SUMMARY OF 2023 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF AUTHORS' SEASONAL AND TWO-WEEK FORECASTS

The 2023 Atlantic hurricane season was an above-normal season based on NOAA's definition, with named storms and named storm days well above the 1991–2020 average. The seasonal hurricane forecasts issued in 2023 by the Tropical Meteorology Project were generally reasonably accurate, correctly anticipating heightened levels of activity with its July and August updates. The season's most significant continental US storm was Hurricane Idalia, which made landfall in the Big Bend of Florida as a Category 3 hurricane. The record warm Atlantic combined with a moderate to strong El Niño led to an extremely challenging forecast setup this year, but CSU's forecasts generally performed well despite these challenges.

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In Memory of William M. Gray[4]

This discussion as well as past forecasts and verifications are available online at http://tropical.colostate.edu

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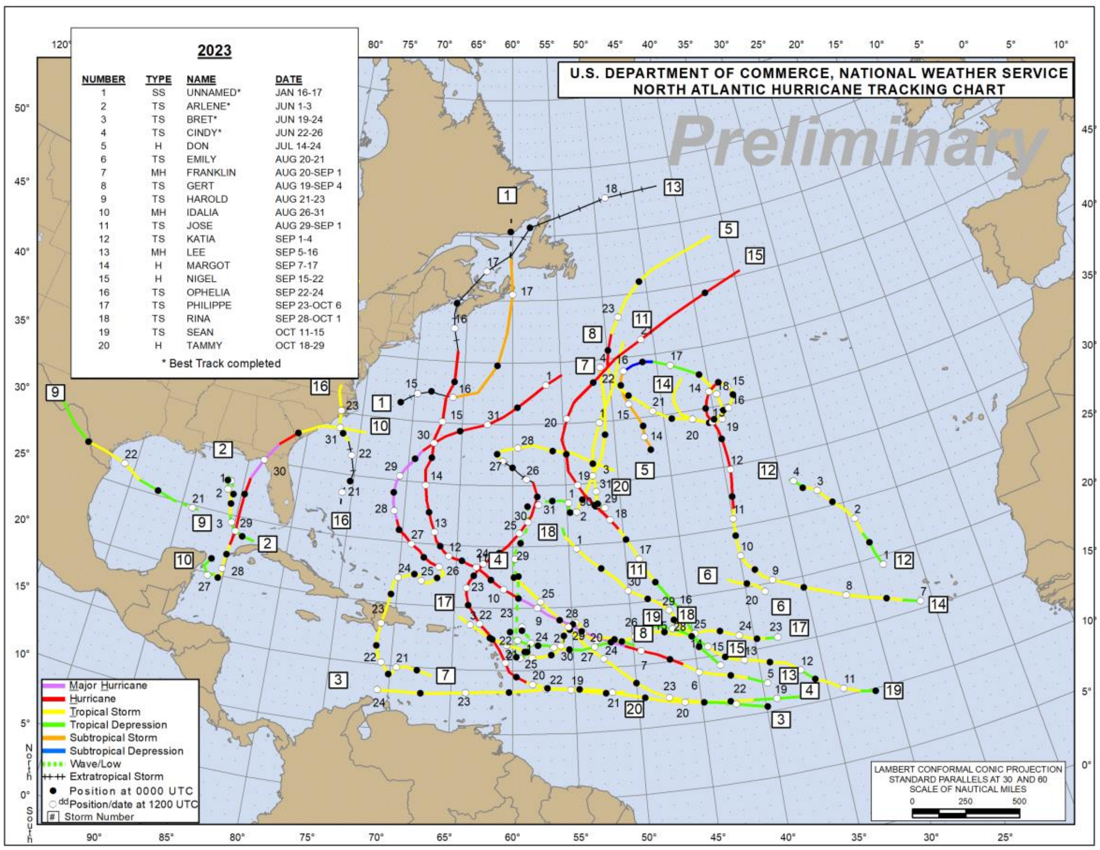
ATLANTIC BASIN SEASONAL HURRICANE FORECASTS FOR 2023

Forecast Parameter and 1991–2020 Average (in parentheses)	Issue Date 13 April 2023	Issue Date 1 June 2023	Issue Date 6 July 2023	Issue Date 3 August 2023	**Observed 2023 Activity Thru 11/28**	% of 1991–2020 Average
Named Storms (NS) (14.4)	13	15	18	18	**20**	139%
Named Storm Days (NSD) (69.4)	55	60	90	90	**99**	143%
Hurricanes (H) (7.2)	6	7	9	9	**7**	97%
Hurricane Days (HD) (27.0)	25	30	35	35	**31**	115%
Major Hurricanes (MH) (3.2)	2	3	4	4	**3**	94%
Major Hurricane Days (MHD) (7.4)	5	7	9	9	**7.75**	105%
Accumulated Cyclone Energy (ACE) (123)	100	125	160	160	**146**	119%
ACE West of 60°W (73)	55	70	82	82	**70**	96%
Net Tropical Cyclone Activity (NTC) (135%)	105	135	170	170	**157**	117%



2023 Atlantic basin tropical cyclone tracks through November 28. 20 named storms, 7 hurricanes and 3 major hurricanes occurred. Figure courtesy of NOAA.

ABSTRACT

This report summarizes tropical cyclone (TC) activity which occurred in the Atlantic basin during 2023 and verifies the authors' seasonal Atlantic basin forecasts. Also verified are six two-week Atlantic basin forecasts issued during the peak months of the hurricane season that were based on a combination of current activity, model forecasts and the phase of the Madden–Julian Oscillation (MJO). We also issued an October–November Caribbean hurricane forecast that slightly over-estimated late-season Caribbean storm activity.

The first quantitative seasonal forecast for 2023 was issued on 13 April with updates on 1 June, 6 July and 3 August. These seasonal forecasts also contained estimates of the probability of US and Caribbean hurricane landfall during 2023. For the first time this year, we also forecast Accumulated Cyclone Energy (ACE) west of 60°W. This metric successfully forecast less overall ACE west of 60°W relative to basinwide ACE.

The 2023 hurricane season was officially an above-normal hurricane season based on NOAA's Accumulated Cyclone Energy (ACE) definition (e.g., the upper tercile from 1951–2020; >126 ACE). Overall numbers of most metrics were slightly above their long-term averages, with named storms and named storm days well above their 1991–2020 averages.

Our July and August seasonal forecasts performed best for named storms and ACE, while our June forecast was the best forecast for hurricanes and major hurricanes.

Six consecutive two-week forecasts were issued during August–October – the peak months of the Atlantic hurricane season. These forecasts were based on current hurricane activity, predicted activity by global models and MJO phase. These forecasts predicted the tercile with the highest probability in 3 out of the 6 outlooks that were issued.

El Niño conditions prevailed throughout the 2023 Atlantic hurricane season. While El Niño typically increases tropical Atlantic and Caribbean vertical wind shear, vertical wind shear was below-normal across most of the tropical Atlantic and Caribbean from August through October.

Tropical Atlantic sea surface temperatures were at record warm levels during the peak of the 2023 hurricane season. These anomalously warm waters and associated low pressures in the tropical Atlantic were likely the reason why El Niño did not have its normal teleconnection to above-normal shear across the tropical Atlantic. Model output included in our forecast methodology was helpful in predicting this anomalous behavior in advance.

The most impactful storm of the 2023 Atlantic hurricane season for the continental US was Hurricane Idalia, which made landfall in the Big Bend region of Florida at Category 3 intensity, causing 5 fatalities and ~$2.5 billion dollars in damage.

DEFINITIONS AND ACRONYMS

Accumulated Cyclone Energy (ACE) - A measure of a named storm's potential for wind destruction defined as the sum of the square of a named storm's maximum wind speed (in 10^4 $knots^2$) for each 6-hour period of its existence. The 1991–2020 average value of this parameter is 123 for the Atlantic basin.

Atlantic Multi-Decadal Oscillation (AMO) – A mode of natural variability that occurs in the North Atlantic Ocean and evidencing itself in fluctuations in sea surface temperature and sea level pressure fields. The AMO is likely related to fluctuations in the strength of the oceanic thermohaline circulation. Although several definitions of the AMO are currently used in the literature, we define the AMO based on North Atlantic sea surface temperatures from 50–60°N, 50–10°W and sea level pressure from 0–50°N, 70–10°W.

Atlantic Basin – The area including the entire North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico.

El Niño – A 12-18 month period during which anomalously warm sea surface temperatures occur in the eastern half of the equatorial Pacific. Moderate or strong El Niño events occur irregularly, about once every 3–7 years on average.

El Niño – Southern Oscillation (ENSO) – A quasi-periodic coupled climate mode of the tropical Pacific Ocean characterized by changes in sea surface temperature, atmospheric pressure and wind patterns.

ENSO Longitude Index – An index defining ENSO that estimates the average longitude of deep convection associated with the Walker Circulation.

Hurricane (H) - A tropical cyclone with sustained low-level winds of 74 miles per hour (33 ms^{-1} or 64 knots) or greater.

Hurricane Day (HD) - A measure of hurricane activity, one unit of which occurs as four 6-hour periods during which a tropical cyclone is observed or is estimated to have hurricane-force winds.

Indian Ocean Dipole (IOD) - An irregular oscillation of sea surface temperatures between the western and eastern tropical Indian Ocean. A positive phase of the IOD occurs when the western Indian Ocean is anomalously warm compared with the eastern Indian Ocean.

Madden Julian Oscillation (MJO) – A globally propagating mode of tropical atmospheric intra-seasonal variability. The wave tends to propagate eastward at approximately 5 ms^{-1}, circling the globe in roughly 30-60 days.

Major Hurricane (MH) - A hurricane which reaches a sustained low-level wind of at least 111 mph (96 knots or 50 ms^{-1}) at some point in its lifetime. This constitutes a category 3 or higher on the Saffir/Simpson scale.

Major Hurricane Day (MHD) - Four 6-hour periods during which a hurricane has an intensity of Saffir/Simpson category 3 or higher.

Named Storm (NS) - A hurricane, a tropical storm or a sub-tropical storm.

Named Storm Day (NSD) - As in HD but for four 6-hour periods during which a tropical or sub-tropical cyclone is observed (or is estimated) to have attained tropical storm-force winds.

Net Tropical Cyclone (NTC) Activity –Average seasonal percentage mean of NS, NSD, H, HD, MH, MHD. Gives overall indication of Atlantic basin seasonal hurricane activity. The 1991-2020 average value of this parameter is 135.

Saffir/Simpson Hurricane Wind Scale – A measurement scale based on maximum wind speed ranging from 1 to 5 of hurricane wind intensity. One is a weak hurricane; whereas, five is the most intense hurricane. Note that this scale does not take storm surge or other deadly hazards into account.

Southern Oscillation Index (SOI) – A normalized measure of the surface pressure difference between Tahiti and Darwin. Low values typically indicate El Niño conditions.

Standard Deviation (SD) – A measure used to quantify the variation in a dataset.

Sea Surface Temperature Anomaly (SSTA) – Differences in sea surface temperature compared to a longer-term average.

Thermohaline Circulation – A large-scale circulation in the Atlantic Ocean that is driven by fluctuations in salinity and temperature. When the thermohaline circulation is stronger than normal, the AMO tends to be in its warm (or positive) phase, and more Atlantic hurricanes typically form.

Tropical Cyclone (TC) - A large-scale circular flow occurring within the tropics and subtropics which has its strongest winds at low levels; including hurricanes, tropical storms and other weaker rotating vortices.

Tropical Storm (TS) - A tropical cyclone with maximum sustained winds between 39 mph (18 ms^{-1} or 34 knots) and 73 mph (32 ms^{-1} or 63 knots).

Vertical Wind Shear – The difference in horizontal wind between 200 hPa (approximately 40000 feet or 12 km) and 850 hPa (approximately 5000 feet or 1.6 km).

1 knot = 1.15 miles per hour = 0.515 meters per second

Acknowledgment

These seasonal forecasts were developed by the late Dr. William Gray, who was lead author on these predictions for over 20 years and continued as a co-author until his death in 2016. In addition to pioneering seasonal Atlantic hurricane prediction, he conducted groundbreaking research on a wide variety of other topics including hurricane genesis, hurricane structure and cumulus convection. His investments in both time and energy to these forecasts cannot be acknowledged enough.

We are grateful for support from Ironshore Insurance, the Insurance Information Institute, Weatherboy, First Onsite and IAA. We acknowledge a grant from the G. Unger Vetlesen Foundation for additional financial support.

Colorado State University's seasonal hurricane forecasts have benefited greatly from several individuals that were former graduate students of William Gray. Among these former project members are Chris Landsea, John Knaff and Eric Blake. We also would like to thank Jhordanne Jones, recent Ph.D. graduate in Michael Bell's research group, for model development and forecast assistance over the past several years.

We would like to acknowledge Tyler Barbero and Angelie Nieves-Jimenez for assistance with preparing these forecasts and handling media inquiries. Thanks also to Angelie for translating our forecast press releases into Spanish.

We thank Louis-Philippe Caron and the data team at the Barcelona Supercomputing Centre for providing data and insight on the statistical/dynamical models. We have also benefited from meteorological discussions with Louis-Philippe Caron, Dan Chavas, Jason Dunion, Brian McNoldy, Paul Roundy, Carl Schreck, Mike Ventrice and Peng Xian over the past few years.

1 Preliminary Discussion

1a. Introduction

The year-to-year variability of Atlantic basin hurricane activity is the largest of any of the globe's tropical cyclone (TC) basins. There has always been and will continue to be much interest in knowing if the coming Atlantic hurricane season is going to be unusually active, very quiet or near average. There was never a way of objectively determining how active the coming Atlantic hurricane season was going to be until the early to mid-1980s when global data sets became more accessible.

Analyzing the available data in the 1980s, we found that the coming Atlantic seasonal hurricane season did indeed have various precursor signals that extended backward in time for up to 6–8 months before the start of the season. These precursor signals involved El Niño-Southern Oscillation (ENSO), Atlantic sea surface temperatures (SSTs) and sea level pressures, West African rainfall, the Quasi-Biennial Oscillation (QBO) and several other global parameters. Much effort has since been expended by our project's current and former members (along with other research groups) to try to quantitatively maximize the best combination of hurricane precursor signals to give the highest amount of reliable seasonal hindcast skill. We have experimented with many various combinations of precursor variables and now find that our most reliable statistical forecasts utilize a combination of three or four variables.

A cardinal rule that has always been followed is to issue no forecast for which we do not have substantial hindcast skill extending back in time for at least 30 years. We now use the high resolution ERA5 dataset as the input to our statistical models. These data products are available in near-real time, allowing us to be able to use the same datasets to make predictor estimates that we used to develop the statistical models.

Beginning with the April 2019 forecast, CSU also began issuing statistical-dynamical model forecasts. In 2023, these predictions used the current ECMWF climate model (SEAS5), Met Office climate model (GloSea6), Japan Meteorological Agency (JMA) climate model and Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC) model to predict large-scale conditions in August–September that are known to significantly impact Atlantic hurricane activity. These statistical-dynamical forecasts have shown skill at predicting Accumulated Cyclone Energy (ACE) based on hindcast data since 1981 for SEAS5 and since 1993 for GloSea6, JMA and CMCC.

The explorative process to skillful prediction should continue to develop as more data becomes available and as more robust relationships are found. There is no one best forecast scheme that can always be confidently applied. We have learned that precursor relationships can change with time and that one must be alert to these changing relationships. For instance, earlier seasonal forecasts relied heavily on the stratospheric QBO and West African rainfall. These precursor signals have not worked in recent years. Because of this, other precursor signals have been substituted in their place. As new data and new insights are gathered in the coming years, it is to be expected that our forecast schemes will in future years also need revision. Keeping up with the changing global climate system, using new data signals, and exploring new physical relationships is a full-time job. Success can never be measured by the success of a few real-time forecasts but only by long-period hindcast relationships and sustained demonstration of real-time forecast skill over a decade or more.

1b. Seasonal Forecast Theory

A variety of atmosphere-ocean conditions interact with each other to cause year-to-year and month-to-month hurricane variability. The interactive physical linkages between these precursor physical parameters and hurricane variability are complicated and cannot be well elucidated to the satisfaction of the typical forecaster making short range (1–5 days) predictions where changes in the current momentum and pressure fields are the crucial factors. Seasonal forecasts, unfortunately, must deal with the much more complicated interaction of the energy-moisture fields along with the momentum fields.

We find that one can explain about 50-60% of the variance in year-to-year hurricane activity when combining 3–4 semi-independent atmospheric-oceanic parameters together. The best predictors (out of a group of 3–4) do not necessarily have the best individual correlations with hurricane activity. The best forecast parameters are those that explain a portion of the variance of seasonal hurricane activity that is not associated with the other variables. It is possible for an important hurricane forecast parameter to show only a marginally significant correlation with the predictand by itself but to have an important influence when included with a set of 2–3 other predictors.

2 Tropical Cyclone Activity for 2023

Figure 1 and Table 1 summarize Atlantic basin TC activity that occurred in 2023. Overall, the season had above-normal activity per NOAA's definition (>126.1 Accumulated Cyclone Energy (ACE); Table 2), with above-normal numbers of named storms and near-normal numbers of hurricanes and major hurricanes. Online entries from Wikipedia are available for in-depth discussions of each TC that occurred in 2023. The National Hurricane Center is also currently in the process of writing up extensive reports on all 2023 TCs.

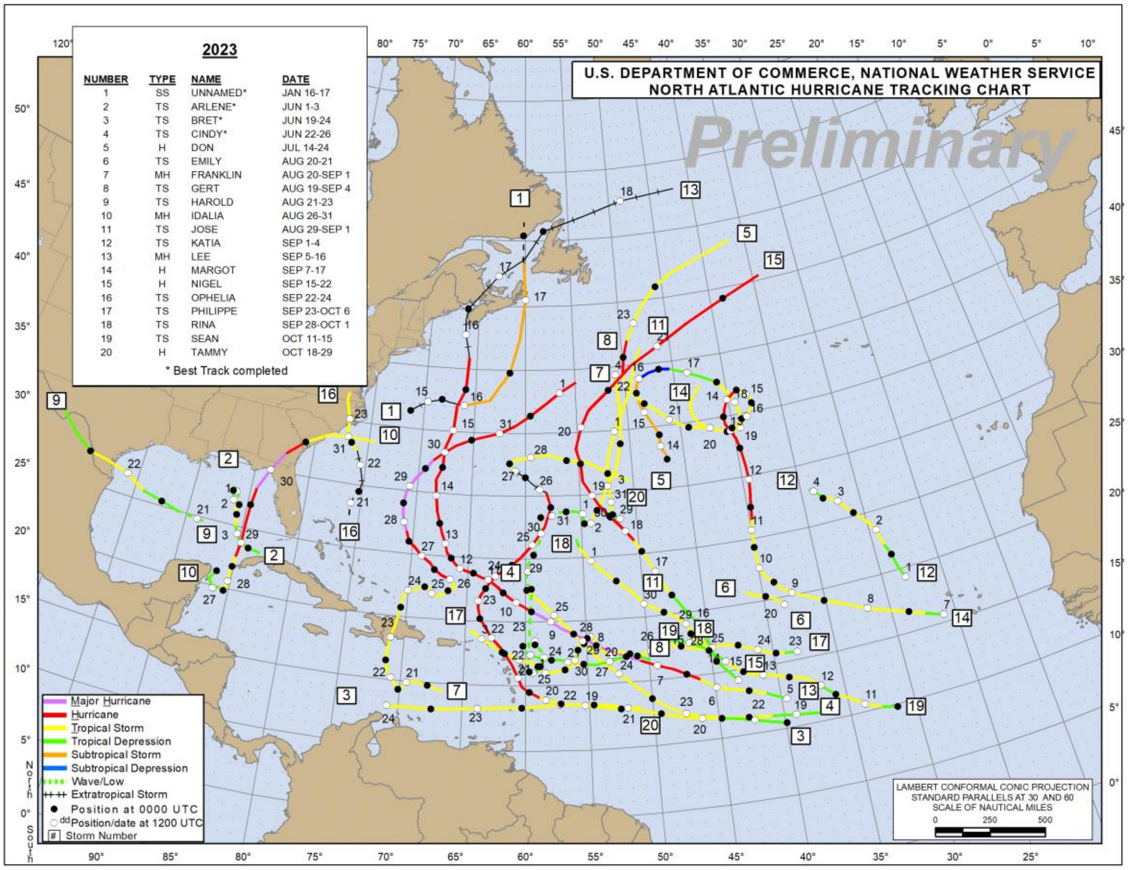


Figure 1: 2023 Atlantic basin TC tracks through November 28. 20 named storms, 7 hurricanes and 3 major hurricanes occurred. Figure courtesy of NOAA.

Table 1: Observed 2023 Atlantic basin TC activity through November 28. Data is calculated from the NHC operational best track and may differ slightly from what was provided in NHC's real-time advisories.

Real-Time North Atlantic Ocean Statistics by Storm for 2023

Year	Storm#	Name	Dates TC Active	Max Wind (kts)	MSLP (mb)	Named Storm Days	Hurricane Days	Major Hurricane Days	Accumulated Cyclone Energy
2023	1	UNNAMED	1/16-1/17	60	976	1.25	0.00	0.00	1.4
2023	2	ARLENE	6/2-6/3	35	998	0.75	0.00	0.00	0.4
2023	3	BRET	6/19-6/24	60	996	5.25	0.00	0.00	4.6
2023	4	CINDY	6/23-6/26	50	1001	3.25	0.00	0.00	2.5
2023	5	DON	7/14-7/24	65	988	9.00	0.50	0.00	7.2
2023	6	GERT	8/21-9/4	50	998	3.25	0.00	0.00	2.4
2023	7	EMILY	8/20-8/21	45	1001	1.00	0.00	0.00	0.7
2023	8	FRANKLIN	8/20-9/1	130	926	12.00	6.25	2.00	26.6
2023	9	HAROLD	8/22-8/22	45	998	0.75	0.00	0.00	0.5
2023	10	IDALIA	8/27-8/31	115	940	4.00	1.75	0.50	7.4
2023	11	JOSE	8/31-9/1	50	997	1.75	0.00	0.00	1.3
2023	12	KATIA	9/2-9/3	50	998	1.75	0.00	0.00	1.2
2023	13	LEE	9/5-9/16	145	926	10.50	9.50	5.25	36.8
2023	14	MARGOT	9/7-9/17	80	970	9.75	3.50	0.00	12.7
2023	15	NIGEL	9/17-9/22	85	971	5.25	4.00	0.00	10.5
2023	16	OPHELIA	9/22-9/23	60	981	1.25	0.00	0.00	1.4
2023	17	PHILIPPE	9/23-10/6	45	998	12.75	0.00	0.00	9.4
2023	18	RINA	9/28-10/1	45	999	3.25	0.00	0.00	1.9
2023	19	SEAN	10/11-10/14	40	1004	2.75	0.00	0.00	1.4
2023	20	TAMMY	10/18-10/29	90	965	9.50	5.50	0.00	15.2

Table 2: NOAA's Atlantic hurricane season definitions.

Forecast Category	ACE
Extremely Active	>159.6
Above-Normal	126.1-159.6
Normal	73.0-126.0
Below-Normal	<73.0

3 Special Characteristics of the 2023 Hurricane Season

The 2023 hurricane season ended up an above-normal season, with several records being set over the course of the year.

Below is a selection of some of the notable statistics from the 2023 season:

Basinwide/Multi-Storm Statistics

- 20 named storms formed in the Atlantic this season. That is tied with 1933 for the 4th most on record, trailing 2020 (30 named storms), 2005 (28 named storms), and 2021 (21 named storms).

- 146 ACE was generated during 2023, making the 2023 Atlantic hurricane season an above-normal season by NOAA's definition. The Atlantic has not had a below-average season per NOAA's definition since 2015.

- 13 named storms formed in the Atlantic from August 20th through September 28th. That is the most on record between August 20 – September 28, breaking the old record of 12 named storm formations set in 2020.

- 5 hurricanes formed in the Atlantic between August 26 – September 18. This ties the record for most hurricane formations between August 26 – September 18, first set in 1955 and occurring in 2004 and 2012.

- Tropical Storms Bret and Cindy formed in the tropical Atlantic (south of 23.5°N, east of 60°W) in June. This is the first time on record that two named storms formed in the tropical Atlantic in June on record.

- Hurricanes Franklin and Idalia had max winds of 95 kt+ simultaneously – the first time that this occurred during August since 1950.

Individual Storm/Landfall Statistics

- Hurricane Franklin's central pressure reached a lifetime maximum low of 926 hPa – the lowest central pressure for a hurricane that far north (29°N) in the open Atlantic on record.

- Hurricane Idalia made landfall with max winds of 110 kt – the strongest hurricane to make landfall in the Big Bend region of Florida since 1896.

- Hurricane Lee intensified by 70 kt in 24 hours. Six other Atlantic hurricanes in the satellite era (since 1966) have intensified by 70+ kt in 24 hours: Wilma (2005), Felix (2007), Ike (2008), Matthew (2016), Maria (2017) and Eta (2020).

- Tropical Storm Philippe was a named storm for 12.75 days but only reached a maximum intensity of 45 kt. All other storms in the Atlantic lasting that long had a maximum intensity of at least 60 kt.

- Tropical Storm Sean formed at 33.1°W on October 10th – the farthest east that a named storm has formed in the tropical Atlantic (south of 23.5°N) this late in the calendar year on record.

- Tammy became a hurricane on October 20 - the latest calendar year hurricane on record in the tropical Atlantic (south of 20°N, east of 60°W)

4 Quantitative Verification of 2023 Atlantic Hurricane Forecasts

4.1 Verification of Seasonal Forecasts

Table 3 is a comparison of our forecasts for 2023 for four different lead times along with this year's observations.

Table 3: Verification of our 2023 seasonal hurricane predictions.

Forecast Parameter and 1991–2020 Average (in parentheses)	Issue Date 13 April 2023	Issue Date 1 June 2023	Issue Date 6 July 2023	Issue Date 3 August 2023	**Observed 2023 Activity Thru 11/28**
Named Storms (NS) (14.4)	13	15	18	18	**20**
Named Storm Days (NSD) (69.4)	55	60	90	90	**99**
Hurricanes (H) (7.2)	6	7	9	9	**7**
Hurricane Days (HD) (27.0)	25	30	35	35	**31**
Major Hurricanes (MH) (3.2)	2	3	4	4	**3**
Major Hurricane Days (MHD) (7.4)	5	7	9	9	**7.75**
Accumulated Cyclone Energy (ACE) (123)	100	125	160	160	**146**
ACE West of 60°W (73)	55	70	82	82	**70**
Net Tropical Cyclone Activity (NTC) (135%)	105	135	170	170	**157**

Table 4 provides the same forecasts but using the ~70% confidence intervals for each forecast calculated using the methodology outlined in Saunders et al. (2020). More details can be found in the individual seasonal forecasts, but in summary, we fit our cross-validated errors to various statistical distributions to more robustly calculate the uncertainty ranges with our forecasts. Forecast quantities that fell within the 70% confidence interval are highlighted in bold-faced font. About 86% of all forecast parameters fell within the 70% confidence interval in 2023. Our April forecast underpredicted activity, while the June, July and August forecasts showed reasonably good levels of skill.

We also successfully predicted a lower percentage of basinwide ACE occurring west of 60°W this season. El Niño typically reduces the strength of the Bermuda High, favoring recurvature of storms. This was certainly the case in 2023, where several storms recurved relatively far east in the basin (Figure 1).

Table 4: Verification of CSU's 2023 seasonal hurricane predictions with 70% confidence intervals.

Forecast Parameter and 1991–2020 Average (in parentheses)	Issue Date 13 April 2023	Issue Date 1 June 2023	Issue Date 6 July 2023	Issue Date 3 August 2023	**Observed 2023 Activity Thru 11/28**
Named Storms (NS) (14.4)	10 – 16	12 – 18	**15 – 21**	**15 – 21**	**20**
Named Storm Days (NSD) (69.4)	35 – 78	40 – 81	**70 – 111**	**71 – 109**	**99**
Hurricanes (H) (7.2)	**4 – 8**	**5 – 9**	**7 – 11**	**7 – 11**	**7**
Hurricane Days (HD) (27.0)	**14 – 39**	**18 – 44**	**23 – 48**	**24 – 47**	**31**
Major Hurricanes (MH) (3.2)	**1 – 4**	**2 – 5**	**3 – 6**	**3 – 5**	**3**
Major Hurricane Days (MHD) (7.4)	**1 – 8**	**4 – 11**	**6 – 14**	**6 – 13**	**7.75**
Accumulated Cyclone Energy (ACE) (123)	**57 – 153**	**79 – 178**	**112 – 212**	**116 – 209**	**146**
ACE West of 60°W (73)	**28 – 91**	**40 – 107**	**48 – 113**	**50 – 111**	**70**
Net Tropical Cyclone Activity (NTC) (135%)	62 – 156	**89 – 186**	**124 – 220**	**127 – 216**	**157**

4.2 Verification of Two-Week Forecasts

This is the 15th year that we have issued shorter-term forecasts of tropical cyclone activity (TC) starting in early August. These two-week forecasts are based on a combination of observational and modeling tools. The primary tools that are used for this forecast are as follows: 1) current storm activity, 2) National Hurricane Center Tropical Weather Outlooks, 3) forecast output from global models, 4) the current and projected state of the MJO (Figure 2) and 5) the current seasonal forecast. Figure 2 displays MJO propagation from 1 August to 20 November. In general, the MJO was relatively favorable for Atlantic TC activity from the latter part of August through most of September, with the MJO concentrated in phases 1–4. These phases tend to be associated with enhanced Atlantic hurricane activity, given that increased anomalous upward vertical motion over Africa, the Indian Ocean and western Maritime Continent broadly favor anomalously low wind shear in the tropical Atlantic. During October, the MJO was relatively weak, while in November the MJO has predominately been in phases 6–7 which tend to suppress Atlantic hurricane activity (see Section 7.3).

The metric that we tried to predict with these two-week forecasts is the Accumulated Cyclone Energy (ACE) index, which is defined to be the square of a named storm's maximum wind speed (in 10^4 knots^2) for each 6-hour period of its existence over the two-week forecast period. These forecasts are too short in length to show significant skill for individual event parameters such as named storms and hurricanes.

Our forecast definition of above-normal, normal, and below-normal ACE periods are defined by ranking observed activity in the satellite era from 1966–2022 and defining above-normal, normal and below-normal two-week periods based on terciles. Since there are 57 years from 1966–2022, we include 19 years for each tercile (e.g., below-normal, normal and above-normal). Forecasts are issued in probabilistic format for each tercile.

Table 5 displays the six two-week forecasts that were issued during the 2023 hurricane season and shows their verification. We assigned the highest probability to the correct category for three of the six two-week periods and missed a fourth correct forecast by ~1 ACE. The most challenging of the two-week forecasts was the one from September 28–October 11 where the interaction between Philippe/Rina was not well handled by most global models. We assigned a 60% chance of above-normal TC activity occurring during that two-week period given models were indicating that either Philippe or Rina were likely to reach hurricane strength. Rina was weak and short lived, while Philippe lasted for several days but also remained weak, generating relatively little ACE in the process. Overall, activity during that two-week period was normal.

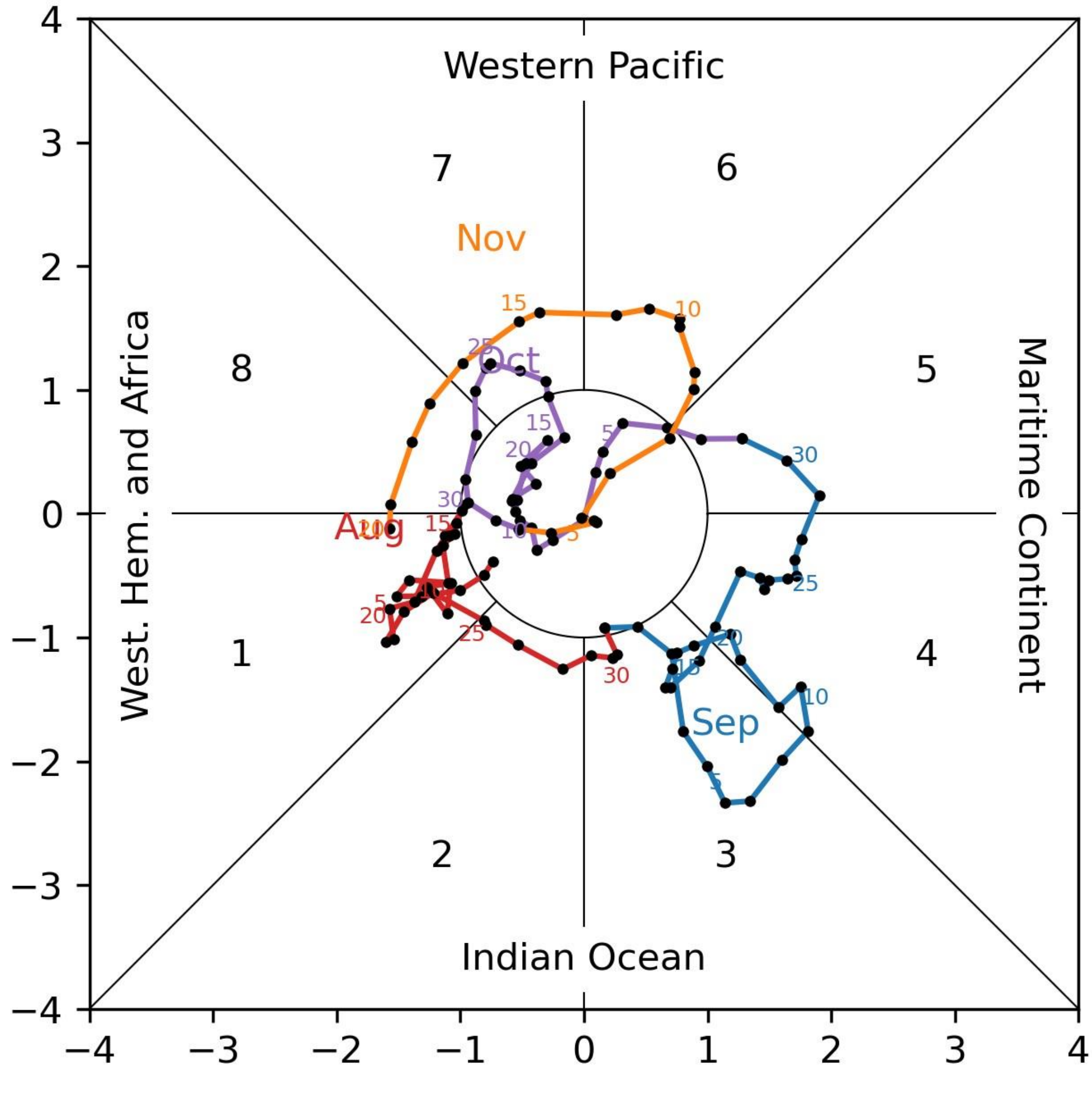


Figure 2: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 1 to November 20. The Maritime Continent refers to Indonesia and the surrounding islands. RMM stands for Real-Time Multivariate MJO. Figure courtesy of Carl Schreck.

Table 5: Two-week Atlantic ACE forecast verification for 2023. Forecasts that verified in the correct category (or the category with the highest probability assigned) are highlighted in green, while forecasts that missed by one category are highlighted in blue. The probability listed in the "Predicted ACE" column in parentheses is the forecast probability for that particular category, while the probability listed in the observed ACE category was the probability assigned for the ACE category that was observed.

Forecast Period	Category with Highest Probability	Observed ACE
8/3 – 8/16	**Normal (2–5) (50%)**	**0 (30%)**
8/17 – 8/30	**Above-Normal (>18) (50%)**	**31 (50%)**
8/31 – 9/13	**Above-Normal (>27) (70%)**	**49 (70%)**
9/14 – 9/27	**Above-Normal (>26) (85%)**	**25 (15%)**
9/28 – 10/11	**Above-Normal (>12) (60%)**	**8 (35%)**
10/12 – 10/25	**Above-Normal (>8) (55%)**	**14 (55%)**

4.3 Verification of October–November Caribbean ACE Forecast

In 2011, we published a paper detailing a model that forecast October–November Caribbean hurricane days (Klotzbach 2011) using the state of ENSO and sea surface temperatures in the western tropical Atlantic and Caribbean (e.g., the Atlantic Warm Pool). In an analysis of a recently published article on the October–November portion of the 2020 Atlantic hurricane season (Klotzbach et al. 2022), we revised the model slightly to use the ENSO Longitude Index (Williams and Patricola 2018) to assess the state of ENSO and now use ACE as our primary forecast metric.

For 2023, the ENSO Longitude Index was strongly positive in October–November, indicating a robust El Niño event. The Atlantic warm pool was record warm this October–November. These two predictors, in combination, favored a somewhat below-average end to the Atlantic hurricane season in the Caribbean, due to strong El Niños historically dominating over warm Atlantic warm pools. The 1991–2020 average October–November Caribbean ACE is 8.

The two-predictor model that comprises the Caribbean ACE forecast called for 5 ACE. We adjusted the statistical model output upwards and predicted 8 ACE with our final forecast for the two-month period, given the extremely warm Atlantic warm pool.

The October–November Caribbean ACE forecast for 2023 was a slight over forecast. We define ACE generated in the region between 10–20°N, 88–60°W as Caribbean ACE. Both Philippe and Tammy tracked through the far eastern part of the Caribbean during October, generating 5 ACE in the process. Overall vertical wind shear in the Caribbean during October–November was below normal (Figure 3). This reduced shear was highly anomalous for a strong El Niño event, which typically favors strong Caribbean shear.

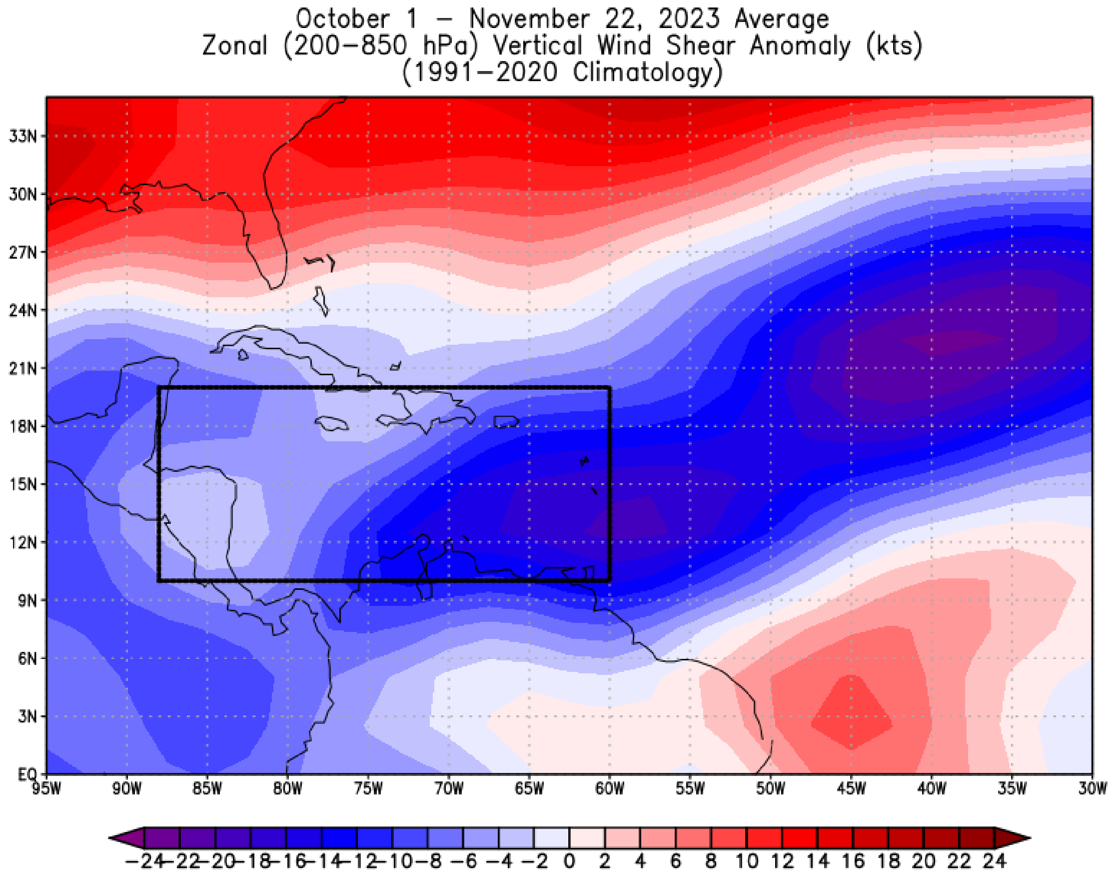


Figure 3: October 1 – November 22-averaged shear in the tropical Atlantic. The black box denotes the Caribbean region.

5 Landfall Analysis

The 2023 Atlantic hurricane season was near average for continental US landfall frequency, with three named storms (Harold, Idalia and Ophelia) and one major hurricane (Idalia) making landfall (Figure 4). The average number of continental US landfalls (excluding multiple landfalls from the same system) from 1900–2020 are 3.2 named storms, 1.6 hurricanes and 0.5 major hurricanes per year. The most notable continental US hurricane landfall was Idalia, which made landfall as a Category 3 major hurricane in the Big Bend region of Florida. Idalia was responsible for 5 fatalities in the continental United States and ~$2.5 billion USD in damage according to the National Centers for Environmental Information.

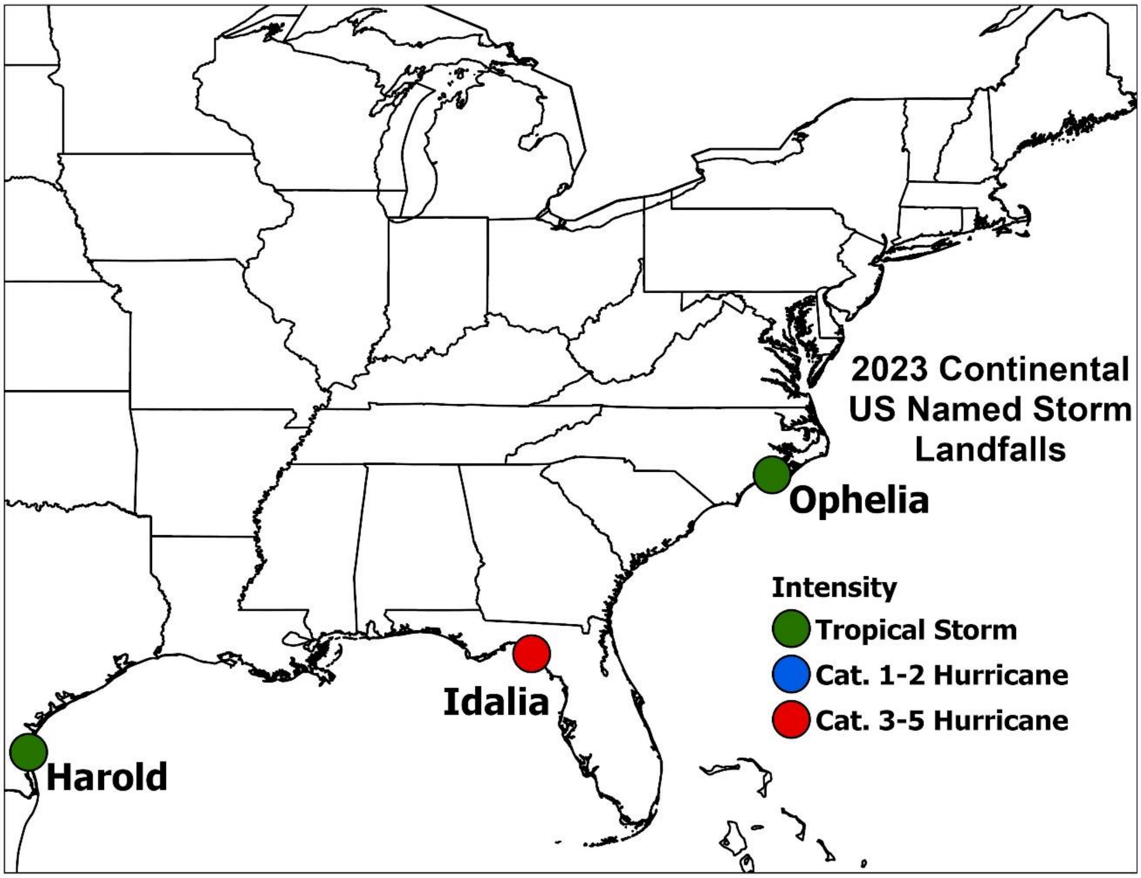


Figure 4: Location of the named storms making landfall in the continental US during the 2023 Atlantic hurricane season.

This year, we continued to calculate the impacts of TCs for each state and county/parish along the Gulf and East Coasts, tropical cyclone-prone provinces of Canada, islands in the Caribbean and countries in Central America. We used NOAA's Historical Hurricane Tracks website and selected all named storms, hurricanes and major hurricanes that have tracked within 50 miles of each landmass from 1880–2020. This approach allowed for TCs that may have made landfall in an immediately adjacent region to be counted for all regions that were near the landfall location of the storm. We then fit the observed frequency of storms within 50 miles of each landmass using a Poisson distribution to calculate the climatological odds of one or more events within 50 miles. These probabilities were then adjusted based on our forecast of ACE relative to the 1991–2020 climatology.

Since the 2023 Atlantic hurricane season was predicted to be below-average in April, near-average in June and above-average in July and August, landfall probabilities were below-average in April, near-average in June and above-average in July and August. As an example, Table 6 displays the landfall probabilities that were issued with the 5 July 2023 outlook. As noted earlier, the 2023 Atlantic hurricane season had a near-average number of continental US named storm landfalls including one major hurricane landfall (Idalia).

Table 6: Post 5–July probability of >=1 named storm, hurricane and major hurricane tracking within 50 miles of each coastal state from Texas to Maine. Probabilities were provided for both the 1880–2020 climatological average as well as the probability for 2023, based on the early July CSU seasonal hurricane forecast of ACE.

			2023 Probability				Climatological	
		Probability >=1	event within	50 miles		Probability >=1	event within	50 miles
State		Named Storm	Hurricane	Major Hurricane		Named Storm	Hurricane	Major Hurricane
Alabama		65%	33%	10%		58%	28%	8%
Connecticut		26%	9%	2%		22%	8%	1%
Delaware		27%	7%	1%		23%	6%	1%
Florida		91%	63%	34%		86%	56%	29%
Georgia		70%	36%	7%		63%	30%	6%
Louisiana		73%	44%	17%		66%	38%	14%
Maine		25%	8%	2%		21%	7%	1%
Maryland		36%	13%	1%		31%	11%	1%
Massachusetts		38%	17%	3%		33%	14%	3%
Mississippi		60%	33%	9%		53%	28%	8%
New Hampshire		22%	7%	2%		18%	6%	1%
New Jersey		27%	8%	1%		23%	7%	1%
New York		31%	11%	3%		26%	9%	2%
North Carolina		75%	44%	9%		68%	38%	8%
Rhode Island		24%	9%	2%		20%	8%	1%
South Carolina		64%	34%	10%		57%	29%	8%
Texas		68%	43%	19%		61%	36%	16%
Virginia		52%	24%	2%		46%	20%	1%

6 Summary of Atmospheric/Oceanic Conditions

In this section, we go into more detail discussing large-scale conditions that we believe significantly impacted the 2023 Atlantic basin hurricane season.

6.1 ENSO

NOAA officially declared the development of El Niño in early June, and since that time, these El Niño conditions have intensified. The August-October-averaged value of the Oceanic Nino Index was 1.5°C, meeting NOAA's threshold of a strong El Niño for the peak of the Atlantic hurricane season. From our early April forecast, we correctly predicted that El Niño was likely to develop. Our confidence for a moderate/strong El Niño grew with our latter seasonal forecast updates. Below are some quotes excerpted from our seasonal forecasts issued this year discussing our thoughts on the likely state of ENSO.

(13 April 2023) –

"Based on the above information, our best estimate is that we will have El Niño conditions for the peak of the Atlantic hurricane season."

(1 June 2023) –

"At this point, our best estimate is that we will have a robust El Niño, but likely not quite as strong as 1997 or 2015."

(3 August 2023) –

"We currently expect to see either a moderate or strong El Niño for the peak of this year's season."

The dynamical and statistical models initialized during the late winter/early spring generally provided reasonably good guidance for ENSO SSTs during the peak of the Atlantic hurricane season. Figure 5 displays the ECMWF seasonal forecast for Niño 3.4 from 1 April, which is the forecast that we had available for our early April seasonal forecast. The observed values were near the ensemble average value at most lead times.

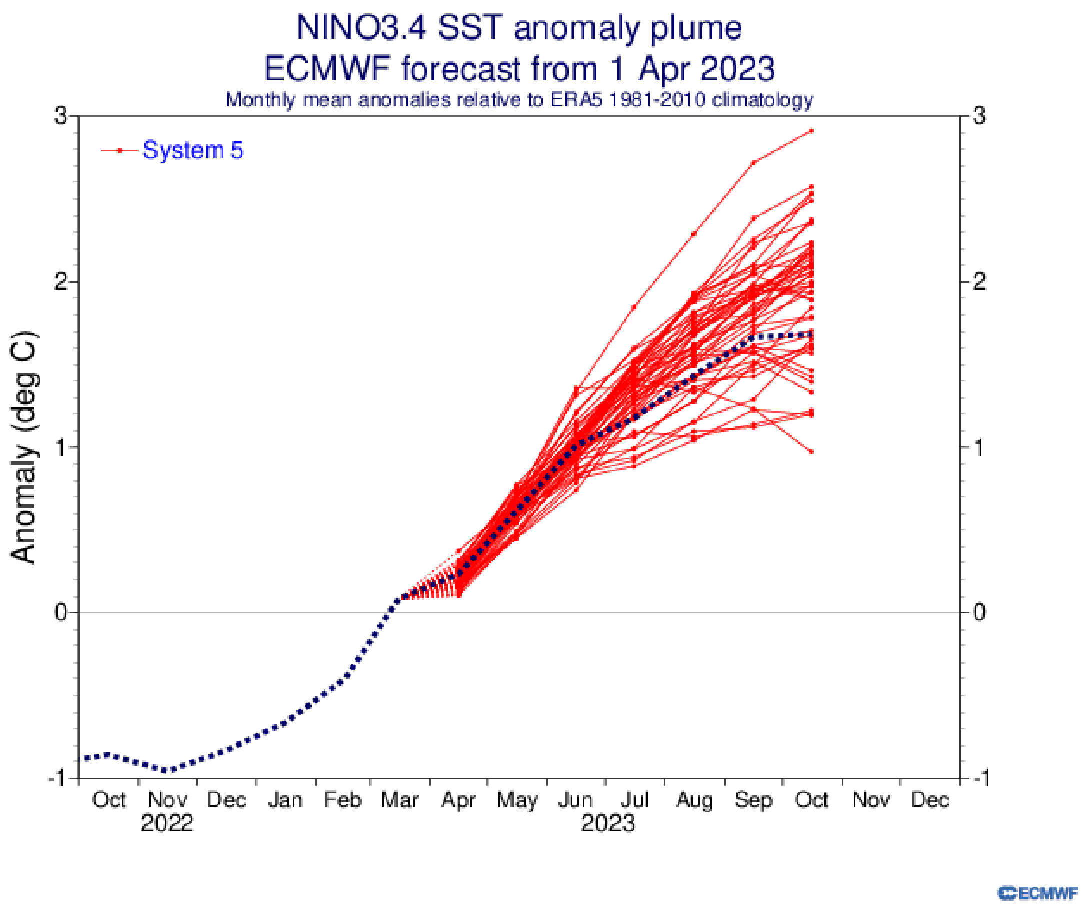


Figure 5: ECMWF ensemble prediction for Niño 3.4 from 1 April 2023. The blue dotted line represents the observed value.

Figure 6 displays the March ENSO prediction plume from 24 statistical and dynamical models. This was the prediction plume that we had available at the time of the early April forecast. The observed monthly ENSO values during the Atlantic hurricane season were warmer than most forecast models for the peak of the Atlantic hurricane season. The three models with the most successful predictions (all calling for Nino 3.4 values averaged for August–October of 1.2°C–1.3°C) were the University of Pretoria model, the NASA model and the GFDL model.

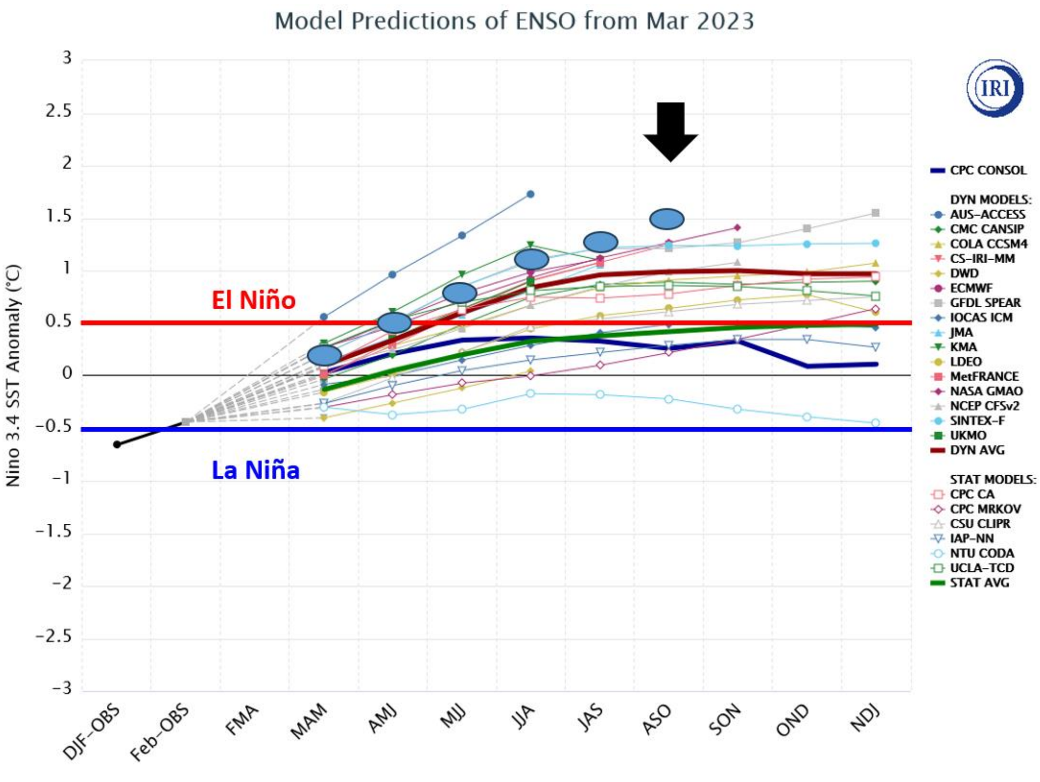


Figure 6: Model prediction plume from 22 statistical and dynamical models for Niño 3.4 from mid-March. The black arrow highlights August–October – the peak three months of the Atlantic hurricane season. Blue dots represent observed values for each three-month period. Figure adapted from the International Research Institute website.

La Niña quickly waned during the early part of 2023, transitioning to neutral conditions during the spring and El Niño conditions by June. Since then, El Niño has intensified. Table 7 displays anomalies in the various Niño regions in January, April, July and October 2023, respectively.

Table 7: January 2023 anomalies, April 2023 anomalies, July 2023 anomalies, and October 2023 anomalies for the Niño 1+2, Niño 3, Niño 3.4 and Niño 4 regions. SST anomaly differences from January 2023 are in parentheses.

Region	January 2023 Anomaly (ºC)	April 2023 Anomaly (ºC)	July 2023 Anomaly (ºC)	October 2023 Anomaly (ºC)
Niño 1+2	-0.2	+2.5 (+2.7)	+3.2 (+3.4)	2.5 (+2.7)
Niño 3	-0.5	+0.4 (+0.9)	+1.6 (+2.1)	2.0 (+2.5)
Niño 3.4	-0.7	+0.2 (+0.9)	+1.1 (+1.8)	1.6 (+2.3)
Niño 4	-0.6	+0.3 (+0.9)	+0.7 (+1.3)	1.2 (+1.8)

An additional way to visualize the changes in ENSO that occurred over the past year is to look at upper-ocean heat content anomalies in the eastern and central tropical Pacific (Figure 7). Upper-ocean heat content anomalies were below-average late last fall, and then anomalously warmed quickly through early June, associated with the transition to ENSO neutral and then El Niño conditions. Ocean heat content anomalies remained around 1.0°C for most of August and September and have since increased.

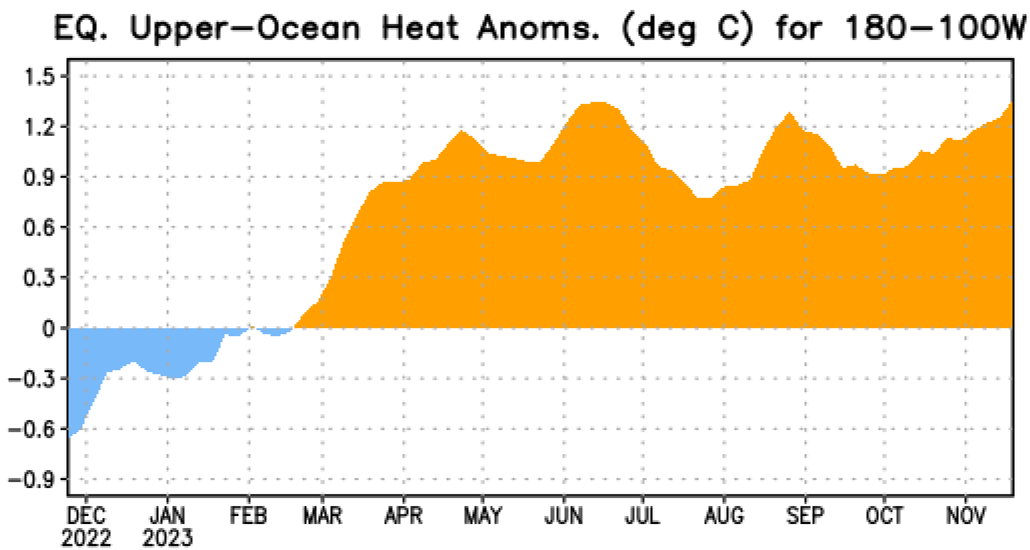


Figure 7: Upper ocean (0–300 meter) heat content anomalies in the eastern and central tropical Pacific from December 2022 – November 2023.

6.2 Intra-Seasonal Variability

The MJO index was generally favorable for Atlantic hurricane activity in August and September, with very slow eastward propagation based on the Real-time Multivariate MJO (RMM) index (Figure 8). Phases 1–4 historically have accounted for more than 60% of Atlantic hurricane activity (Figure 9), as these phases typically generate lower levels of vertical wind shear across the Main Development Region (MDR; 10–20°N, 85–20°W). These favorable MJO phases were likely part of the reason why the Atlantic was so active from mid-August through late September.

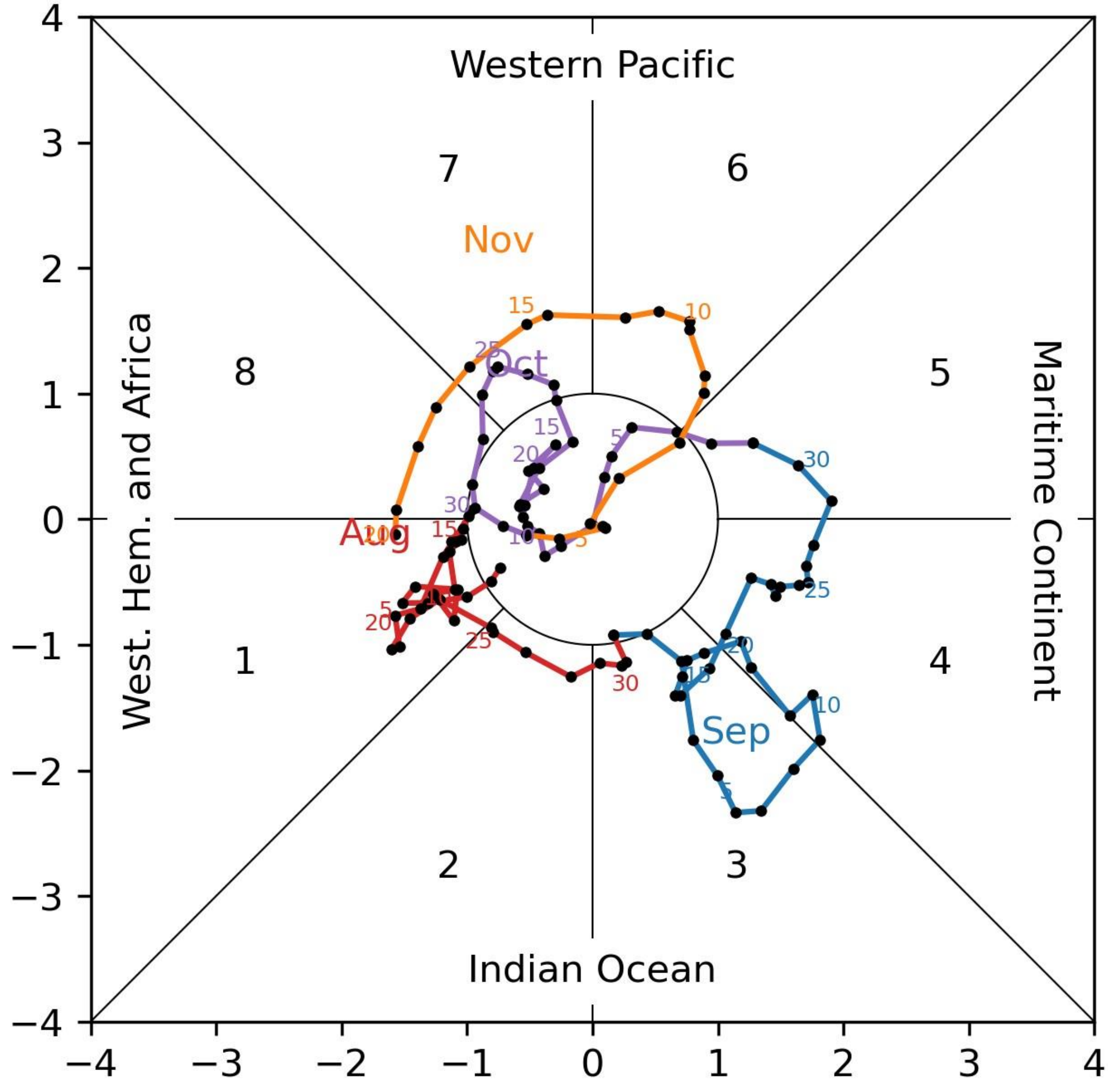


Figure 8: Propagation of the Madden–Julian Oscillation (MJO) based on the Wheeler–Hendon classification scheme over the period from August 1 to November 20. Figure courtesy of Carl Schreck.

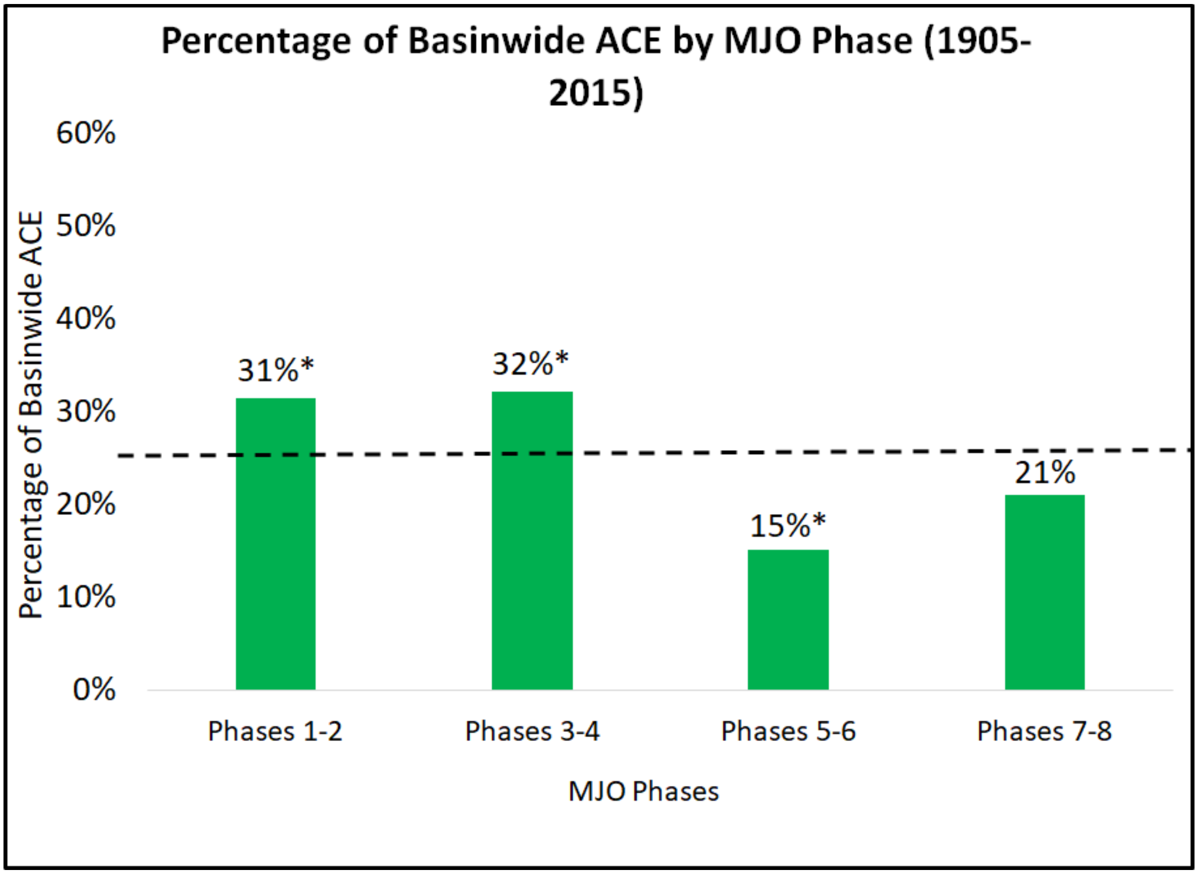


Figure 9: Percentage of basinwide normalized ACE generated by each MJO phase pair from 1905–2015. Normalized ACE is the amount of ACE generated in each phase pair divided by the number of days that the MJO spends in each MJO phase pair. Only days when the RMM MJO index is >1 (~60% of the time) are counted in this analysis. Asterisks mean statistically significant differences at the 10% level from the null hypothesis (e.g., 25% for each phase pair)

When looking at monthly ACE in 2023 compared with normal (Figure 10), the season was quite active in June, August and September, with near-average activity in July and October. November had no activity, which is below the average for the month. The early-season flurry of storms in June may have been tied to a convectively-favorable MJO pulse that occurred at that time. As noted earlier, the latter part of August and most of September were favorable from a sub-seasonal perspective, with the MJO generally acting to counter the El Niño event that intensified throughout the summer and fall. The MJO was generally weak in October. In November, the MJO was generally in phases 6-7, which tend to be associated with quieter periods for Atlantic hurricane activity.

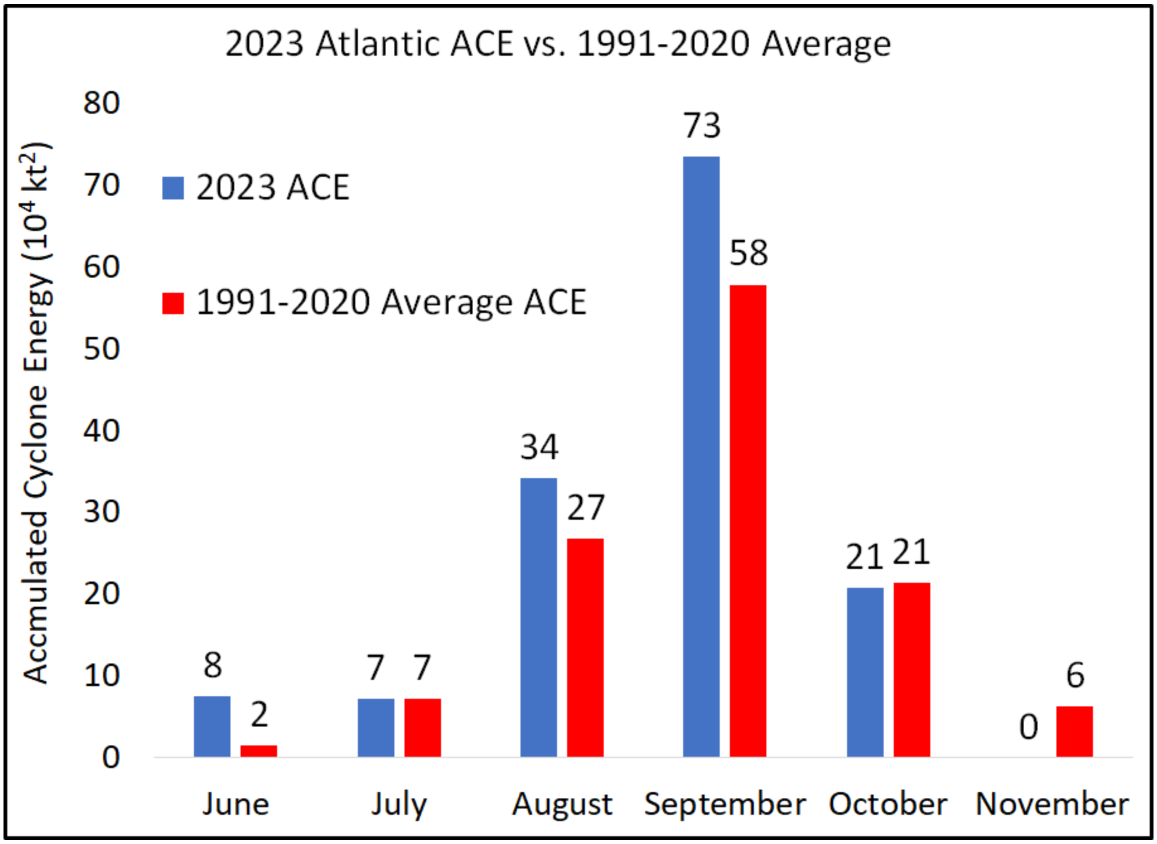


Figure 10: Atlantic Accumulated Cyclone Energy generated by month during 2023 (blue columns) compared with the 1991–2020 average (red columns).

Table 8 displays the number of storms that were first named in each phase of the MJO over the course of the 2023 Atlantic hurricane season. While the MJO preferentially concentrated in phases 1–4 throughout most of the peak of the season, it is still quite remarkable that only 1 out of 20 named storms that formed in 2023 did so in phases 5–8.

Table 8: TC formations by MJO phase during the 2023 Atlantic hurricane season.

MJO Phase	TC Formations
1	9
2	2
3	5
4	3
5	0
6	0
7	0
8	1

6.3 Atlantic SST

One of the biggest stories of the 2023 Atlantic hurricane season was the extremely warm SSTs that prevailed across the entire basin. A question going into the peak of the season was how the extremely warm Atlantic would interact with the El Niño and what the resulting hurricane season would look like. Additional discussion of the large-scale environment that resulted from this interaction appears in the next few sections, while this section discusses how these anomalously warm SST came to be.

During February, SSTs across most of the tropical Atlantic were near to slightly above average (Figure 11). However, for most of March, the subtropical high in the Atlantic was much weaker than normal (Figure 12), resulting in weaker trade winds blowing across the MDR. This led to anomalous warming of the tropical and subtropical Atlantic, especially in the eastern part of the basin (Figure 13). This anomalous warmth in the eastern tropical and subtropical Atlantic was the main reason our early April forecast only called for a slightly below-average season despite the anticipation of a robust El Niño event.

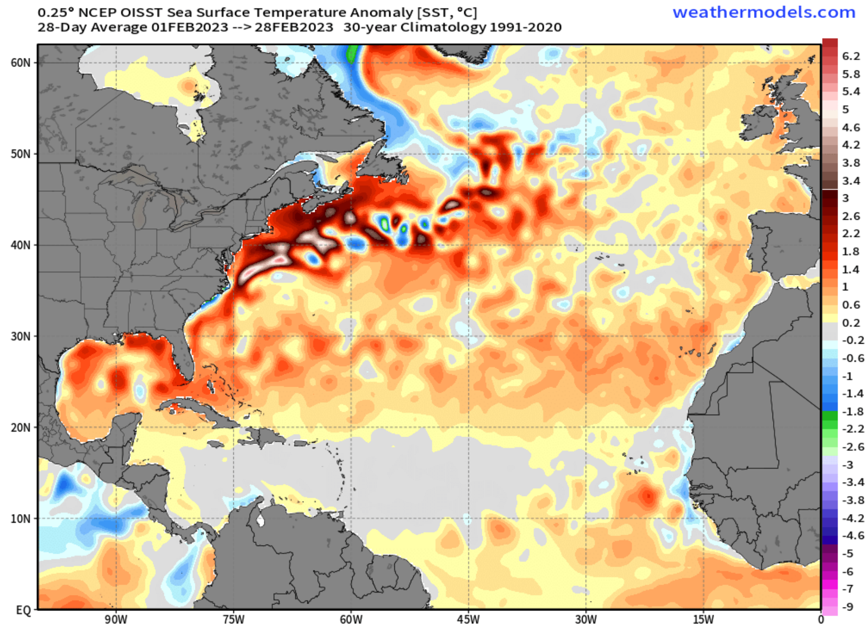


Figure 11: 28-day-averaged SST anomalies ending on 28 February.

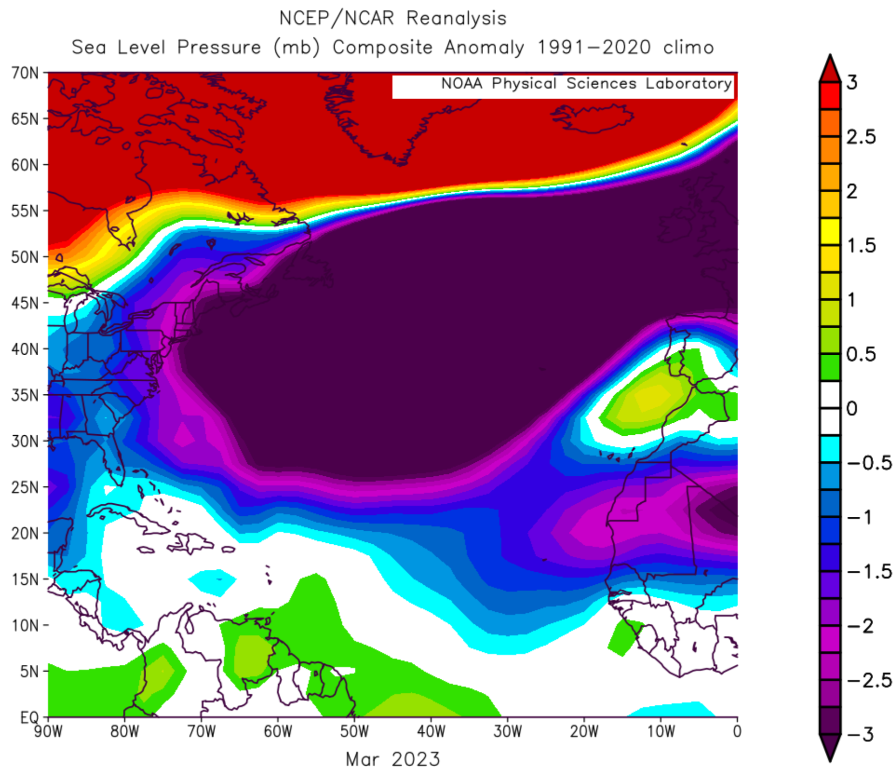


Figure 12: March-averaged sea level pressure anomalies across the Atlantic Ocean.

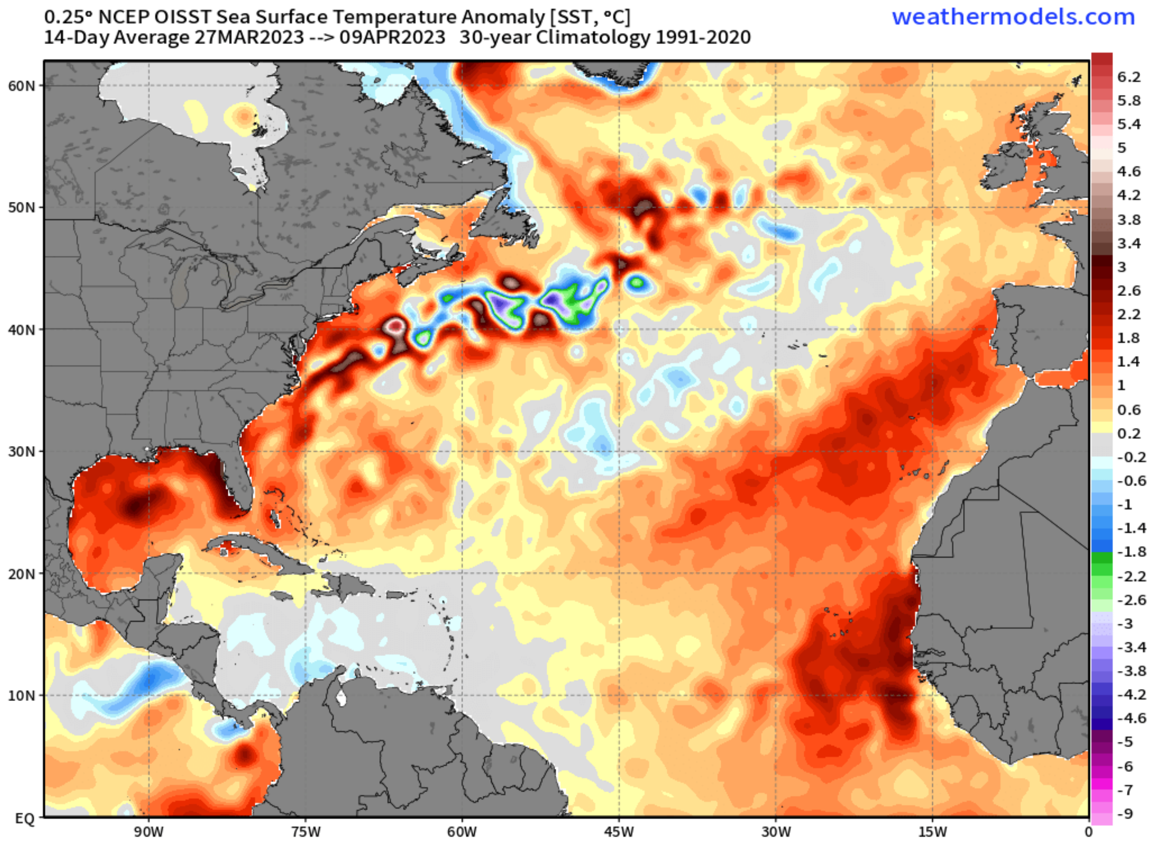


Figure 13: 14-day-averaged SST anomaly pattern across the Atlantic Ocean, ending on 9 April, as displayed in our early April forecast outlook.

Over the next two months, the subtropical ridge in the Atlantic remained weak, with associated reduced trade winds blowing across the tropical Atlantic (Figure 14). This led to continued anomalous warming of the tropical Atlantic, with the MDR becoming much warmer than normal by the time of the early June update (Figure 15). This extreme anomalous warmth in the Atlantic was the primary reason for the increase in predicted activity from the April to June forecasts despite development of El Niño conditions during this time.

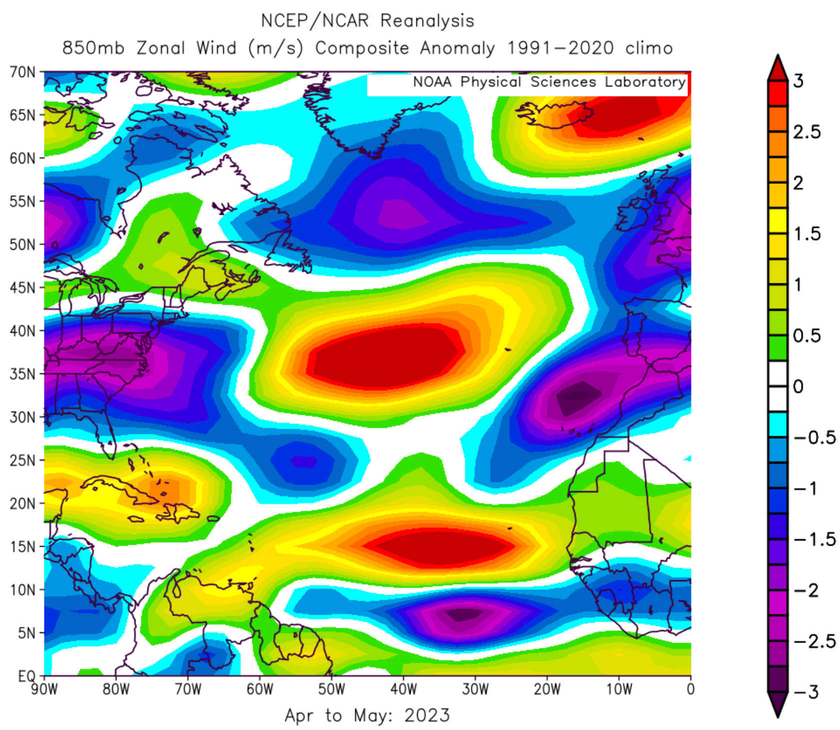


Figure 14: 850 hPa zonal winds averaged across the Atlantic during April–May of 2023.

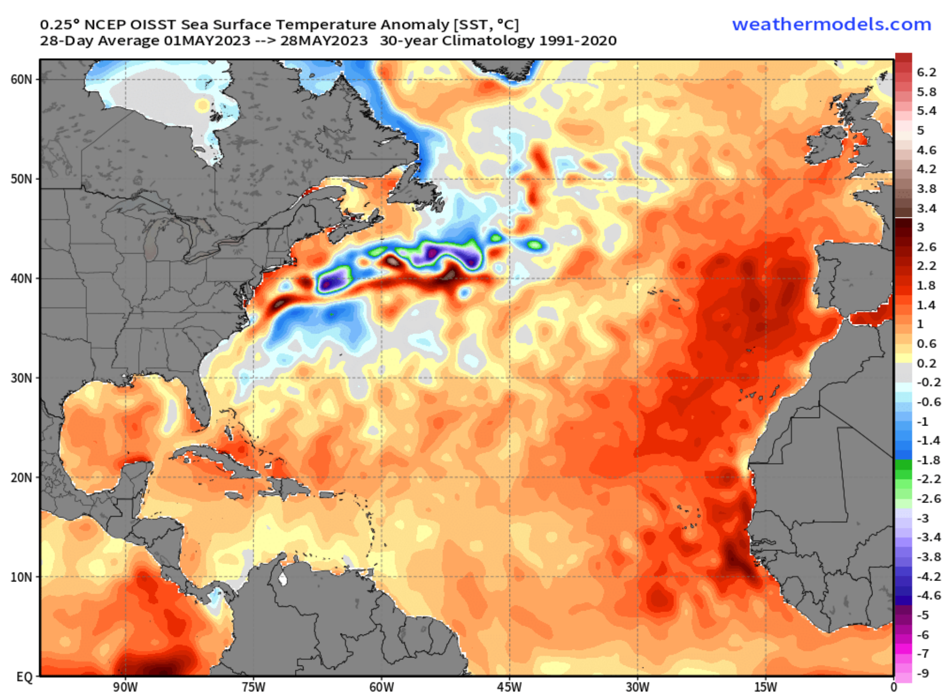


Figure 15: 14-day-averaged SST anomaly pattern across the Atlantic Ocean, ending on 28 May, as displayed in our early June forecast outlook.

During June and July, the subtropical ridge remained remarkably weak (Figure 16), resulting in continued anomalous warming and record warm SSTs averaged across the MDR by the time of the early August forecast (Figure 17). SSTs averaged across the MDR were their warmest on record during June and July. Overall, subtropical Atlantic pressures (25–40°N, 70–0°W) were the lowest on record (since 1979) from March through July, breaking the old record set in 2005.

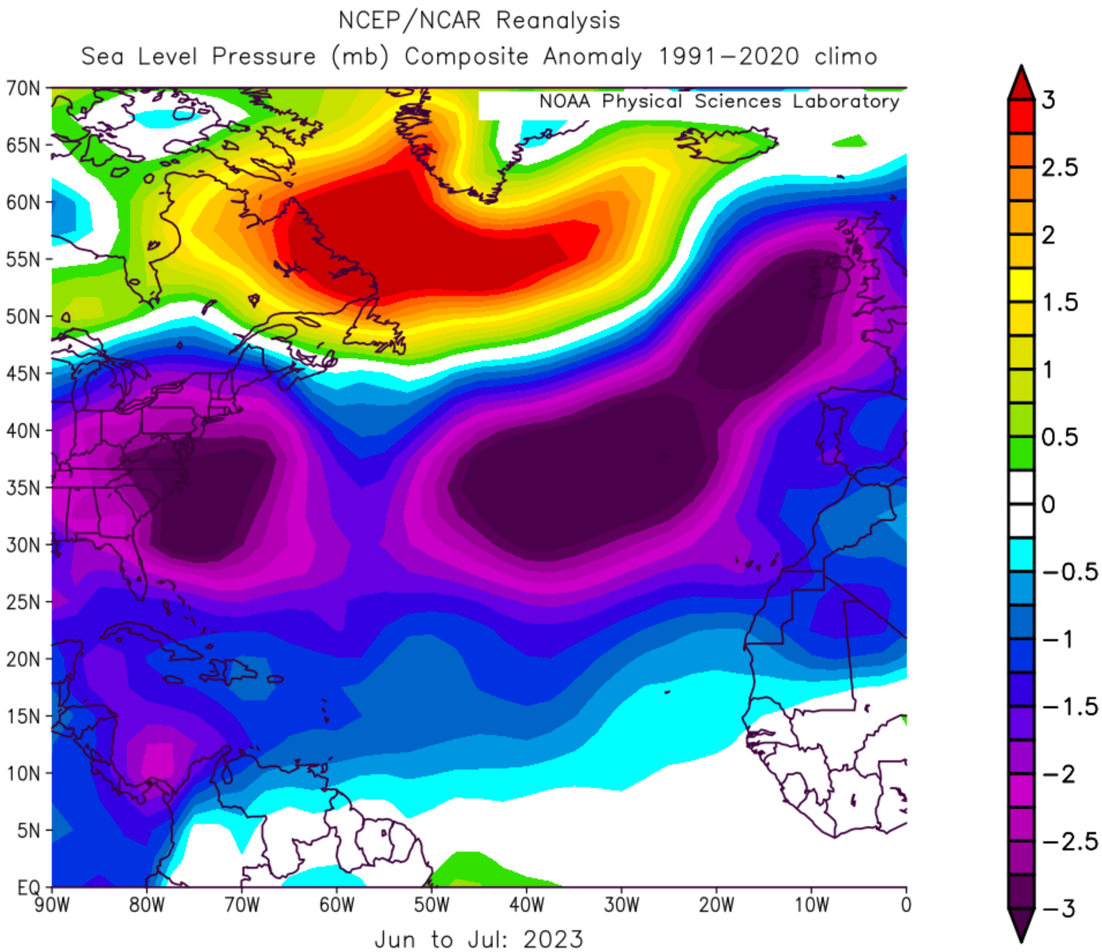


Figure 16: June–July-averaged sea level pressure anomalies across the Atlantic.

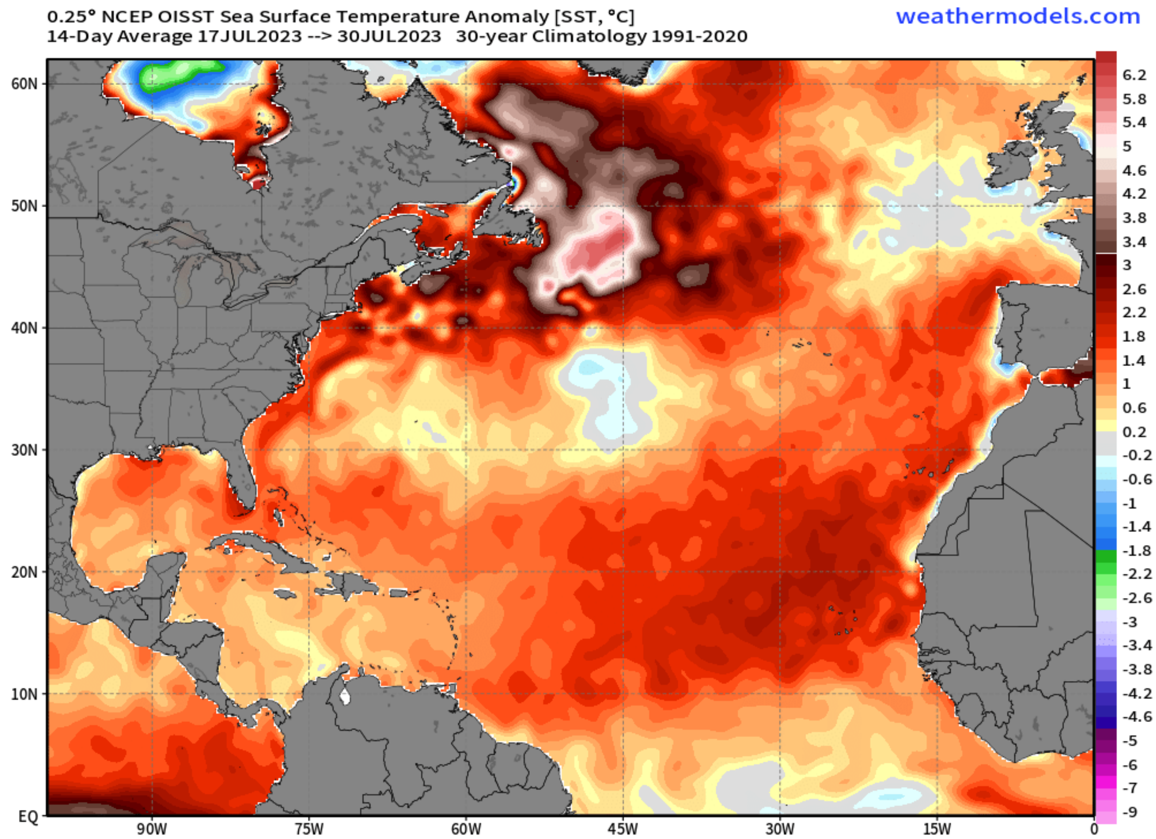


Figure 17: 14-day-averaged SST anomaly pattern across the Atlantic Ocean, ending on 30 July, as displayed in our early August forecast outlook.

These anomalously warm SSTs persisted throughout the peak of the hurricane season from August–October, with the MDR setting monthly SSTs record for August, September and October. The September MDR-averaged SST anomaly was the most impressive, breaking the old record set in September 2010 by 0.7°C (29.5°C vs. 28.8°C). Figure 18 displays SST anomalies across the Atlantic in September with a notable cool anomaly in the subtropics near 65°W which resulted from peak season TC activity such as Hurricane Franklin and the remnants of Idalia,.

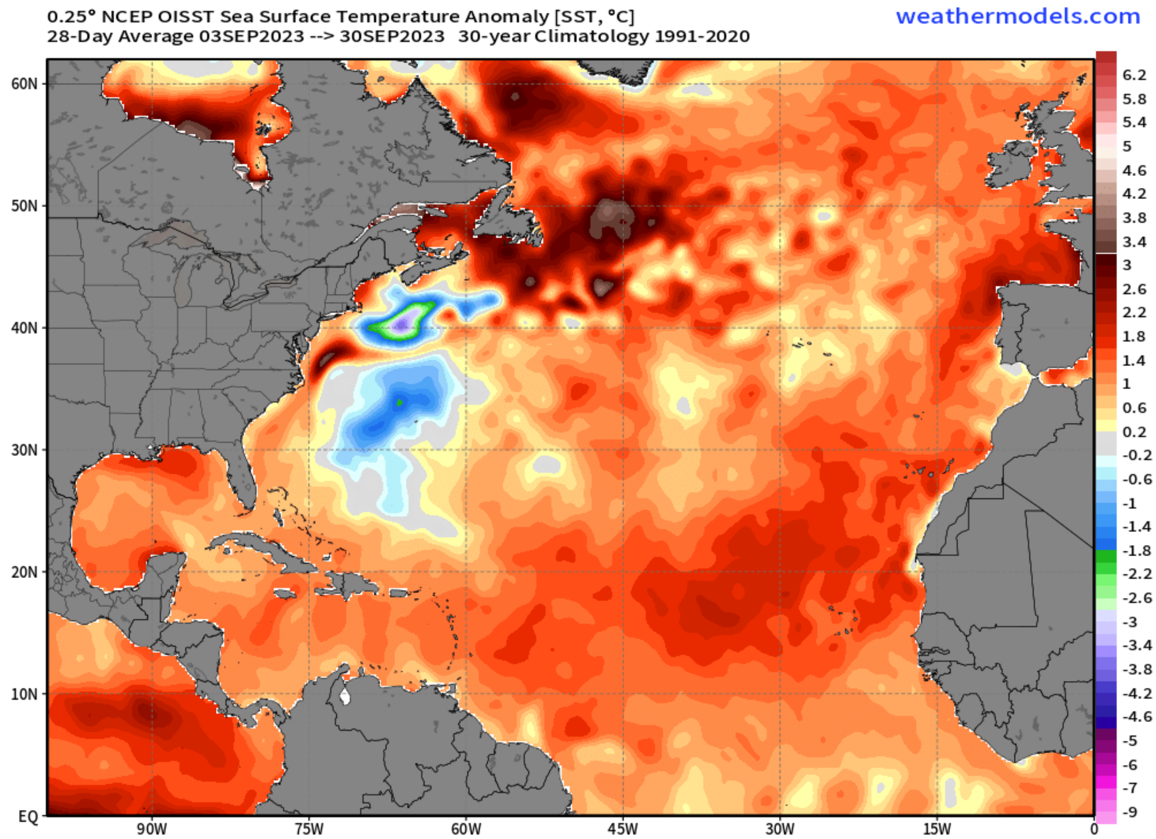


Figure 18: 28-day-averaged SST anomalies ending on 30 September.

6.4 Tropical Atlantic Sea Level Pressure

Tropical Atlantic sea level pressure values are another important parameter to consider when evaluating likely TC activity in the Atlantic basin. In general, lower sea level pressures across the tropical Atlantic imply increased instability, increased low-level moisture, and conditions that are generally favorable for TC development and intensification. Generally, when El Niño conditions are present, the MDR has higher than normal sea level pressures due to anomalous subsidence associated with the eastward-shifted Walker Circulation (Figure 19). August–October 2023, however, had the lowest SLPs on record across the MDR (Figure 20), likely due to the extremely warm Atlantic creating a favorable thermodynamic environment for increased instability, upward vertical motion and associated lower pressure.

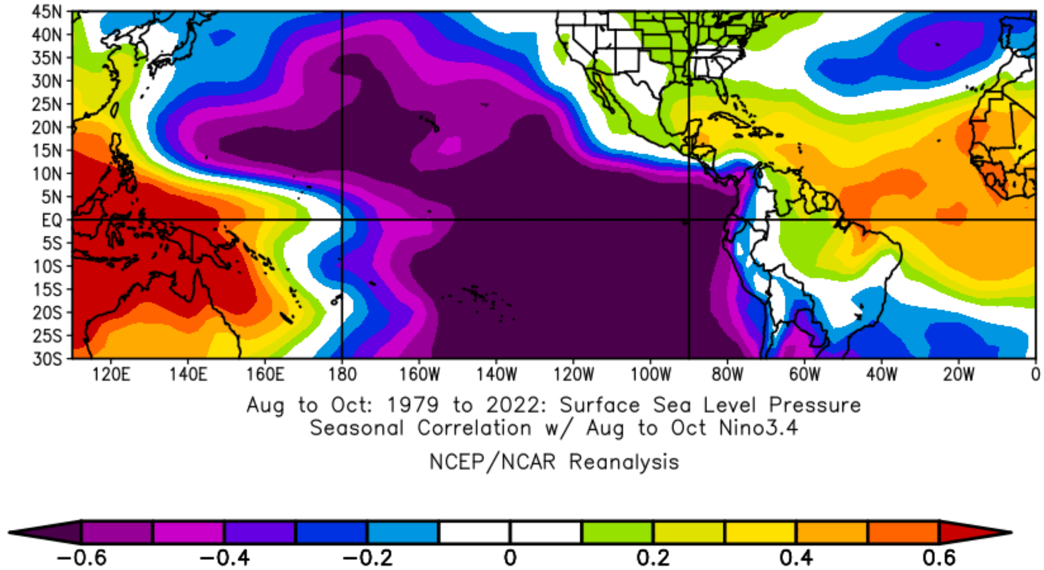


Figure 19: August–October correlation between sea level pressures and the Nino 3.4 index.

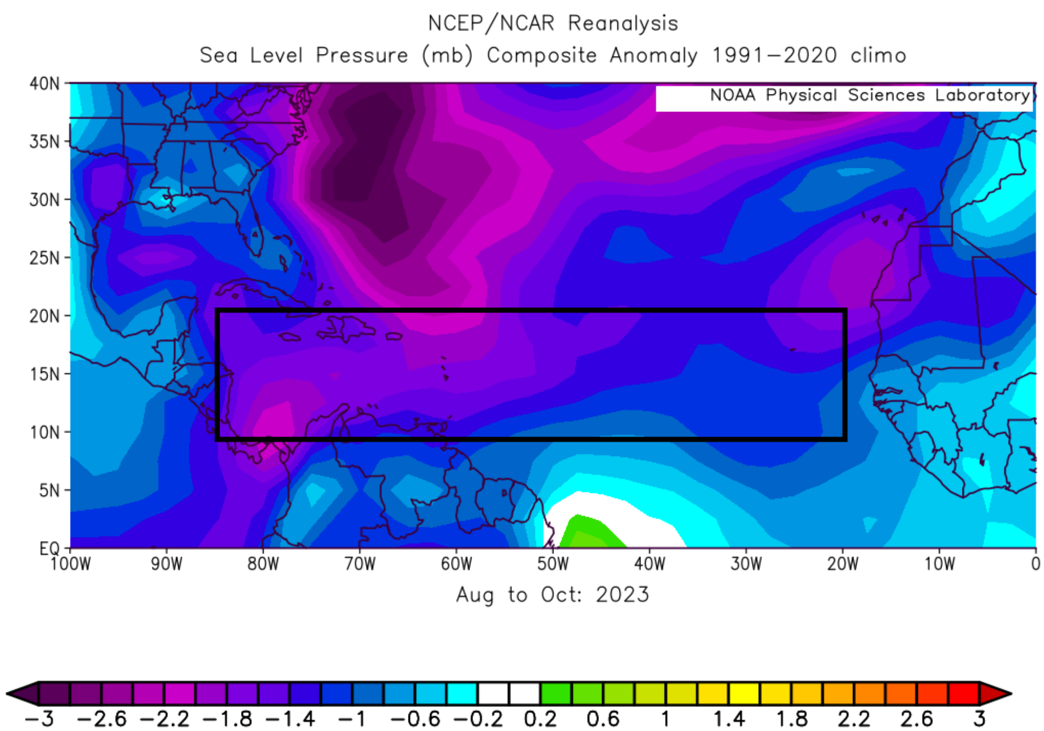


Figure 20: August–October 2023 tropical and sub-tropical North Atlantic sea level pressure anomalies. The black box denotes the MDR.

6.5 Tropical Atlantic Vertical Wind Shear

During August through October, wind shear anomalies were much lower than what would be expected in an El Niño year (Figure 21). Typically El Niño increases vertical wind shear, especially in the Caribbean, while in 2023, vertical wind shear averaged below normal across most of the Caribbean. Figure 22 displays a scatterplot between August–October-averaged shear across the western Atlantic (10–20°N, 85–50°W) and the August–October-averaged Nino 3.4 index, highlighting how typically El Niño is associated with increased vertical wind shear in the western Atlantic. This scatterplot also highlights how far off the typical wind shear-El Niño relationship 2023 was, likely due to the extremely warm Atlantic favoring anomalous upward motion over the Atlantic. August-October-averaged zonal vertical wind shear in 2023 was the sixth lowest on record (since 1979), trailing in order from the lowest: 2010, 2005, 2020, 1995 and 1999.

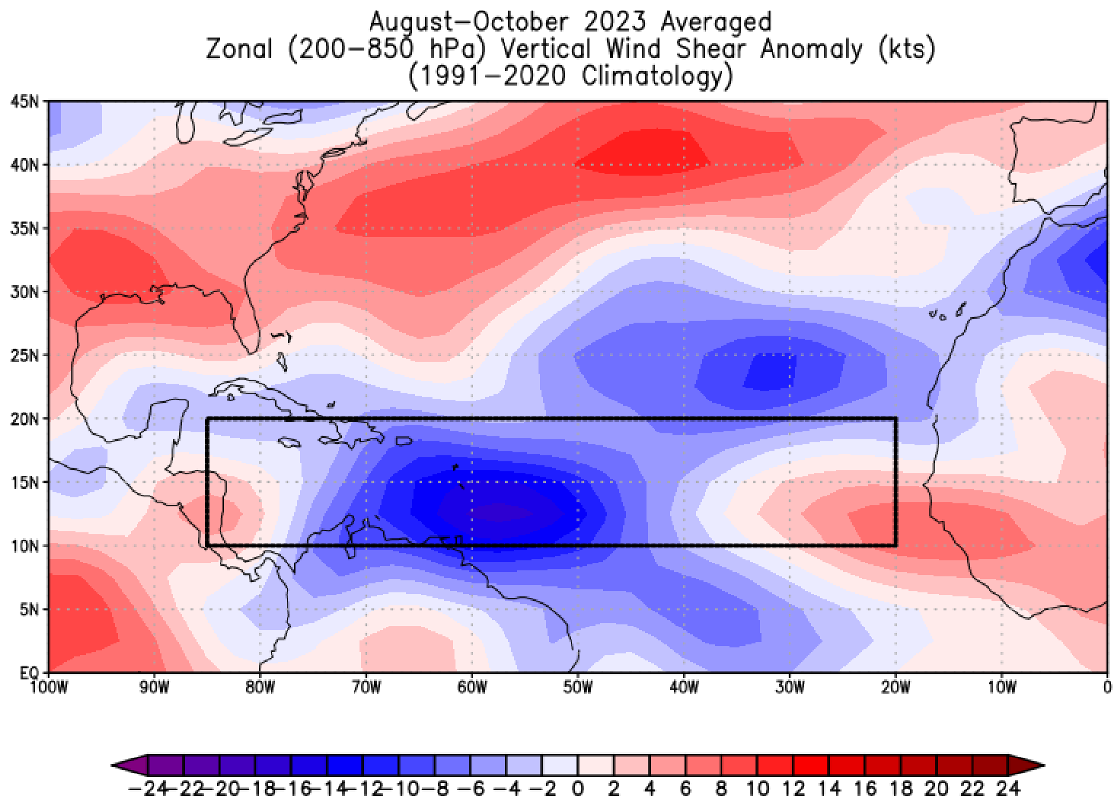


Figure 21: Anomalous vertical wind shear observed across the Atlantic from August to October 2023. The black box denotes the western Atlantic, defined to be 10–20°N, 85–50°W.

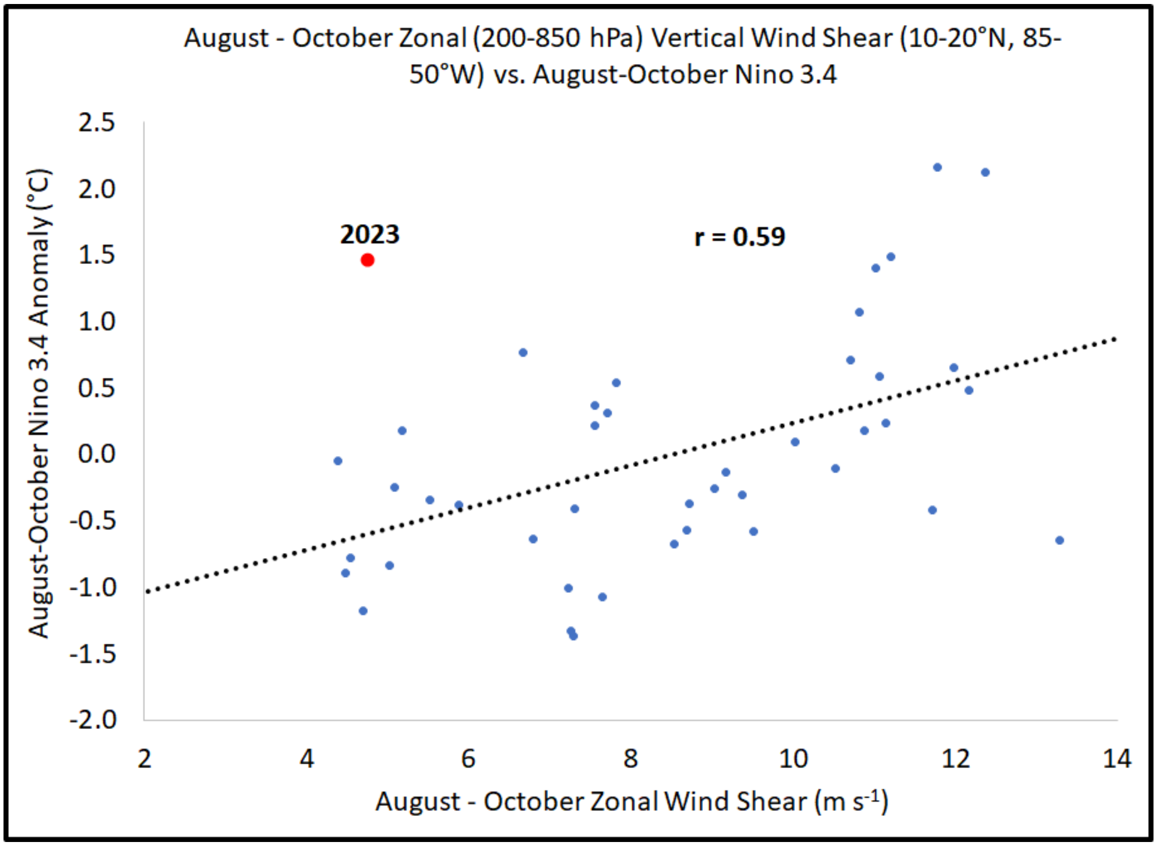


Figure 22: Relationship between the August–October-averaged Nino 3.4 index and August–October-averaged zonal wind shear in the western Atlantic.

7 Brief Analysis of August, September and October 2023 Large-Scale Conditions

Here we analyze the peak three months of the Atlantic hurricane season (August–October) individually to better understand why TC activity behaved the way that it did during these three months.

7.1 August 2023 Analysis

August started out slowly from a TC perspective, with no named storm formations until 20 August. From 20 August – 31 August, however, six named storms and two hurricanes (Franklin and Idalia) formed. Vertical wind shear was near average when averaged across the entire MDR from 1 – 19 August, although high shear in the eastern MDR likely suppressed TC formation during that time period (Figure 23). On the other hand, vertical wind shear was generally below average across the MDR from 20 – 31 August (Figure 24). Anomalous subsidence also began to develop over the tropical eastern and central Pacific in late August (Figure 25), helping to generate upper-level easterly anomalies. The more favorable shear anomalies, as well as climatologically more favorable large-scale conditions in late August than in early August are the likely reasons why the season picked up substantially towards the end of the month.

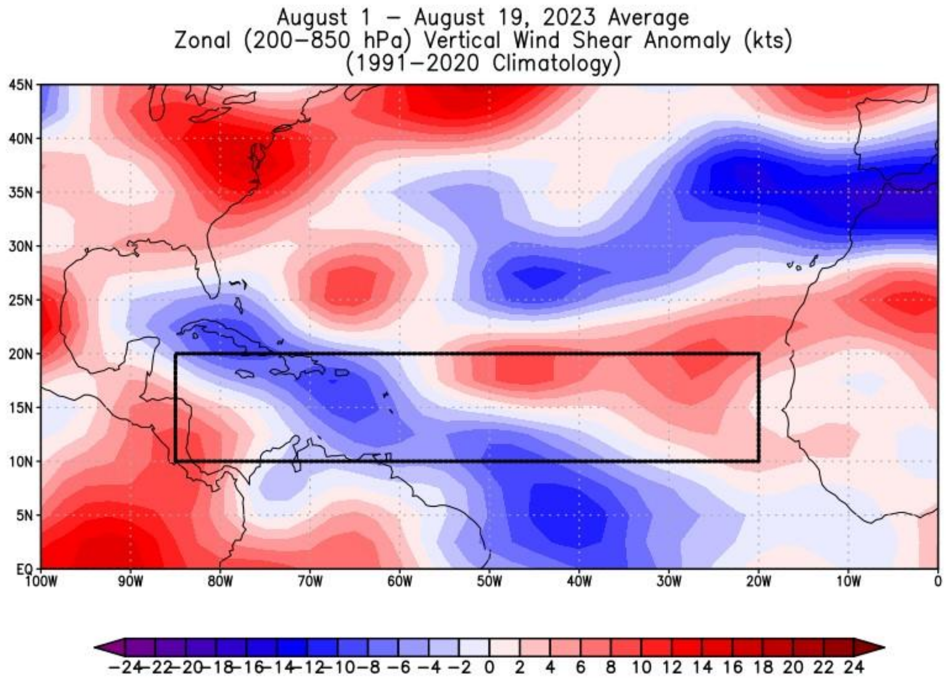


Figure 23: Anomalous vertical wind shear observed across the Atlantic from August 1 – 19. The black box highlights the Main Development Region for Atlantic TCs, defined to be 10–20°N, 85–20°W.

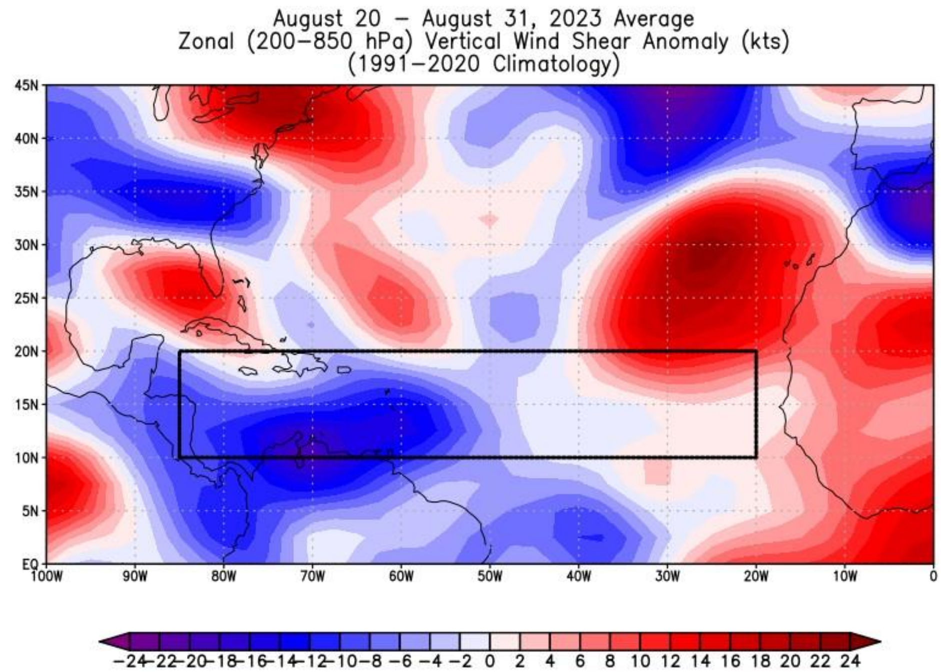


Figure 24: Anomalous vertical wind shear observed across the Atlantic from August 20 – 31. The black box highlights the Main Development Region for Atlantic TCs, defined to be 10–20°N, 85–20°W.

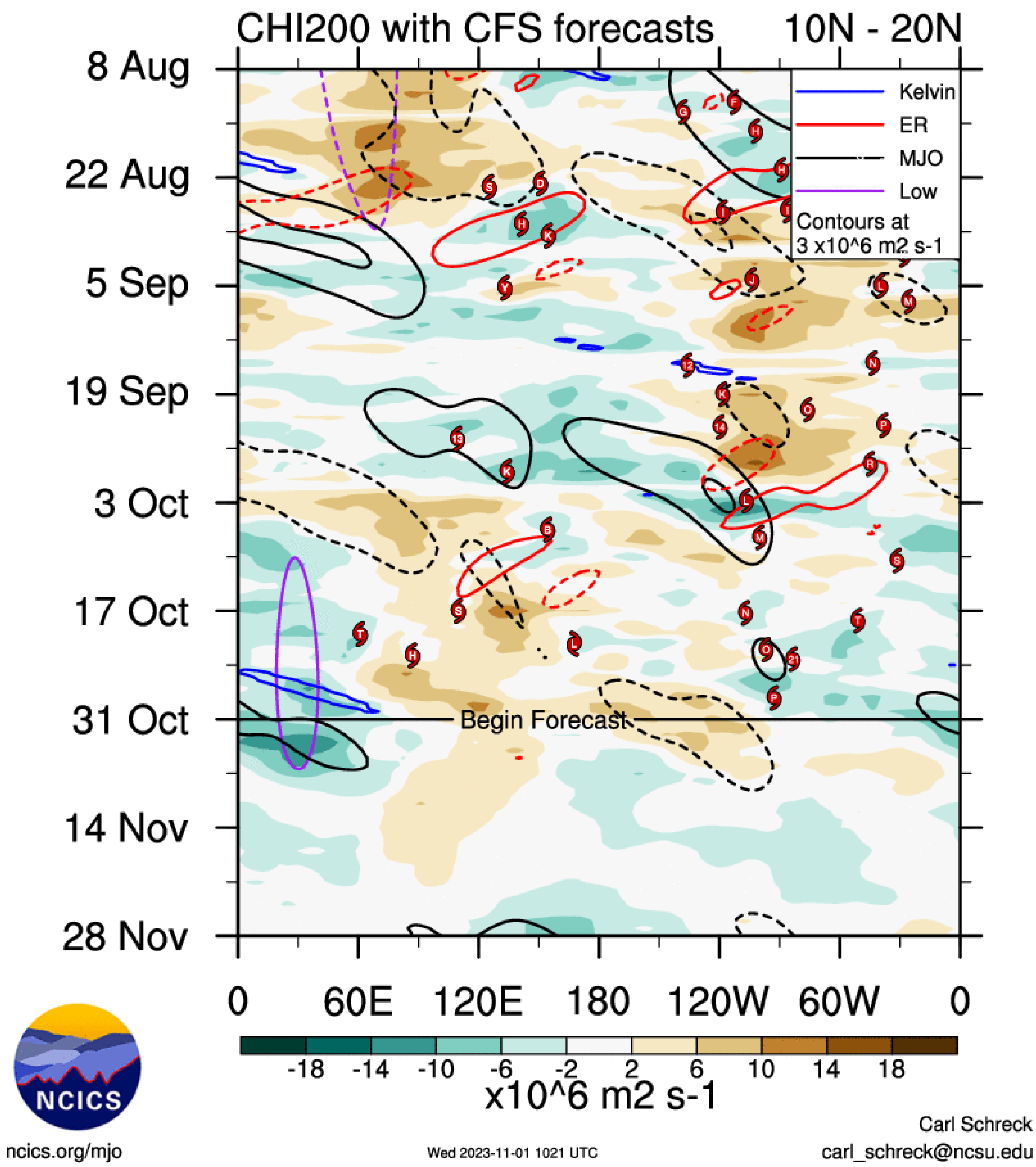


Figure 25: 200 hPa velocity potential anomalies averaged from 10–20°N from early August through late October, with Climate Forecast System predicted OLR anomalies for November also displayed. Figure courtesy of Carl Schreck.

7.2 September 2023 Analysis

September 2023 had above-average Atlantic TC activity by most metrics, with seven named storms, three hurricanes and one major hurricane occurring. ACE was also above average during September (Figure 10). As would be expected given the above-average activity, vertical wind shear was below-average across most of the tropical

Atlantic during September (Figure 26). Elevated vertical wind shear was present in the western Caribbean, however, which is likely why no TCs formed in or tracked through the western Caribbean during the month.

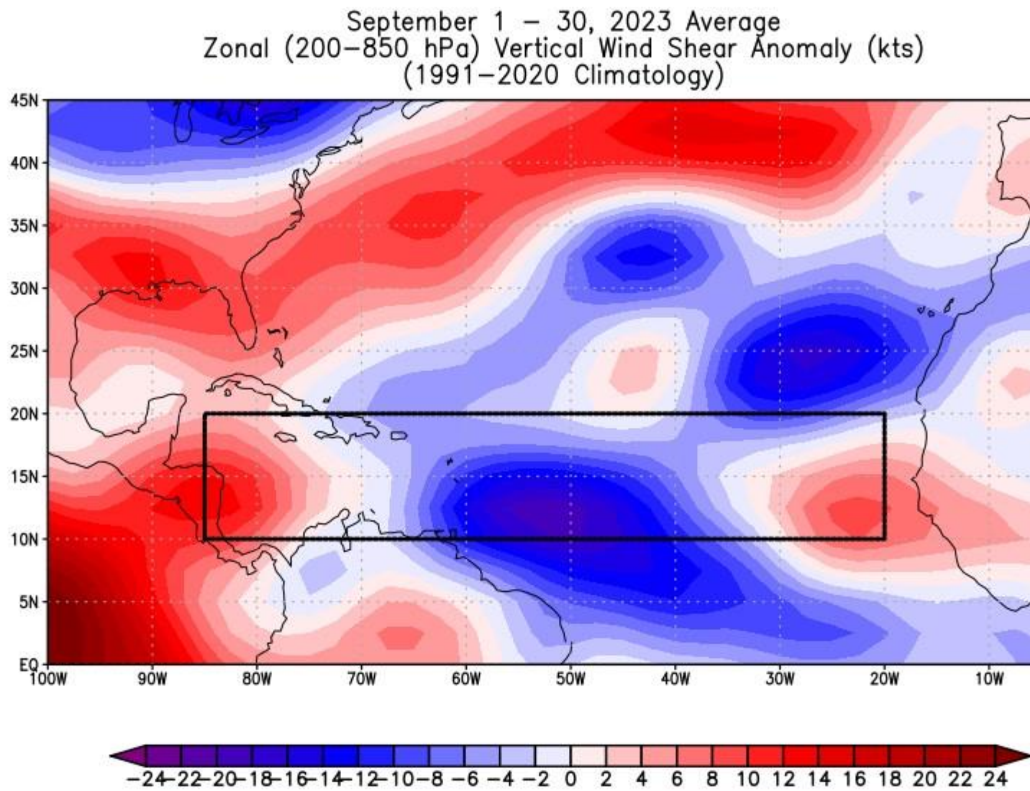


Figure 26: Anomalous vertical wind shear observed across the Atlantic in September 2023. The black box highlights the Main Development Region for Atlantic TCs, defined to be 10–20°N, 85–20°W.

Vertical motion during September (as inferred from upper-level velocity potential) was broadly characterized by rising motion for the Maritime Continent and Central Pacific with sinking motion maximized in the far eastern North Pacific as well as the Caribbean (Figure 27). The large-scale circulation associated with this anomalous vertical motion pattern tends to reduce vertical wind shear across the eastern and central tropical Atlantic. The anomalous sinking motion over the Caribbean is likely another reason why September did not witness any TC activity in the Caribbean.

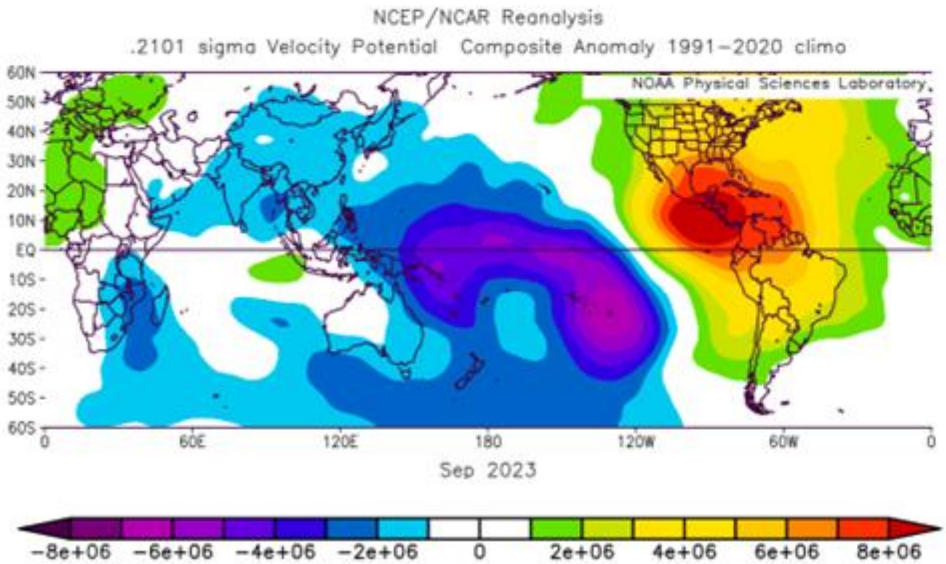


Figure 27: Anomalous ~200 hPa velocity potential anomalies in September 2023. Negative upper-level velocity potential anomalies generally indicate upward motion.

7.3 October 2023 Analysis

October 2023 had near-average activity, with two named storms forming during the month (Sean and Tammy). Tammy was a relatively long-lived hurricane, generating ~75% of the Accumulated Cyclone Energy that occurred during the month. Vertical wind shear was generally below average during October (Figure 28), which favored Tammy's trek across the tropical and subtropical Atlantic.

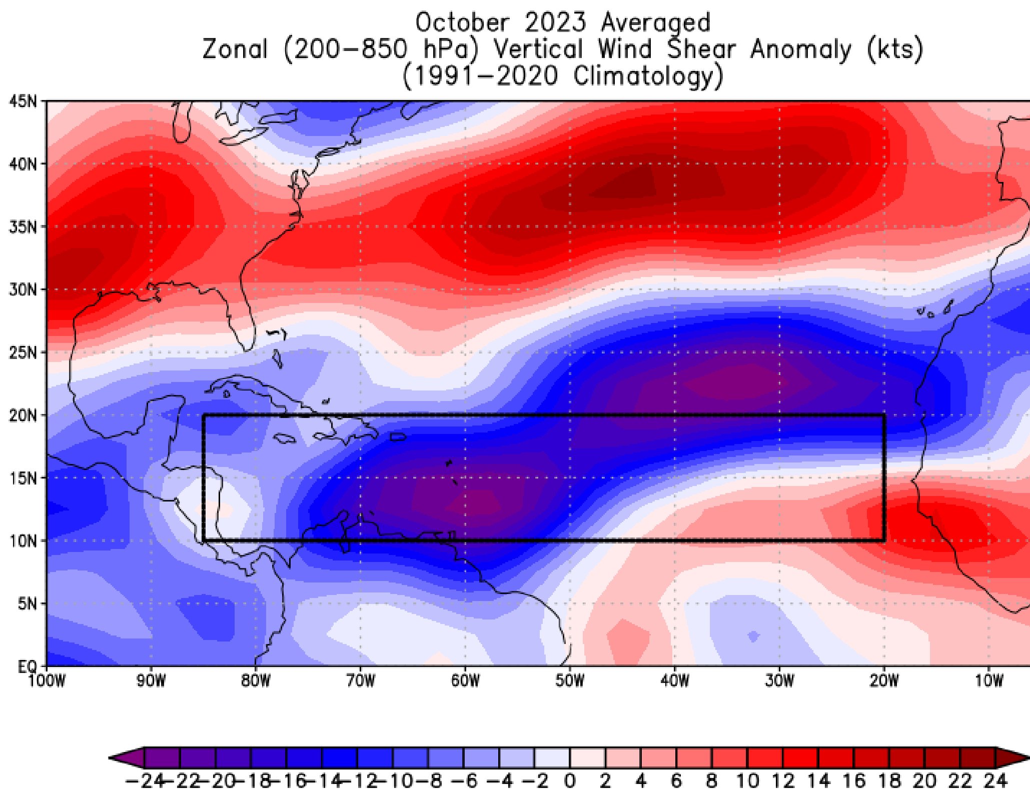


Figure 28: Anomalous vertical wind shear observed across the Atlantic in October 2023. The black box highlights the Main Development Region for Atlantic TCs, defined to be 10–20°N, 85–20°W.

Despite the relatively favorable wind conditions, enhanced vertical motion over the eastern North Pacific (Figure 25) resulted in increased subsidence over the Caribbean. This led to a relatively dry mid-level environment (Figure 29), which is likely why we did not see any storm formations in the Caribbean. The Caribbean is typically favored for late season Atlantic hurricane activity.

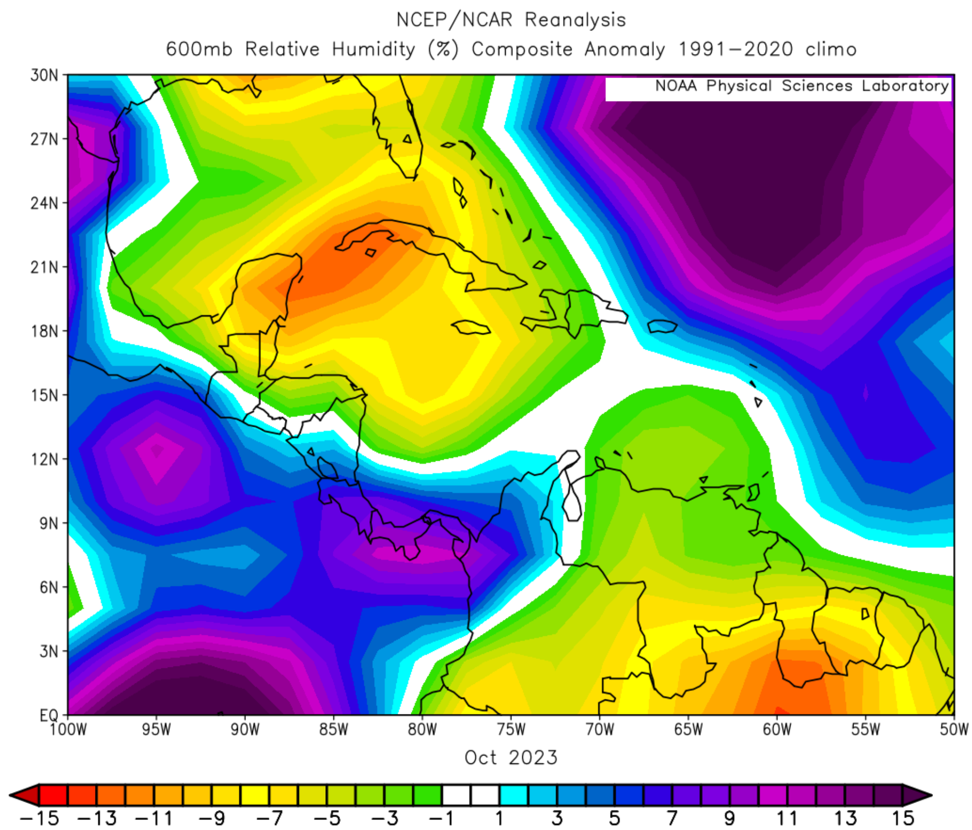


Figure 29: October 600 hPa relative humidity anomalies across the western Atlantic.

8 Forecasts of 2024 Hurricane Activity

We will be issuing our first outlook for the 2024 hurricane season on Thursday, 4 April 2024. This April forecast will include the dates of all our updated 2024 forecasts. All these forecasts will be made available online.

8 Verification of Previous Forecasts

Figure 30 displays the observed versus predicted real-time CSU August seasonal named storm forecasts from 1984–2023. The forecast correlates with observations at 0.79, indicating that CSU's August seasonal named storm forecast can explain ~60% of the variance in observed Atlantic named storm counts.

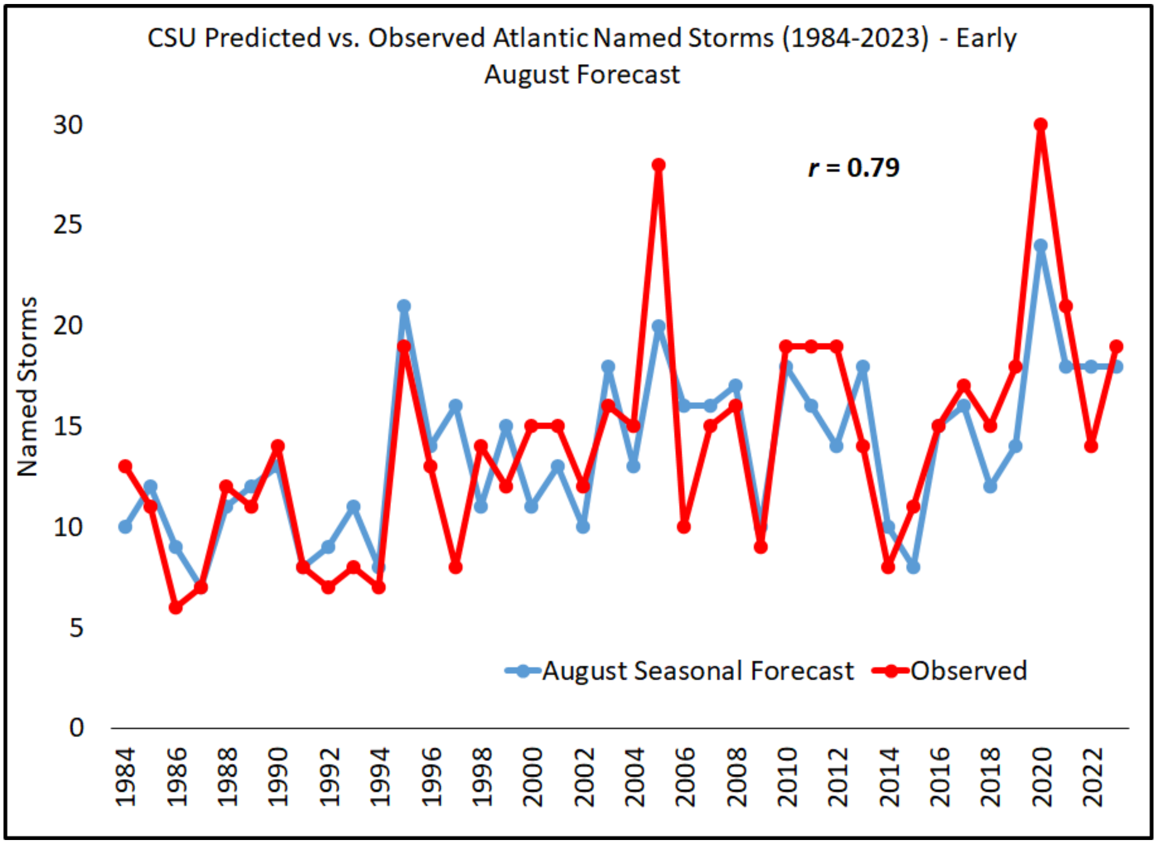


Figure 30: Observed versus predicted Atlantic named storms from 1984–2023.

CSU's seasonal hurricane forecasts have generally shown considerable improvement in recent years, likely due to a combination of improved physical understanding, adoption of statistical/dynamical models and more reliable reanalysis products. Figures 31 and 32 display correlations between observed and predicted Atlantic hurricanes and ACE from 1984–2013, from 2014–2023 and from 1984–2023, respectively. Correlation skill has improved at all lead times in recent years for hurricanes, with the most noticeable improvements at longer lead times. More modest improvements in skill have occurred for ACE. While ten years is a relatively short sample size, improvements in both modeling and physical understanding should continue to result in future improvements in seasonal Atlantic hurricane forecast skill.

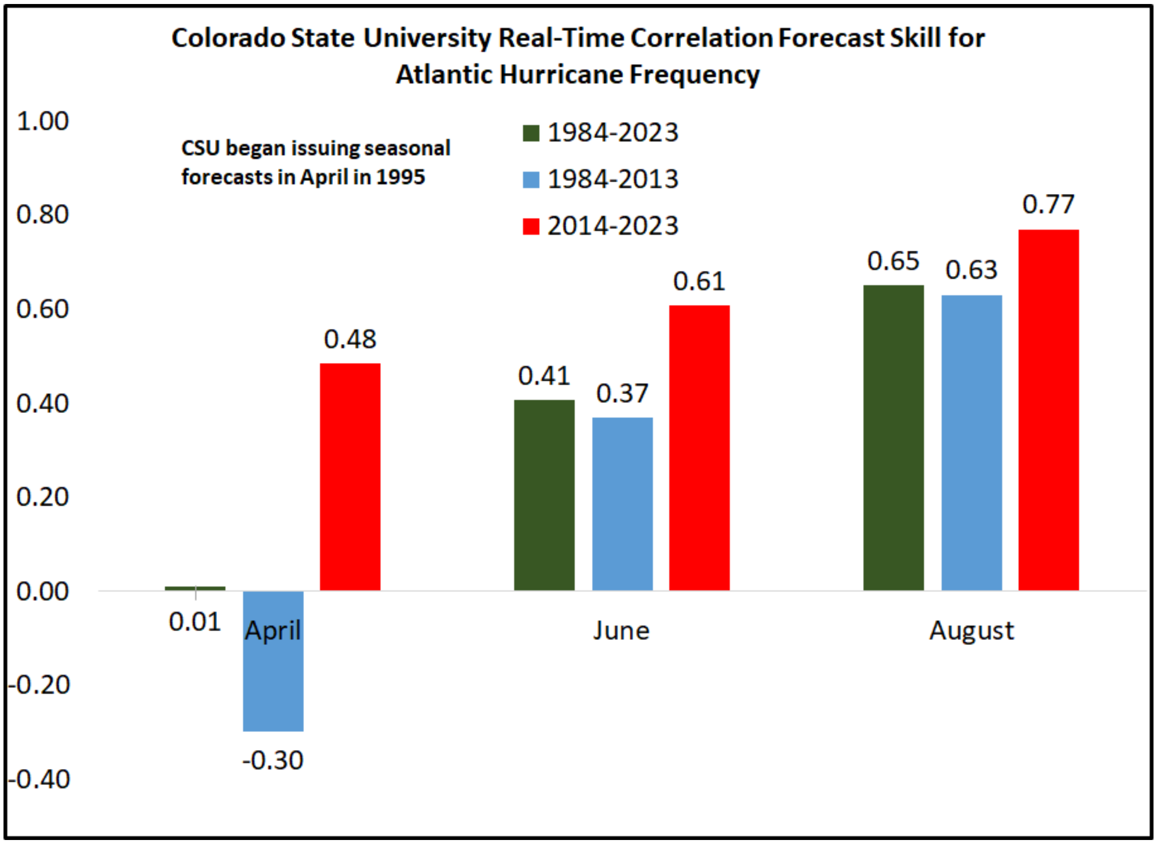


Figure 31: CSU's real-time forecast skill for Atlantic hurricanes using correlation as the skill metric. Correlation skills are displayed for three separate time periods: 1984–2013, 2014–2023 and 1984–2023, respectively.

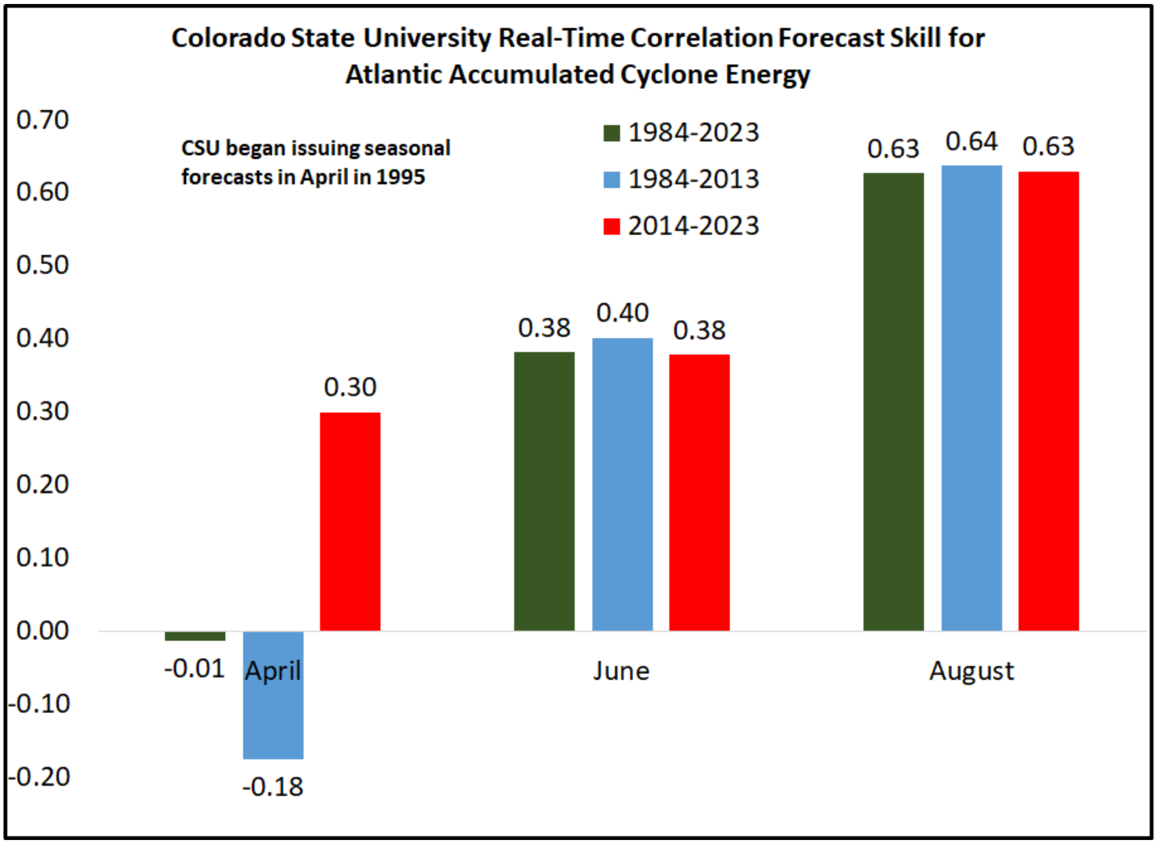


Figure 32: CSU's real-time forecast skill for Atlantic ACE using correlation as the skill metric. Correlation skills are displayed for three separate time periods: 1984–2013, 2014–2023 and 1984–2023, respectively.