76.8	148.5	366.7
CMCI	24.7	38.5	55.7	73.0	90.4	110.2	179.7	**259.4**
HWFI	23.1	35.0	47.0	49.5	**44.4**	60.4	125.5	**252.0**
HMNI	23.8	**27.3**	**33.1**	**37.5**	**40.4**	54.0	134.4	291.4
CTCI	24.1	30.7	40.2	49.4	49.6	56.4	**97.4**	**197.7**
AEMI	23.9	29.9	39.8	49.4	52.3	62.1	109.4	192.7
HCCA	**20.9**	**22.7**	**28.8**	**34.7**	**40.5**	**45.2**	**84.0**	**255.8**
FSSE	**19.9**	**22.4**	**32.1**	**38.4**	**42.9**	53.2	**88.7**	**246.2**
GFEX	**21.8**	**26.7**	**33.0**	**38.0**	**42.5**	**49.7**	**86.2**	**244.6**
TVCA	**22.0**	**24.3**	**31.3**	**38.2**	**42.7**	**48.7**	**93.7**	**250.7**
TVCX	**21.4**	**23.5**	**30.5**	**37.8**	**42.5**	**47.4**	**94.0**	**259.8**
TVDG	**21.8**	**24.9**	**31.8**	39.8	**44.2**	**48.8**	**94.1**	**255.2**
TABD	31.8	55.5	81.5	111.5	147.1	187.0	280.8	385.5
TABM	28.9	41.0	51.4	60.0	69.2	102.6	180.2	246.0
TABS	43.6	79.7	103.3	120.4	141.0	172.9	237.5	297.3
Forecasts	28	26	24	22	20	18	14	10

Table 5a. NHC official (OFCL) and climatology-persistence skill baseline (OCD5) intensity forecast errors (kt) for Hurricane Earl, 2–10 September 2022. 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	6.7	8.0	11.2	12.6	12.4	12.1	14.7	17.7
OCD5	7.3	7.8	8.7	10.9	15.8	17.1	23.5	18.9
Forecasts	29	27	25	23	21	19	15	11
OFCL (2017-21)	5.4	8.0	9.5	10.9	11.0	12.1	13.1	14.7
OCD5 (2017-21)	7.0	11.1	14.5	17.1	18.0	20.2	21.9	22.1

Table 5b. Homogeneous comparison of selected intensity forecast guidance models (in kt) for Hurricane Earl, 2–10 September 2022. Errors smaller than the NHC official forecast are shown in boldface type.

Model ID	Forecast Period (h)							
	12	24	36	48	60	72	96	120
OFCL	6.7	8.0	11.2	12.6	12.4	12.1	14.7	17.7
OCD5	7.3	**7.8**	**8.7**	**10.9**	15.8	17.1	23.5	18.9
HWFI	7.4	8.8	**8.3**	**8.1**	**5.9**	**9.4**	**13.6**	20.4
HMNI	**6.4**	9.7	**11.0**	**11.8**	14.4	14.3	**12.1**	**17.0**
CTCI	**6.6**	**6.1**	**8.0**	**11.6**	**12.1**	12.1	16.4	23.6
DSHP	7.0	8.4	**11.0**	**11.7**	**10.2**	**8.6**	**8.9**	**11.9**
LGEM	7.4	9.8	13.4	15.6	15.7	14.5	**13.3**	**13.7**
ICON	**6.6**	8.5	**10.1**	**11.5**	**11.0**	**10.7**	**11.7**	**14.9**
IVCN	**6.3**	**7.9**	**9.2**	**10.9**	**10.9**	**10.8**	**12.6**	**15.9**
IVDR	**6.1**	**7.7**	**8.6**	**9.8**	**10.0**	**10.1**	**12.5**	**16.1**
HCCA	**6.6**	8.4	11.6	**11.3**	**12.0**	12.3	**13.8**	17.7
FSSE	**6.3**	8.1	**10.6**	**11.9**	13.0	12.5	17.9	23.7
GFSI	6.9	8.1	**8.8**	**8.6**	**7.2**	**7.3**	**9.1**	**9.1**
EMXI	8.3	11.6	14.6	16.2	17.9	20.3	26.7	40.2
Forecasts	29	27	25	23	21	19	15	11

Table 6. Watch and warning summary for Hurricane Earl, 2–10 September 2022.

Date/Time (UTC)	Action	Location
6 / 2100	Tropical Storm Watch issued	Bermuda
7 / 0900	Tropical Storm Watch changed to Tropical Storm Warning	Bermuda
7 / 2100	Hurricane Watch issued	Bermuda
9 / 0300	Hurricane Watch discontinued	Bermuda
9 / 1500	Tropical Storm Warning discontinued	Bermuda

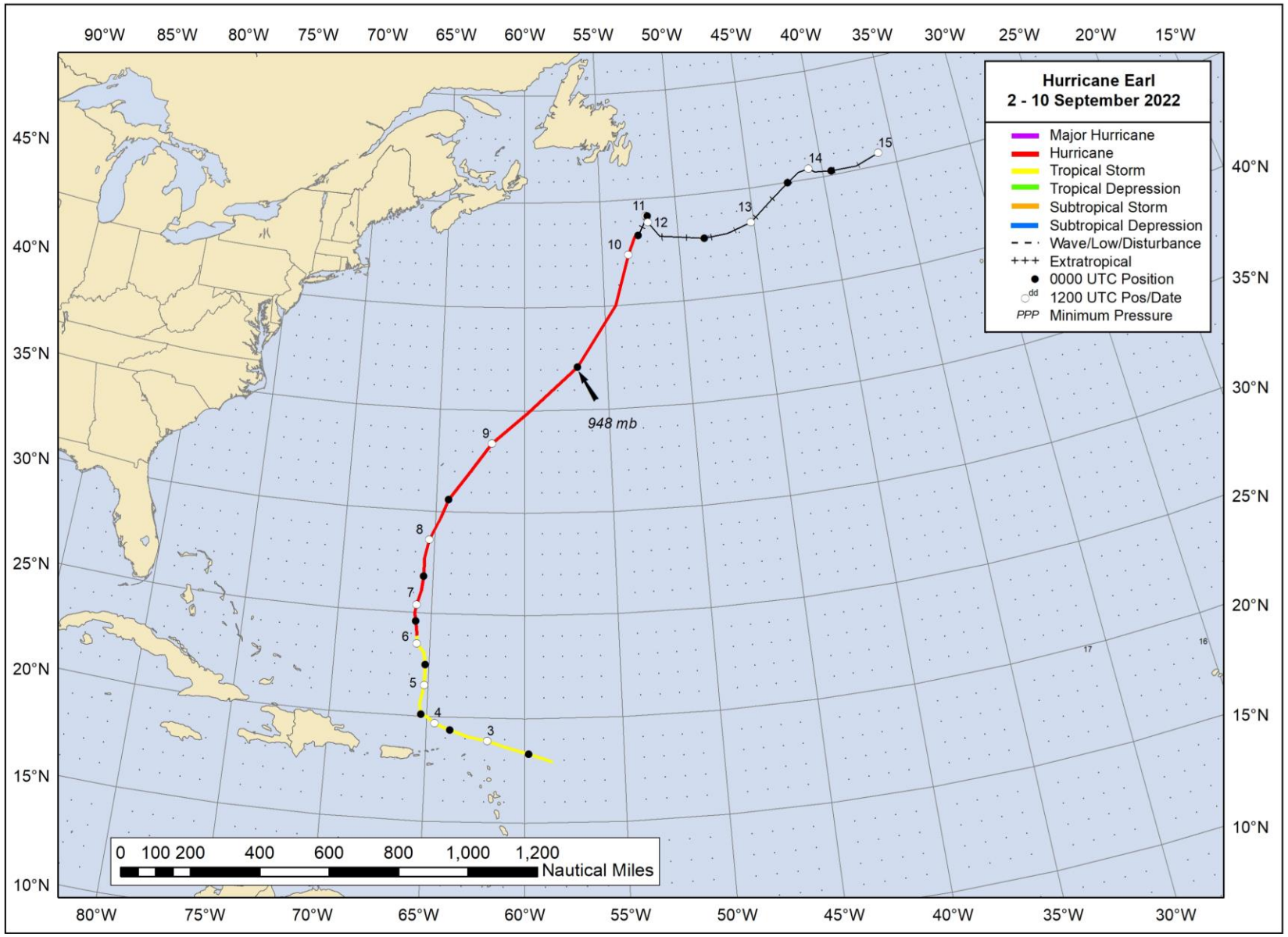

Figure 1. Best track positions for Hurricane Earl, 2–10 September 2022. Positions during the extratropical stage are primarily based on analyses from the Ocean Prediction Center.

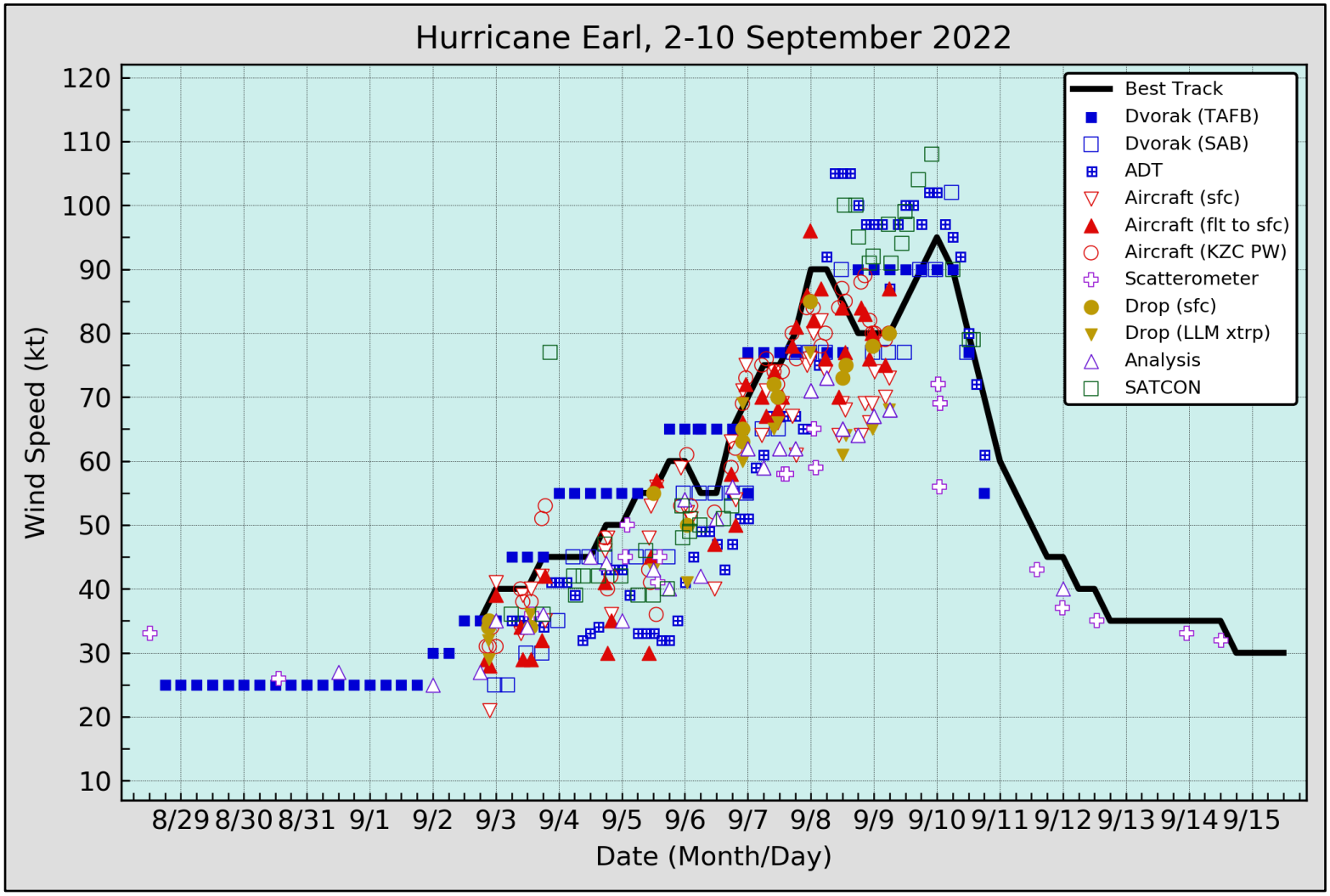

Figure 2. Selected wind observations and best track maximum sustained surface wind speed curve for Hurricane Earl. Aircraft observations have been adjusted for elevation using 90%, 80%, 75% and 80% adjustment factors for observations from 700 mb, 850 mb, 925 mb, and 1500 ft, respectively. Dropwindsonde 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. SATCON intensity estimates are from the Cooperative Institute for Meteorological Satellite Studies. Dashed vertical lines correspond to 0000 UTC.

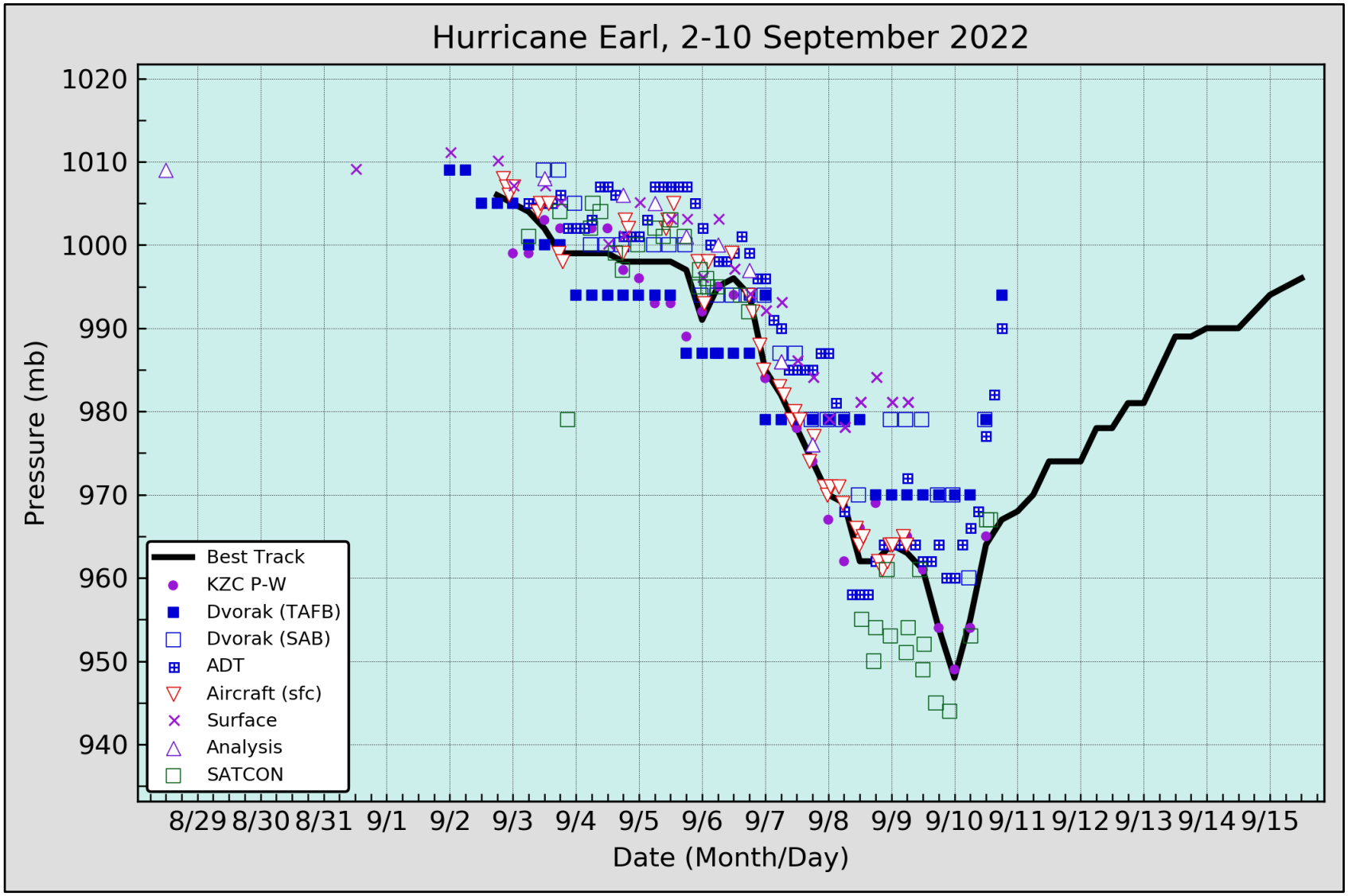

Figure 3. Selected pressure observations and best track minimum central pressure curve for Hurricane Earl. Advanced Dvorak Technique estimates represent the Current Intensity at the nominal observation time. SATCON intensity estimates are from the Cooperative Institute for Meteorological Satellite Studies.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

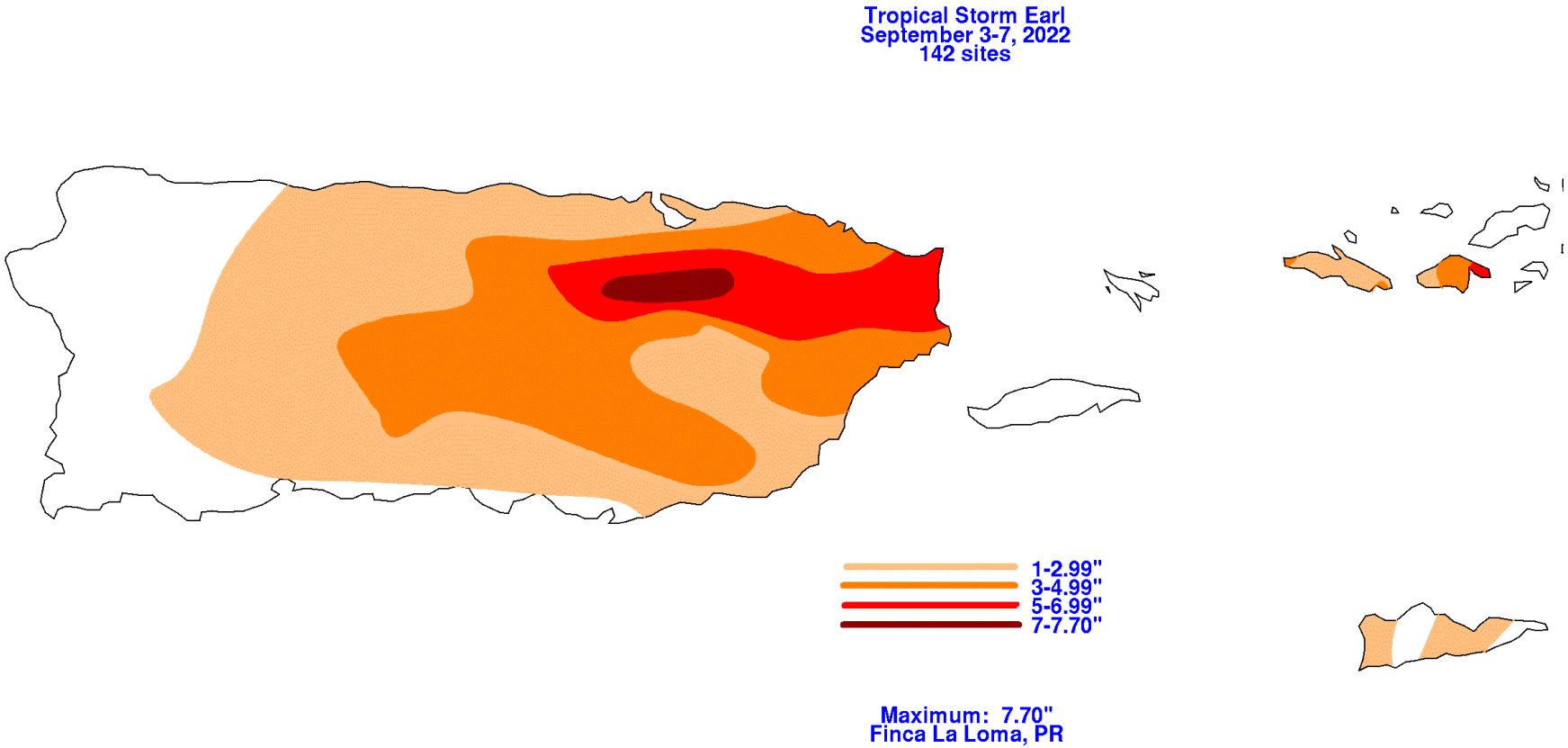

Figure 4. Rainfall totals in Puerto Rico and the U.S. Virgin Islands from 3-7 September 2022. Image courtesy of David Roth (NOAA Weather Prediction Center).

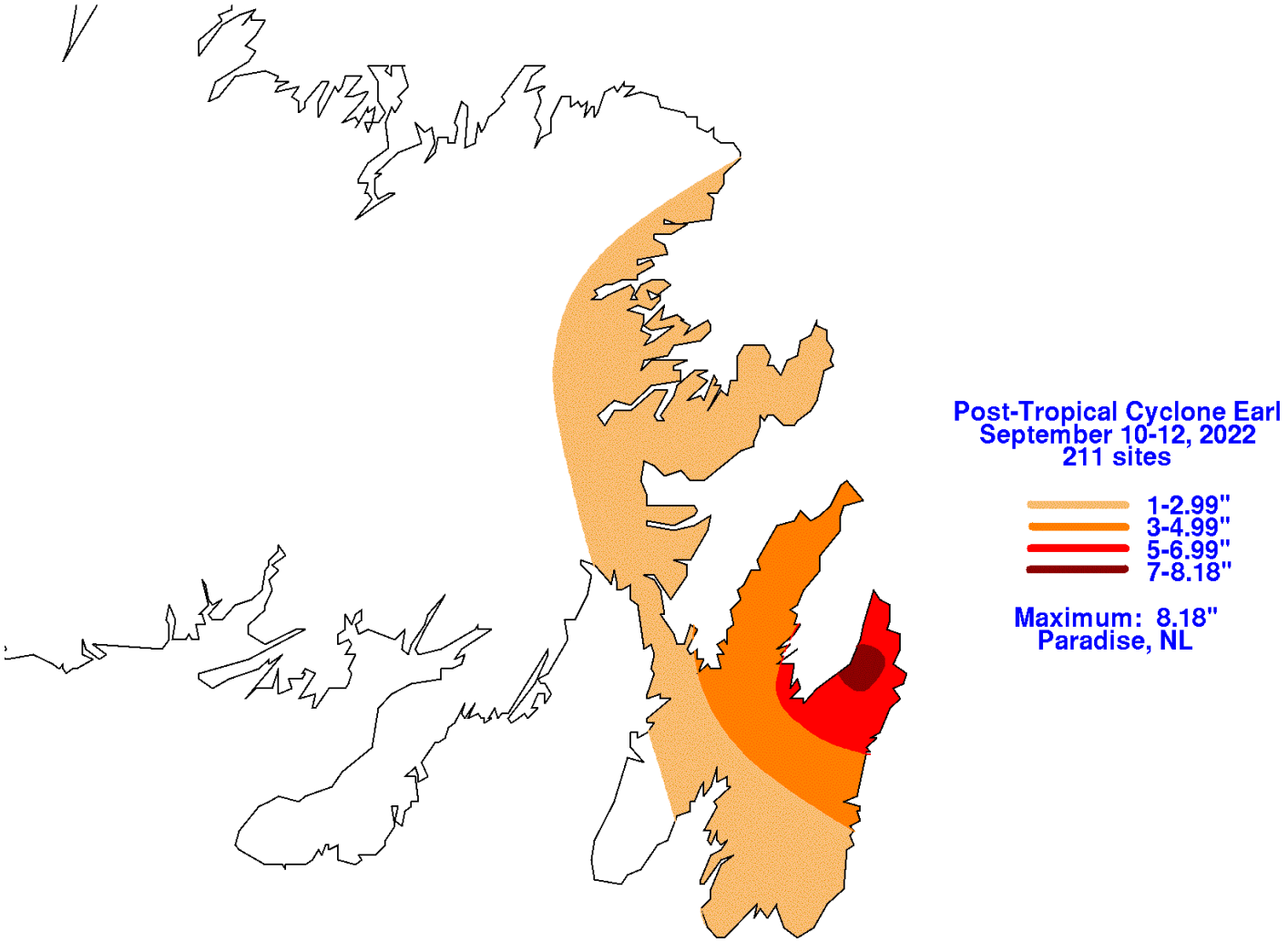

Figure 5. Rainfall totals in Newfoundland from 10-12 September 2022. Image courtesy of David Roth (NOAA Weather Prediction Center).

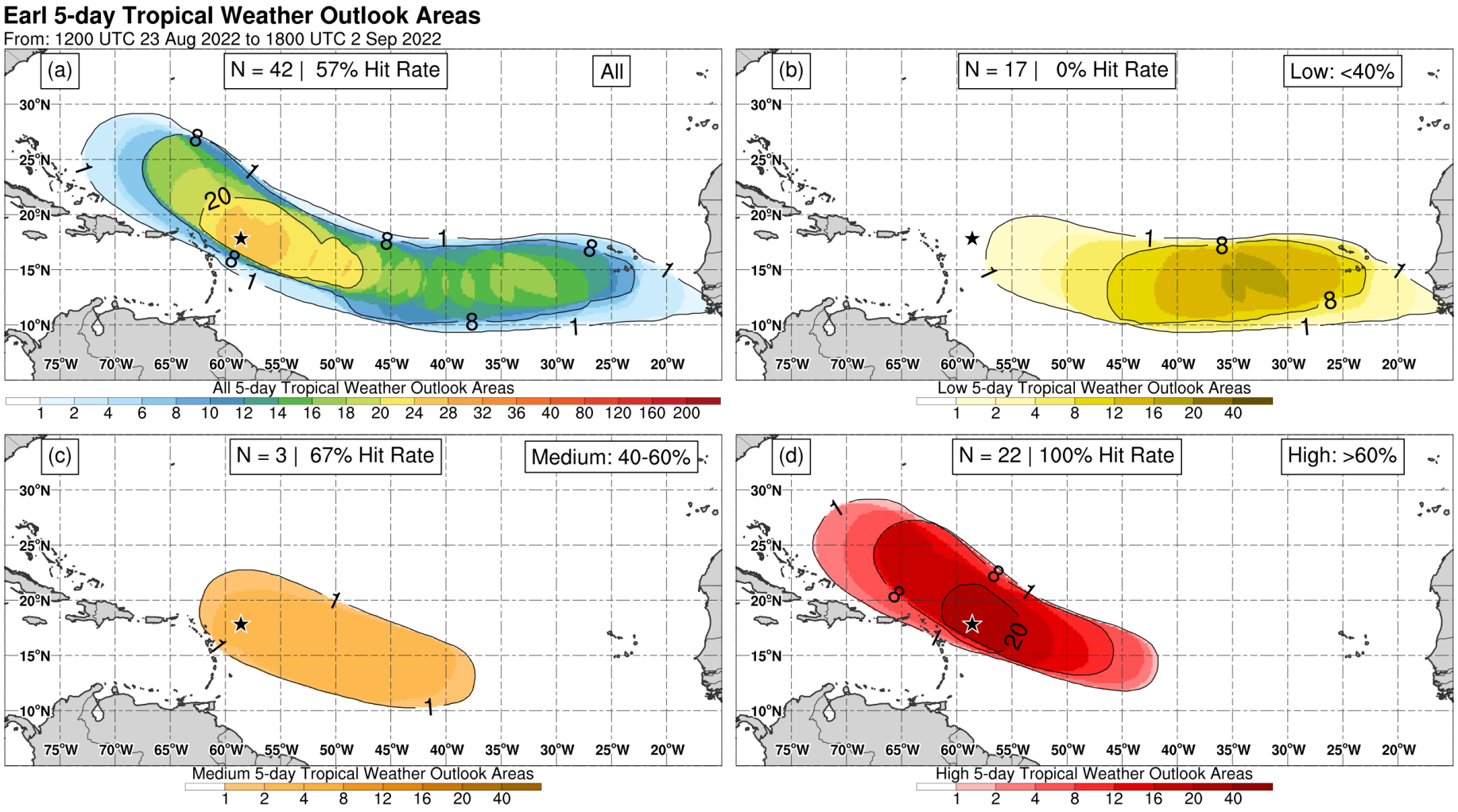

Figure 6. Composites of 5-day tropical cyclone genesis areas depicted in NHC's Tropical Weather Outlooks prior to the formation of Hurricane Earl for (a) all probabilistic genesis categories, (b) the low (<40%) category, (c) medium (40–60%) category, and (d) high (>60%) category. Earl's location of genesis is indicated by the black star.