# SUMMARY OF 2024 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF AUTHORS' SEASONAL AND TWO-WEEK FORECASTS

The 2024 Atlantic hurricane season was a hyperactive season based on NOAA's definition, with hurricanes and major hurricanes well above the 1991–2020 average. Our seasonal hurricane forecasts issued in 2024 were generally a modest over forecast of activity that occurred. The season's most significant continental US hurricanes were Hurricanes Helene and Milton, which devastated the southeast US. The record warm Atlantic combined with cool neutral ENSO led to broadly hurricane-favorable conditions in 2024, although with a marked peak season lull in activity.

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In Memory of William M. Gray[6]

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

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As of 26 November 2024

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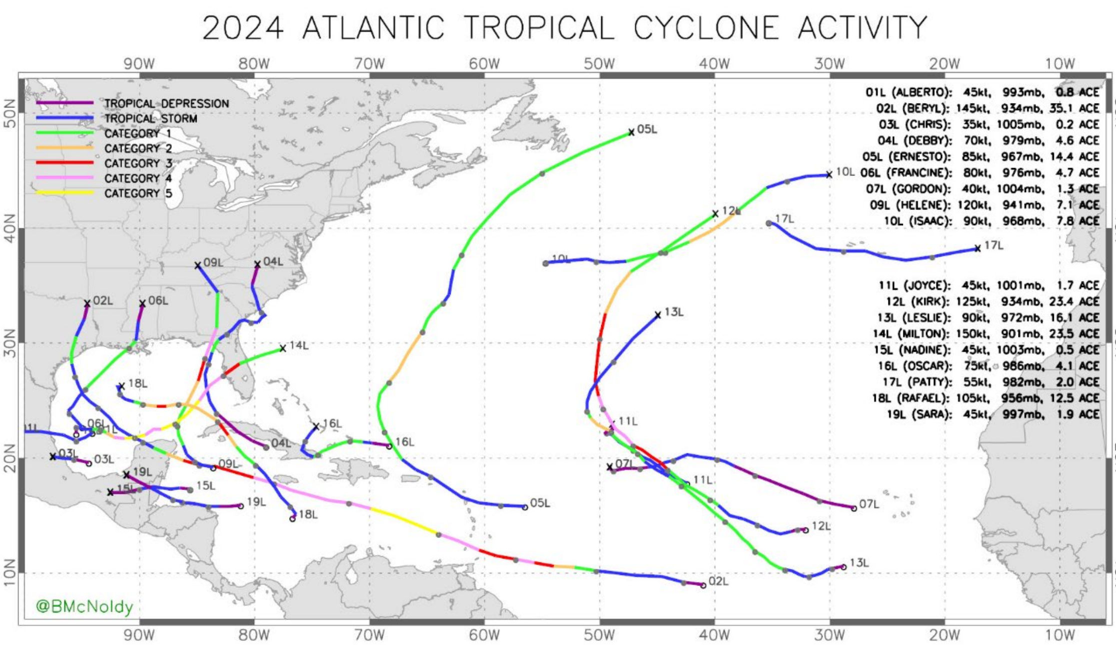
## ATLANTIC BASIN SEASONAL HURRICANE FORECASTS FOR 2024

| Forecast Parameter and 1991–2020 Average (in parentheses) | Issue Date 4 April 2024 | Issue Date 11 June 2024 | Issue Date 9 July 2024 | Issue Date 6 August 2024 | **Observed 2024 Activity Thru 11/26** | % of 1991–2020 Average |
|---|---|---|---|---|---|---|
| Named Storms (NS) (14.4) | 23 | 23 | 25 | 23 | **18** | 125% |
| Named Storm Days (NSD) (69.4) | 115 | 115 | 120 | 120 | **77.25** | 111% |
| Hurricanes (H) (7.2) | 11 | 11 | 12 | 12 | **11** | 153% |
| Hurricane Days (HD) (27.0) | 45 | 45 | 50 | 50 | **37.50** | 139% |
| Major Hurricanes (MH) (3.2) | 5 | 5 | 6 | 6 | **5** | 156% |
| Major Hurricane Days (MHD) (7.4) | 13 | 13 | 16 | 16 | **11.50** | 155% |
| Accumulated Cyclone Energy (ACE) (123) | 210 | 210 | 230 | 230 | **162** | 132% |
| ACE West of 60°W (73) | 125 | 125 | 140 | 140 | **100** | 137% |
| Net Tropical Cyclone Activity (NTC) (135%) | 220 | 220 | 240 | 240 | **189** | 140% |




2024 Atlantic basin tropical cyclone tracks through 26 November. 18 named storms, 11 hurricanes and 5 major hurricanes occurred. Figure courtesy of Brian McNoldy (University of Miami).

ABSTRACT

This report summarizes tropical cyclone (TC) activity which occurred in the Atlantic basin during 2024 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 over-estimated late-season Caribbean storm activity.

The first quantitative seasonal forecast for 2024 was issued on 4 April with updates on 11 June, 9 July and 6 August. These seasonal forecasts also contained estimates of the probability of US and Caribbean hurricane landfall during 2024. We also continued to forecast Accumulated Cyclone Energy (ACE) west of 60°W. This metric successfully forecast a higher percentage of overall ACE west of 60°W relative to basinwide ACE.

The 2024 hurricane season was officially an extremely active, or hyperactive, hurricane season based on NOAA's Accumulated Cyclone Energy (ACE) definition (e.g., >159.6 ACE). Named storm days were slightly above their long-term average, while all other metrics were well above their long-term averages.

Our April and June seasonal forecasts performed best for all metrics. The slight increase in overall activity that we predicted with our July and August updates did not verify. We characterize our forecasts for 2024 as a modest over-forecast of overall activity.

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 phases. The forecasts predicted whether the upcoming two-week period would be in the above-normal, normal, or below-normal tercile (e.g., top third, middle third or bottom third of the distribution). These forecasts predicted the tercile with the highest probability in 4 out of the 6 outlooks that were issued.

Cool neutral ENSO conditions prevailed throughout the 2024 Atlantic hurricane season. These cool neutral ENSO conditions favored below-normal tropical Atlantic and Caribbean vertical wind shear. Vertical wind shear during August–October of 2024 was the lowest on record.

Tropical Atlantic sea surface temperatures were at near record warm levels during the peak of the 2024 hurricane season. These anomalously warm waters helped fuel the hyperactive season that occurred.

While the season ended up hyperactive, there was a marked lull in activity that occurred between 20 August – 23 September. This period is typically the peak of the

Atlantic hurricane season. The lull was likely due to a combination of factors including a northward shift in easterly wave activity and associated increased dry air advection, anomalously warm upper-level temperatures, too much easterly shear in the eastern/central Atlantic and TC-unfavorable MJO phases during the early to middle part of September.

In addition to being a hyperactive season, it was extremely busy for continental US hurricane landfalls, with five hurricanes making landfall during the season: Beryl, Debby, Francine, Helene and Milton. Helene and Milton made landfall ~12 days apart and devastated the southeast US, causing over 250 fatalities and a preliminary estimate of ~$100 billion USD 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. ACE is often calculated over a season to reflect overall storm activity that year. 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.

ENSO Longitude Index (ELI) – 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.

Oceanic Nino Index (ONI) – Three-month running mean of SST anomalies in the Nino 3.4 region (5°S–5°N, 170–120°W) based on centered 30-year base periods.

Saffir/Simpson Hurricane Wind Scale – A measurement scale ranging from 1 to 5 of hurricane wind intensity. One is a weak hurricane; whereas, five is the most intense hurricane.

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) – Observed sea surface temperature differenced from a long-period average, typically 1991–2020 which is the current NOAA climate baseline.

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 Commodity Weather Group, Gallagher Re, the Insurance Information Institute, Ironshore Insurance, IAA, and Weatherboy. 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. Thanks also extend to several current members of Michael Bell's research group who have provided valuable comments and feedback throughout the forecast preparation process. These members include: Tyler Barbero, Delián Cólon Burgos, Jen DeHart, Nick Mesa, Angelie Nieves-Jiménez and Isaac Schluesche.

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 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 2024, these predictions used the 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 Quasi-biennial oscillation and West African rainfall. These precursor signals have not worked as well 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 be revised in future years. 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

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 2024

Figure 1 and Table 1 summarize Atlantic basin TC activity that occurred in 2024. Overall, the season was "extremely active", or "hyperactive", per NOAA's definition (>159.6 Accumulated Cyclone Energy (ACE); Table 2), with well above-normal values for all parameters other than named storm days. The National Hurricane Center is currently in the process of writing up extensive reports on all 2024 TCs.

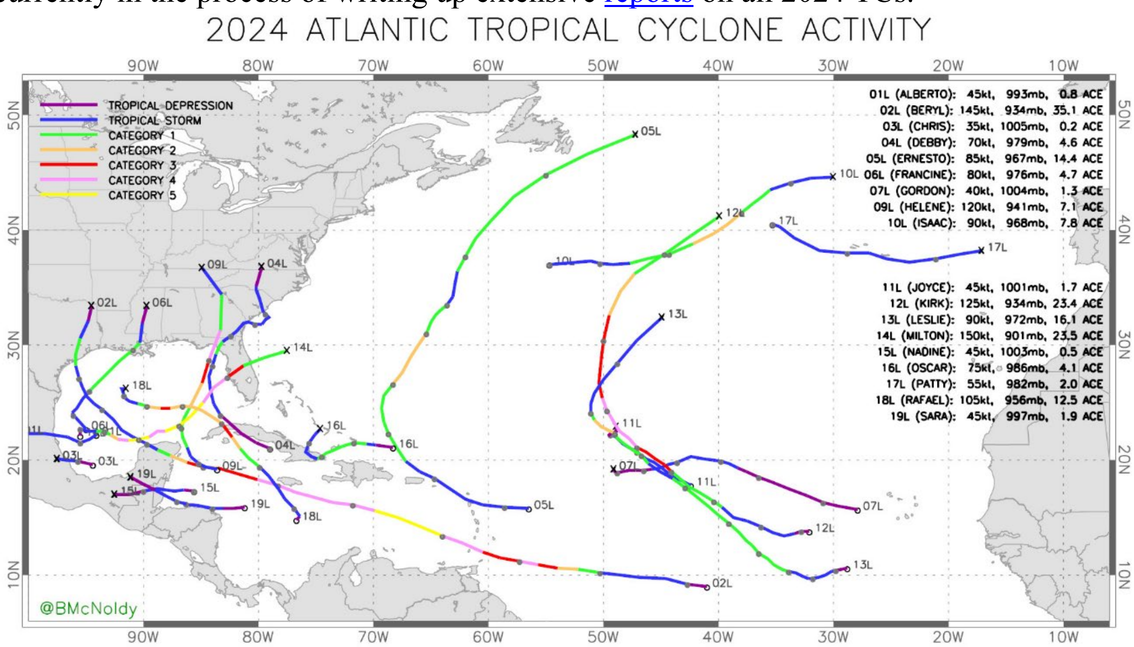



Figure 1: 2024 Atlantic basin TC tracks through 26 November. 18 named storms, 11 hurricanes and 5 major hurricanes occurred. Figure courtesy of Brian McNoldy (University of Miami).

Table 1: Observed 2024 Atlantic basin TC activity through 26 November. 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 2024

| Year | Storm# | Name | Dates TC Active | Max Wind (kts) | MSLP (mb) | Named Storm Days | Hurricane Days | Major Hurricane Days | Accumulated Cyclone Energy |
|---|---|---|---|---|---|---|---|---|---|
| 2024 | 1 | ALBERTO | 6/19-6/20 | 45 | 993 | 1.25 | 0.00 | 0.00 | 0.8 |
| 2024 | 2 | BERYL | 6/29-7/8 | 145 | 934 | 10.00 | 6.25 | 4.50 | 35.1 |
| 2024 | 3 | CHRIS | 7/1-7/1 | 35 | 1005 | 0.50 | 0.00 | 0.00 | 0.2 |
| 2024 | 4 | DEBBY | 8/4-8/8 | 70 | 979 | 5.00 | 0.50 | 0.00 | 4.6 |
| 2024 | 5 | ERNESTO | 8/12-8/20 | 85 | 967 | 7.75 | 5.25 | 0.00 | 14.4 |
| 2024 | 6 | FRANCINE | 9/9-9/12 | 85 | 972 | 3.00 | 1.25 | 0.00 | 4.7 |
| 2024 | 7 | GORDON | 9/13-9/15 | 40 | 1004 | 2.25 | 0.00 | 0.00 | 1.3 |
| 2024 | 8 | HELENE | 9/24-9/27 | 120 | 938 | 3.25 | 2.00 | 0.50 | 7.1 |
| 2024 | 9 | ISAAC | 9/26-9/30 | 90 | 968 | 4.50 | 2.25 | 0.00 | 7.8 |
| 2024 | 10 | JOYCE | 9/27-9/29 | 45 | 1001 | 2.50 | 0.00 | 0.00 | 1.7 |
| 2024 | 11 | KIRK | 9/30-10/7 | 125 | 934 | 7.25 | 5.75 | 3.25 | 23.4 |
| 2024 | 12 | LESLIE | 10/3-10/12 | 90 | 972 | 9.50 | 5.50 | 0.00 | 16.1 |
| 2024 | 13 | MILTON | 10/5-10/10 | 155 | 897 | 5.00 | 4.00 | 2.75 | 23.5 |
| 2024 | 14 | NADINE | 10/19-10/19 | 45 | 1003 | 0.75 | 0.00 | 0.00 | 0.5 |
| 2024 | 15 | OSCAR | 10/19-10/22 | 75 | 986 | 3.25 | 1.50 | 0.00 | 4.1 |
| 2024 | 16 | PATTY | 11/2-11/4 | 55 | 982 | 2.50 | 0.00 | 0.00 | 2.0 |
| 2024 | 17 | RAFAEL | 11/4-11/10 | 105 | 956 | 6.00 | 3.25 | 0.50 | 12.5 |
| 2024 | 18 | SARA | 11/14-11/17 | 45 | 997 | 3.00 | 0.00 | 0.00 | 1.9 |

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 2024 Hurricane Season

The 2024 hurricane season ended up a hyperactive season, with several records being set over the course of the year. Most statistics displayed below are from the National Hurricane Center's operational best track.

Below is a selection of some of the notable statistics from the 2024 season:

*Seasonal Statistics*

- 11 hurricanes formed in the Atlantic. 2024 tied with 1995 for 5th place for most hurricanes produced in the satellite era (1966–onwards).

- 5 major hurricanes formed in the Atlantic. 2024 tied with 1995, 1999, 2008 and 2010 for 6th place for major hurricanes produced in the satellite era (1966–onwards).

- 5 hurricanes made landfall in the continental US (Beryl, Debby, Francine, Helene and Milton). 2024 tied with 1893, 2004 and 2005 for the 2nd-most continental US hurricane landfalls in a season. 1886, 1985 and 2020 had 6 continental US hurricane landfalls.

- 162 ACE was generated during 2024, making the season hyperactive by NOAA's definition. 2024 is the 11th hyperactive season in the satellite era (1966–onwards).

*Intra-Seasonal Statistics*

- 36 ACE were generated by 8 July – the most on record by that date. The prior record through 8 July was 32 ACE set in 1933.

- 3 hurricanes formed in the Atlantic by 14 August. Four other years in the satellite era (1966–onwards) have had 3+ hurricane formations by 14 August: 1966, 1968, 1995, 2005.

- No named storms formed in the Atlantic between 13 August – 8 September. The last time that this occurred was in 1968.

- 7 ACE were generated in the Atlantic between 20 August – 23 September. 2024 produced the least ACE between 20 August – 23 September since 1994.

- 11 named storms formed in the Atlantic since 24 September. 2024 is tied with 2005 for the record for most named storm formations from 24 September – onwards.

- 7 hurricanes formed in the Atlantic since 25 September – the most on record from 25 September – onwards.

- 4 major hurricanes formed in the Atlantic since 26 September – the 2nd most on record from 26 September – onwards. 2024 trails 2020 which produced 5 major hurricanes from 26 September – onwards.

- 100 ACE was generated in the Atlantic since 24 September – the 2nd most on record from 24 September – onwards. 2024 trails 1878 which produced 109 ACE from 24 September – onwards.

*Multi-Storm Statistics*

- Hurricanes Kirk and Leslie both set the easternmost record for hurricane formations in the tropics (<=23.5°N) from October – onwards.

- Kirk, Leslie and Milton were hurricanes simultaneously – the first time on record that the Atlantic has had 3 hurricanes simultaneously from October – onwards.

*Individual Storm/Landfall Statistics*

- Hurricane Beryl became a Category 5 hurricane on 2 July – the earliest forming Atlantic Category 5 hurricane on record. The prior record was Emily (2005) on 17 July.

- Hurricane Beryl intensified by 55 kt 24 $hr^{-1}$ from 29 June (18UTC) – 30 June (UTC) – the most rapid 24-hr intensification by an Atlantic hurricane prior to 1 July on record. The old record was Hurricane Alice (1954) – 45 kt 24 $hr^{-1}$.

- Hurricane Beryl had maximum sustained winds of 145 kt – the strongest Atlantic hurricane prior to August on record. The prior record was Emily (2005; 140 kt).

- Hurricane Beryl made landfall on Carriacou Island, Grenada with maximum sustained winds of 130 kt – the strongest Grenada hurricane landfall on record. Hurricane Ivan (2004) passed ~10 miles south of the main island of Grenada with maximum winds estimated at 110 kt.

- Hurricane Helene (Category 4; 120 kt) was the strongest hurricane to make landfall in the Big Bend on record. The prior record was the Cedar Keys Hurricane of 1896 (Category 3; 110 kt).

- Hurricane Kirk reached hurricane strength at ~40°W on 1 October – the farthest east that an Atlantic hurricane had formed in the tropical Atlantic (<=23.5°N) from October – onwards on record. Old record was ~59°W set by Jose (1999) and then tied by Tammy (2023).

- Hurricane Kirk reached Category 4 intensity at ~47°W, breaking the old record for farthest east a Category 4-5 Atlantic hurricane had occurred on record in October – November. The old record was Sam (2021) at ~60°W.

- Hurricane Leslie reached hurricane strength at ~34°W on 4 October – the farthest east that an Atlantic hurricane had formed in the tropical Atlantic (<=23.5°N) from October – onwards on record, breaking the old record set by Kirk just three days prior.

- Hurricane Milton had maximum sustained winds of 155 kt – the strongest for an Atlantic hurricane since Dorian (2019) and the strongest for a Gulf of Mexico hurricane since Rita (2005).

- Hurricane Milton had a lifetime minimum central pressure of 897 hPa – the lowest for an Atlantic hurricane since Wilma (2005).

- Hurricane Milton intensified by 80 kt 24 $hr^{-1}$ from 6 October (18UTC) – 7 October (18UTC) – the most rapid 24-hr intensification by an Atlantic hurricane since Felix in 2007 (85 kt 24 $hr^{-1}$ ).

- Hurricane Rafael made landfall in Cuba as a major hurricane with maximum sustained winds of 100 kt – the first major hurricane landfall in Cuba in November since Michelle (2001).

- Hurricane Rafael was only the 2nd major hurricane on record in the Gulf of Mexico in November. The other Gulf major hurricane in November was Kate (1985).

# 4 Quantitative Verification of 2024 Atlantic Hurricane Forecasts

## 4.1 Verification of Seasonal Forecasts

Table 3 is a comparison of our forecasts for 2024 for four different lead times along with this year's observations.

Table 3: Verification of our 2024 seasonal hurricane predictions.

| Forecast Parameter and 1991–2020 Average (in parentheses) | Issue Date 4 April 2024 | Issue Date 11 June 2024 | Issue Date 9 July 2024 | Issue Date 6 August 2024 | **Observed 2024 Activity Thru 11/26** |
|---|---|---|---|---|---|
| Named Storms (NS) (14.4) | 23 | 23 | 25 | 23 | **18** |
| Named Storm Days (NSD) (69.4) | 115 | 115 | 120 | 120 | **77.25** |
| Hurricanes (H) (7.2) | 11 | 11 | 12 | 12 | **11** |
| Hurricane Days (HD) (27.0) | 45 | 45 | 50 | 50 | **37.50** |
| Major Hurricanes (MH) (3.2) | 5 | 5 | 6 | 6 | **5** |
| Major Hurricane Days (MHD) (7.4) | 13 | 13 | 16 | 16 | **11.50** |
| Accumulated Cyclone Energy (ACE) (123) | 210 | 210 | 230 | 230 | **162** |
| ACE West of 60°W (73) | 125 | 125 | 140 | 140 | **100** |
| Net Tropical Cyclone Activity (NTC) (135%) | 220 | 220 | 240 | 240 | **189** |

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 61% of all forecast parameters fell within the 70% confidence interval in 2024. Our April and June forecasts predicted activity reasonably well, while the July and August forecasts were slightly more of an over-forecast. We do note that while hurricane and major hurricane numbers were quite close to our predictions, fewer named storms occurred than predicted.

We also successfully predicted a higher percentage of basinwide ACE occurring west of 60°W this season. Cool ENSO neutral and La Niña typically favor more storm formations in the western part of the basin, which was certainly the case in 2024 (Figure 1). Overall ACE west of 60°W was somewhat less than anticipated given basinwide ACE was also somewhat less than anticipated. However, the percentage of observed ACE west of 60°W to total observed ACE in the basin was nearly identical to the percentage predicted in our forecasts. Our forecast ACE west of 60°W was 60–61% of basinwide ACE depending on the forecast, while observed ACE west of 60°W was 62% of basinwide ACE. For our seasonal forecasts, ACE west of 60°W is calculated on an ENSO-weighted percentage of basinwide ACE, with La Niña typically producing higher ACE west of 60°W than El Niño.

Table 4: Verification of CSU's 2024 seasonal hurricane predictions with 70% confidence intervals.

| Forecast Parameter and 1991–2020 Average (in parentheses) | Issue Date 4 April 2024 | Issue Date 11 June 2024 | Issue Date 9 July 2024 | Issue Date 6 August 2024 | Observed 2024 Activity Thru 11/26 |
|---|---|---|---|---|---|
| Named Storms (NS) (14.4) | 19 – 27 | 20 – 27 | 22 – 28 | 20 – 26 | 18 |
| Named Storm Days (NSD) (69.4) | 91 – 130 | 93 – 130 | 104 – 146 | 101 – 130 | 77.25 |
| Hurricanes (H) (7.2) | **8 – 14** | **9 – 14** | **10 – 14** | **10 – 14** | 11 |
| Hurricane Days (HD) (27.0) | **30 – 61** | **31 – 60** | **37 – 64** | **37 – 63** | 37.50 |
| Major Hurricanes (MH) (3.2) | **3 – 7** | **3 – 7** | **4 – 7** | **4 – 7** | 5 |
| Major Hurricane Days (MHD) (7.4) | **8 – 20** | **8 – 20** | **11 – 23** | **11 – 22** | 11.50 |
| Accumulated Cyclone Energy (ACE) (123) | **151 – 260** | **154 – 260** | 176 – 260 | 180 – 260 | 162 |
| ACE West of 60°W (73) | **83 – 172** | **86 – 169** | 101 – 183 | 104 – 180 | 100 |
| Net Tropical Cyclone Activity (NTC) (135%) | **164 – 279** | **167 – 275** | 190 – 285 | 193 – 280 | 189 |

### 4.2 Verification of Two-Week Forecasts

This is the 16th 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, and 4) the current and projected state of the MJO (Figure 2). Figure 2 displays MJO propagation from 1 August to 19 November. In general, the MJO was relatively favorable for Atlantic TC activity during most of August (e.g., phases 8–3), which is why the overall lack of activity generated in August was surprising. Typically phases 8–3 are associated with reduced vertical wind shear and increased mid-level moisture, both of which favor Atlantic hurricane activity.

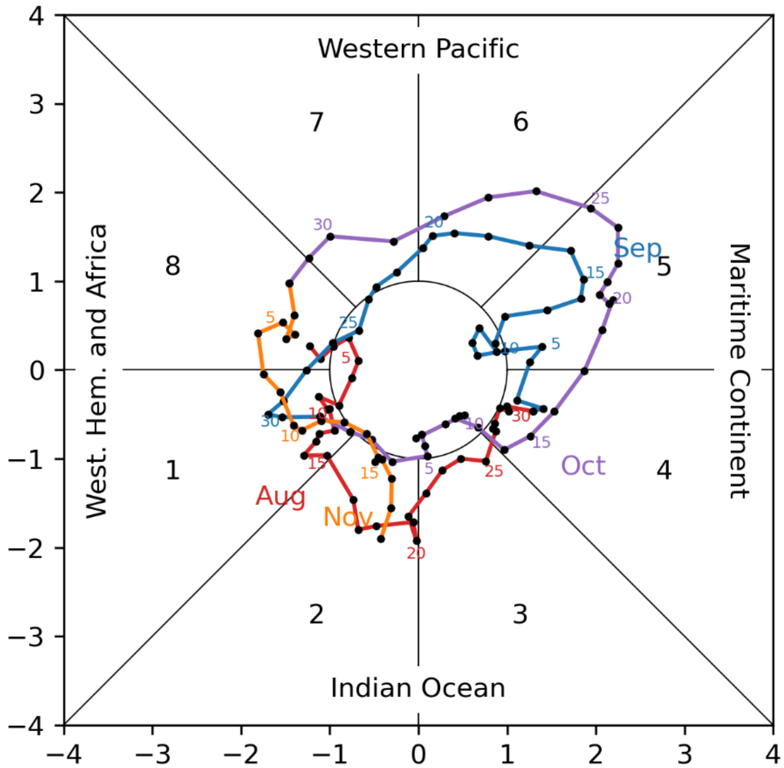



Figure 2: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from 1 August to 19 November. The Maritime Continent refers to Indonesia and the surrounding islands. RMM stands for Real-Time Multivariate MJO. Figure courtesy of Carl Schreck.

During most of September, the MJO was largely unfavorable for Atlantic hurricane activity (e.g., phases 4-7). From late September to mid-October, the MJO was quite favorable for Atlantic hurricane activity, and the Atlantic became extremely busy during that time period. Following another relatively quiet period for TC activity during mid to late October associated with less favorable MJO phases, the MJO again became more conducive in late October/early November. Three storms, including a major hurricane (Rafael), formed during this time period.

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 1966–2023 and defining above-normal, normal and below-normal two-week periods based on terciles. Since there are 58 years from 1966–2023, we include the 19 years with the most ACE as the upper tercile, the 19 years with the least ACE as the bottom tercile, while the remaining 20 years are counted as the middle tercile. Forecasts are issued in a probabilistic format.

Table 5 displays the six two-week forecasts that were issued during the 2024 hurricane season and shows their verification. We assigned the highest probability to the correct category for four of the six two-week periods and missed a fifth correct forecast by ~2 ACE. The forecast which had the worst verification was the period from 20 August to 2 September when we predicted normal activity and had only Ernesto's ACE from its limited time as a hurricane on 20 August. The rest of the period had no named storm activity. This period was the beginning of the prolonged lull which dominated during the peak of the TC season and will be discussed in detail later in this report.

Table 5: Two-week Atlantic ACE forecast verification for 2024. Forecasts that verified in the correct category (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 |
|---|---|---|
| **8/6 – 8/19** | **Above-Normal (>6) (85%)** | **16 (85%)** |
| **8/20 – 9/2** | **Normal (7–22) (55%)** | **1 (25%)** |
| **9/3 – 9/16** | **Below-Normal (<10) (60%)** | **6 (60%)** |
| **9/17 – 9/30** | **Normal (10-27) (50%)** | **17 (50%)** |
| **10/1 – 10/14** | **Above-Normal (>10) (99%)** | **62 (99%)** |
| **10/15 – 10/28** | **Above-Normal (>7) (50%)** | **5 (40%)** |

### 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 article published 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 our predictor model for 2024, the ENSO Longitude Index was slightly negative in July–September, indicating cool neutral ENSO conditions. The Atlantic warm pool was record warm during July–September. These two predictors, in combination, favored an extremely active end to the Atlantic hurricane season in the Caribbean.

The two-predictor model that comprises the Caribbean ACE forecast called for 34 ACE. We adjusted the statistical model output downward and predicted 15 ACE with our final forecast for the two-month period, given the lack of projected Caribbean TC activity in the two weeks following the forecast release on 1 October, as well as broadly less favorable MJO activity during the second half of October. The 1991–2020 average October–November Caribbean ACE is 8.

The October–November Caribbean ACE forecast for 2024 was an over forecast. We define ACE generated in the region between 10–20°N, 88–60°W as Caribbean ACE. Nadine, Rafael and Sara formed in the Caribbean during the two-month period. Nadine generated minimal ACE due to its short lifetime before landfall, while Rafael became a major hurricane but not before moving just north of 20°N. Sara generated ~2 ACE but was hampered throughout its lifetime by its proximity to land. In addition, Oscar also tracked just north of 20°N during October. Overall ACE generated in the Caribbean by our definition was ~4, but if we expanded our northern boundary slightly to 22°N but maintained the same longitude boundary (e.g., 10–22°N, 88–60°W), the two-month period would have produced 10 ACE. Vertical wind shear in the Caribbean from October through mid-November was below normal (Figure 3), favoring TC activity during this time.

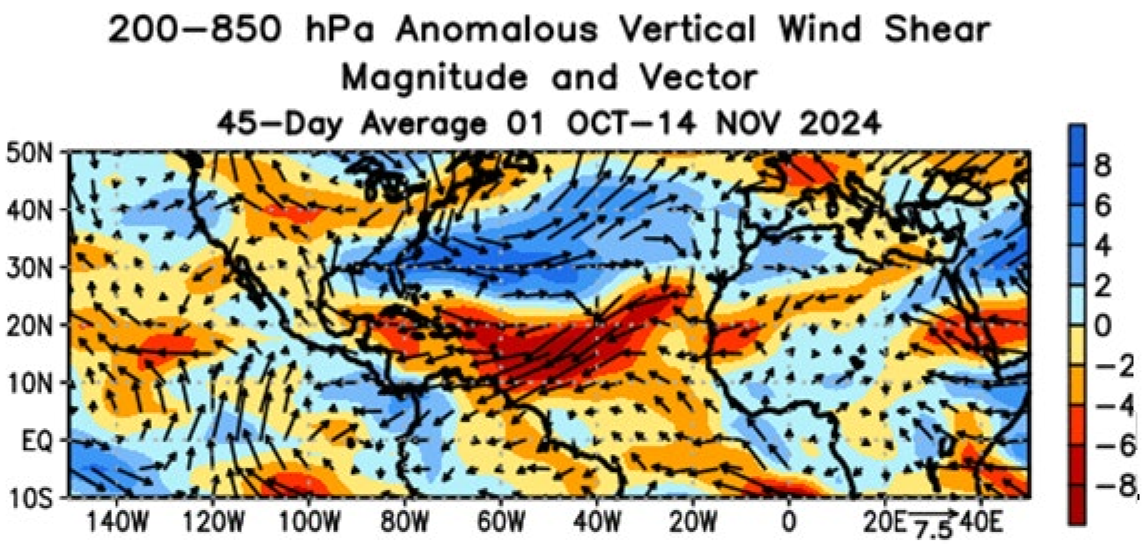



Figure 3: 1 October – 14 November-averaged shear in the tropical Atlantic. Figure courtesy of NOAA/Climate Prediction Center.

## 5 Landfall Analysis

The 2024 Atlantic hurricane season was extremely active for continental US landfalls, with five hurricanes (Beryl, Debby, Francine, Helene and Milton), of which two were major hurricanes (Helene and Milton), making landfall during the season (Figure 4). Debby made a second landfall as a tropical storm in South Carolina. Only 1886, 1985 and 2020 (which each had 6 hurricane landfalls) have had more continental US hurricane landfalls than has 2024. 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. Helene and Milton devastated the southeastern US, combining to cause over 250 fatalities and ~$100 billion USD in damage.

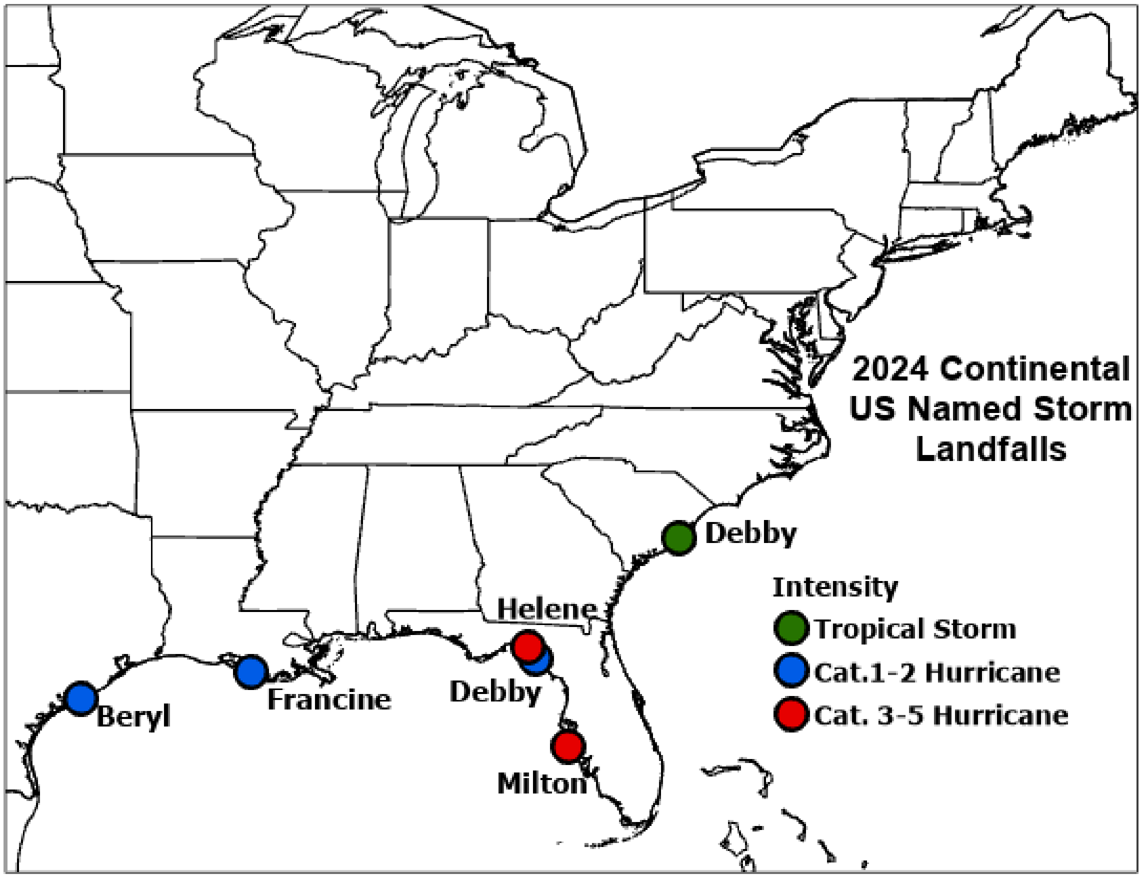



Figure 4: Location of the named storms making landfall in the continental US during the 2024 Atlantic hurricane season.

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 west of 60°W relative to the 1991–2020 climatology.

The 2024 Atlantic hurricane season was predicted to be well above average at all lead times, which consequently led us to forecast well above average continental US hurricane landfall probabilities. As an example, Table 6 displays the landfall probabilities that were issued with the 11 June 2024 outlook

Table 6: Probability of >=1 named storm, hurricane and major hurricane tracking within 50 miles of each coastal state from Texas to Maine based on our 11 June outlook. Probabilities were provided for both the 1880–2020 climatological average as well as the probability for 2024, based on the 11 June CSU seasonal hurricane forecast of ACE west of 60°W.

| | | 2024 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 | 78% | 43% | 14% | 58% | 28% | 8% |
| Connecticut | 35% | 13% | 2% | 22% | 8% | 1% |
| Delaware | 35% | 10% | 1% | 23% | 6% | 1% |
| Florida | 96% | 75% | 44% | 86% | 56% | 29% |
| Georgia | 82% | 46% | 10% | 63% | 30% | 6% |
| Louisiana | 84% | 56% | 23% | 66% | 38% | 14% |
| Maine | 34% | 11% | 2% | 21% | 7% | 1% |
| Maryland | 47% | 18% | 1% | 31% | 11% | 1% |
| Massachusetts | 49% | 23% | 5% | 33% | 14% | 3% |
| Mississippi | 72% | 43% | 13% | 53% | 28% | 8% |
| New Hampshire | 29% | 9% | 2% | 18% | 6% | 1% |
| New Jersey | 35% | 11% | 1% | 23% | 7% | 1% |
| New York | 41% | 16% | 4% | 26% | 9% | 2% |
| North Carolina | 85% | 56% | 13% | 68% | 38% | 8% |
| Rhode Island | 32% | 13% | 2% | 20% | 8% | 1% |
| South Carolina | 76% | 44% | 14% | 57% | 29% | 8% |
| Texas | 80% | 54% | 25% | 61% | 36% | 16% |
| Virginia | 65% | 31% | 2% | 46% | 20% | 1% |

# 6 Summary of Hurricane Season Atmospheric/Oceanic Conditions

In this section, we go into more detail discussing large-scale conditions that we believe significantly impacted the 2024 Atlantic basin hurricane season for the full 2024 season. In Section 7, we examine in more detail the pronounced Atlantic hurricane lull that occurred from 20 August – 23 September and the hyperactive finish to the season that followed.

## 6.1 ENSO

The 2024 August-October-averaged value of the Oceanic Nino Index was -0.2°C, which qualifies as a cool neutral ENSO season. We anticipated slightly cooler ENSO conditions (e.g., weak La Niña) than what actually occurred (e.g., cool neutral ENSO). Significant subseasonal variability (discussed later in this section) and occasional relaxations of trade winds in the central and eastern Pacific (Figure 5) likely contributed to the lack of La Niña development during the hurricane season.

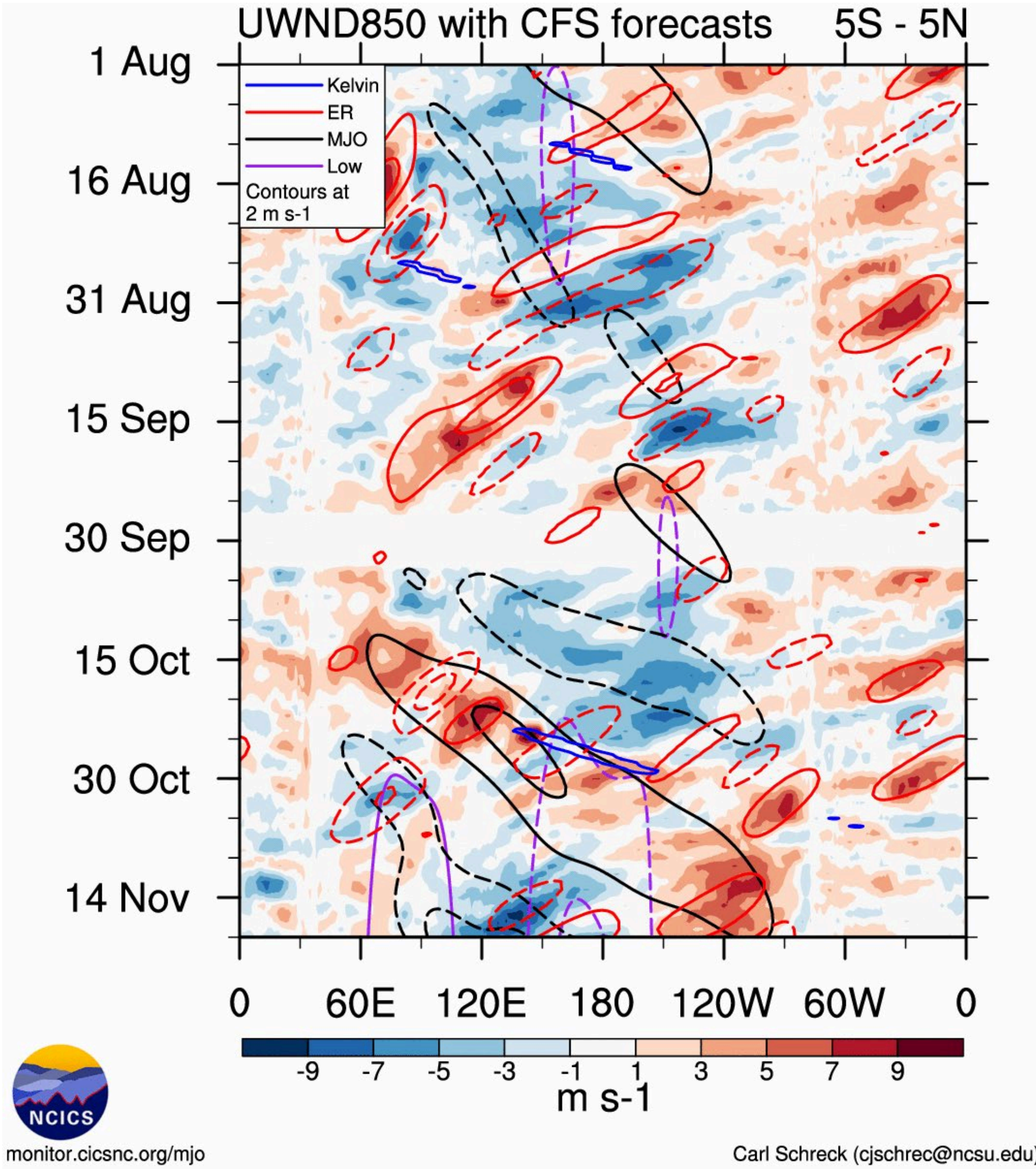



Figure 5: Anomalous equatorial 850 hPa winds from 1 August to 19 November. Figure courtesy of Carl Schreck. Please note that there was a data dropout during late September/early October at the National Centers for Environmental Information due to the extreme flooding from Hurricane Helene.

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 6 displays the ECMWF seasonal forecast for Niño 3.4 from 1 April. The observed values were near the ensemble average value at most lead times.

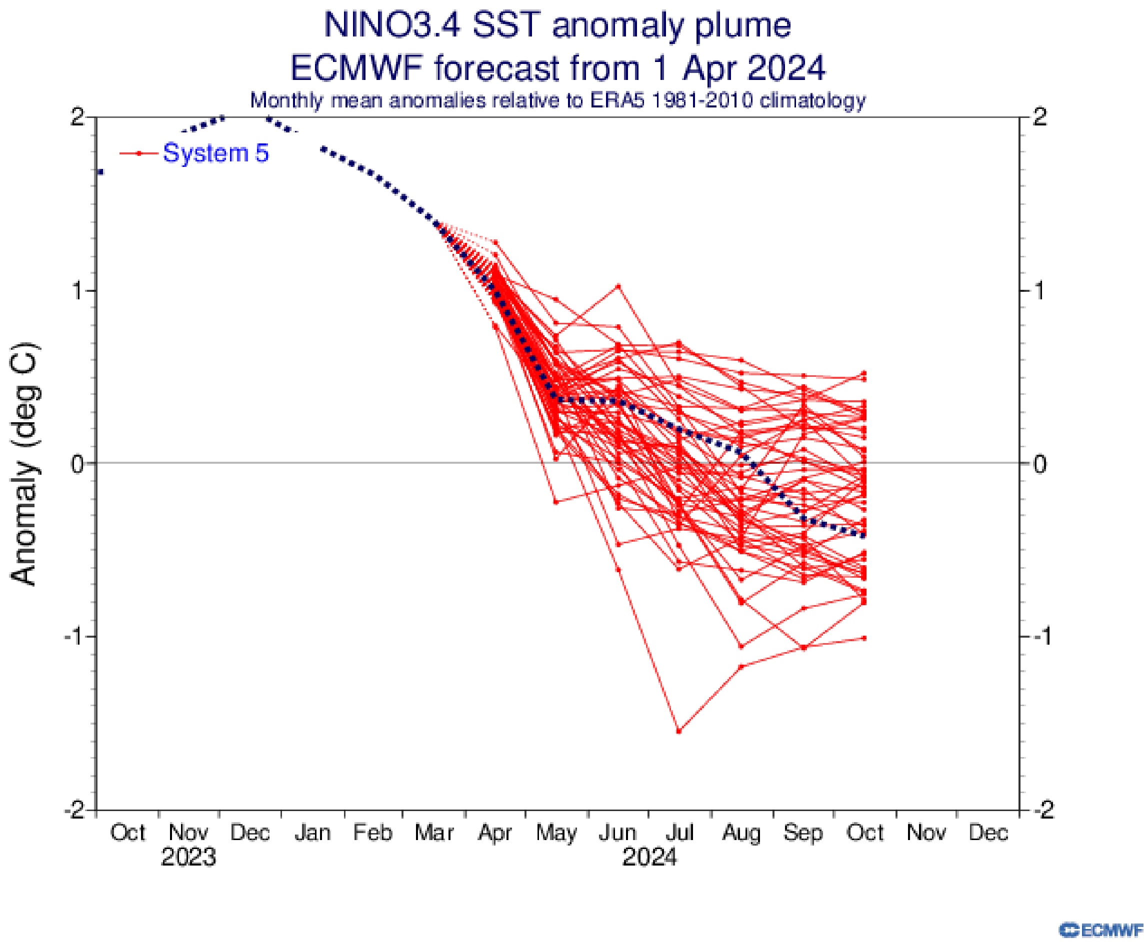



Figure 6: ECMWF ensemble prediction for Niño 3.4 from 1 April 2024. The blue dotted line represents the observed value.

El Niño quickly waned during the early part of 2024, transitioning to neutral conditions during the spring. Since then, ENSO indices have cooled slightly. They are currently slightly negative but warmer than the La Niña threshold of -0.5°C. Table 7 displays anomalies in the various Niño regions in January, April, July and October 2024, respectively.

Table 7: January 2024 anomalies, April 2024 anomalies, July 2024 anomalies, and October 2024 anomalies for the Niño 1+2, Niño 3, Niño 3.4 and Niño 4 regions. SST anomaly differences from January 2024 are in parentheses.

| Region | January 2024 Anomaly (ºC) | April 2024 Anomaly (ºC) | July 2024 Anomaly (ºC) | October 2024 Anomaly (ºC) |
|---|---|---|---|---|
| Niño 1+2 | +0.8 | +0.1 (-0.7) | -0.4 (-1.2) | -0.3 (-1.1) |
| Niño 3 | +1.9 | +0.6 (-1.3) | -0.1 (-2.0) | -0.1 (-2.0) |
| Niño 3.4 | +1.8 | +0.8 (-1.0) | +0.2 (-1.6) | -0.3 (-2.1) |
| Niño 4 | +1.5 | +0.8 (-0.7) | +0.6 (-0.9) | +0.1 (-1.4) |

An additional way to visualize 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 well above average in December 2023. Those anomalies rapidly decreased to below average by mid-February. Since early March, upper ocean heat content anomalies have remained between –0.5°C – –1.0°C. There has been a slight increase in upper ocean heat content anomalies since early August.

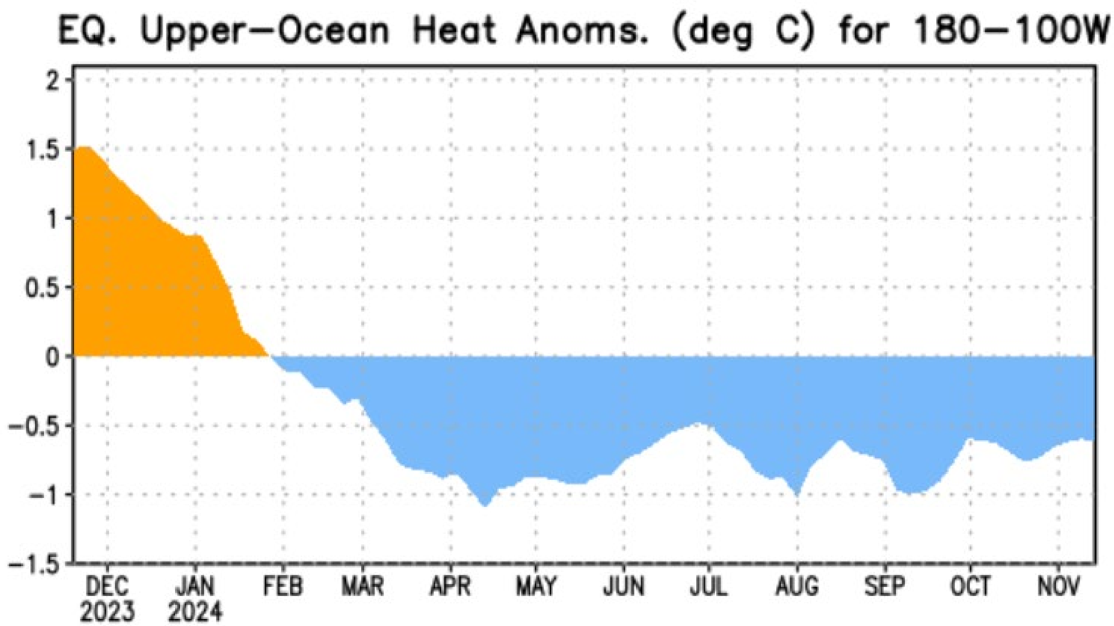



Figure 7: Upper ocean (0–300 meter) heat content anomalies in the eastern and central tropical Pacific from December 2023 – November 2024. Figure courtesy of NOAA.

### 6.2 Intra-Seasonal Variability

The MJO index was generally favorable for Atlantic hurricane activity in August but unfavorable during most of September (Figure 2). Phases 8–3 typically favor lower levels of vertical wind shear across the Main Development Region (MDR; 10–20°N, 85–20°W) than do Phases 4–7. One of the biggest surprises of the 2024 season was that late

August was extremely quiet in the Atlantic despite favorable MJO phases. The reasons for this lack of activity despite favorable MJO phases will be discussed in the next section. The next favorable MJO pulse occurred from late September to mid-October, and during that time period, the Atlantic generated record levels of ACE.

When looking at monthly ACE in 2024 compared with normal (Figure 8), the slightly below-average August does not fit in well with the canonical MJO-TC relationship given favorable MJO phases tended to predominate during the month. September was also below average for ACE, but most of this month was in unfavorable MJO phases. Lastly, October had well above-average ACE, and the month tended to have broadly favorable MJO conditions.

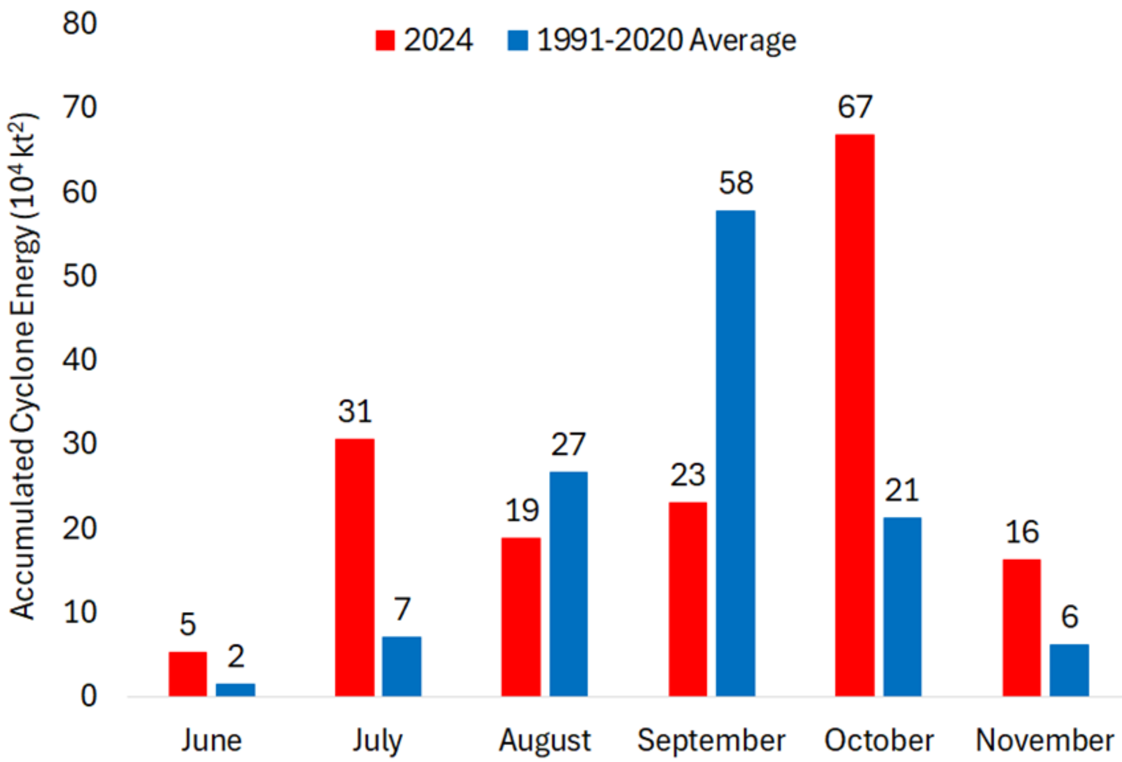



Figure 8: Atlantic Accumulated Cyclone Energy generated by month during 2024 (blue columns) compared with the 1991–2020 average (red columns).

Table 8 displays the number of storms that were first named in each phase of the MJO over the course of the 2024 Atlantic hurricane season. TC formations tended to predominate in hurricane-favorable MJO phases, with only one named storm forming in phases 6–7, which are typically taken to be the least favorable MJO phases for Atlantic TC activity.

Table 8: TC formations by MJO phase during the 2024 Atlantic hurricane season.

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

### 6.3 Atlantic SST

The 2024 Atlantic hurricane season had near-record warm SSTs across the MDR during the hurricane season. One of the questions that we had going into the 2024 season was whether the record warm anomalies that were present during the peak of the 2023 season would persist. The winter of 2023 and spring of 2024 were the warmest on record across the MDR. 2024's MDR SST anomalies did drop below 2023's MDR SST anomalies beginning in July 2024 but were still well above any other year in the high-resolution SST era (~1982 – onwards) (Figure 9). As was the case in 2023, the tropical and subtropical Atlantic had well below-normal sea level pressures during August – October (Figure 10). These low pressures favored anomalously weak trade winds (Figure 11), which resulted in less evaporation off of the ocean surface, helping to maintain the extremely warm SSTs in the MDR.

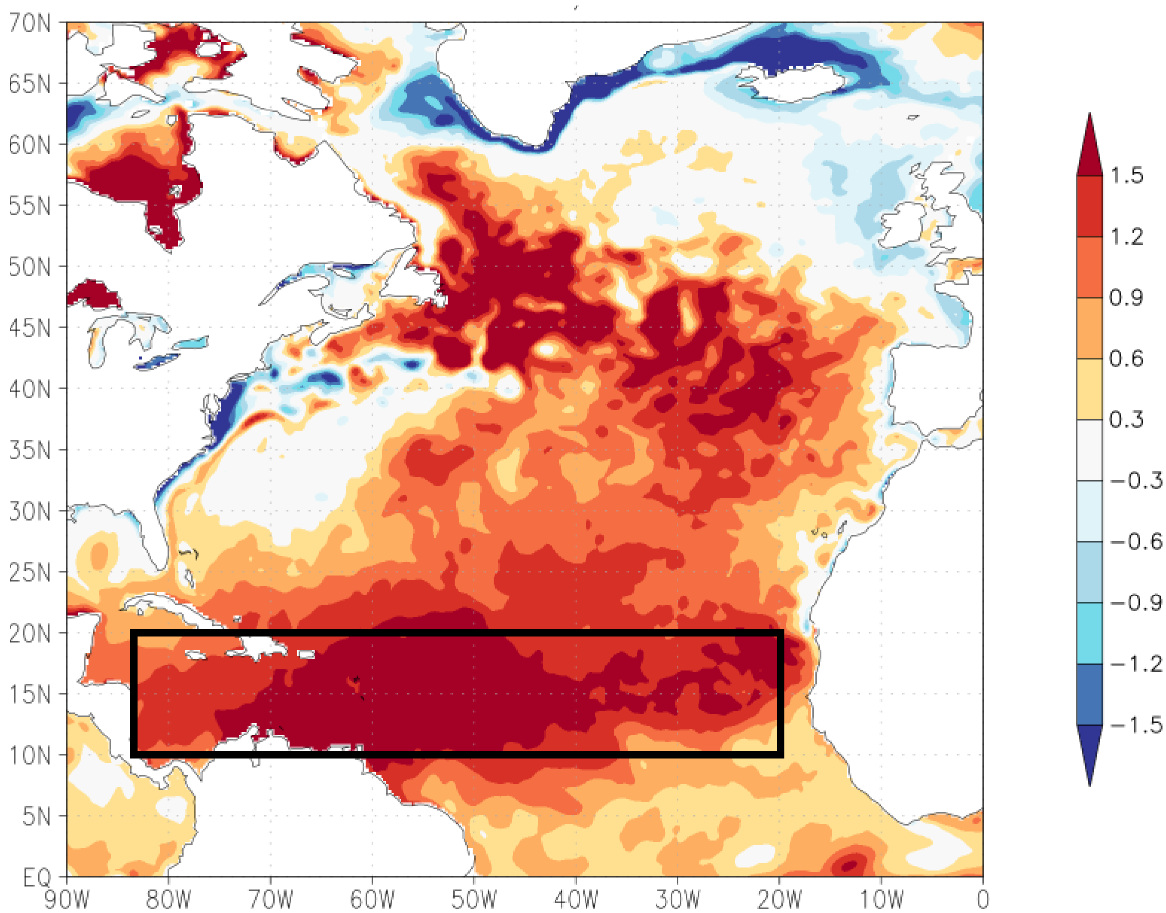



Figure 9: 2024 August–October-averaged SST anomalies. The black rectangle denotes the MDR.

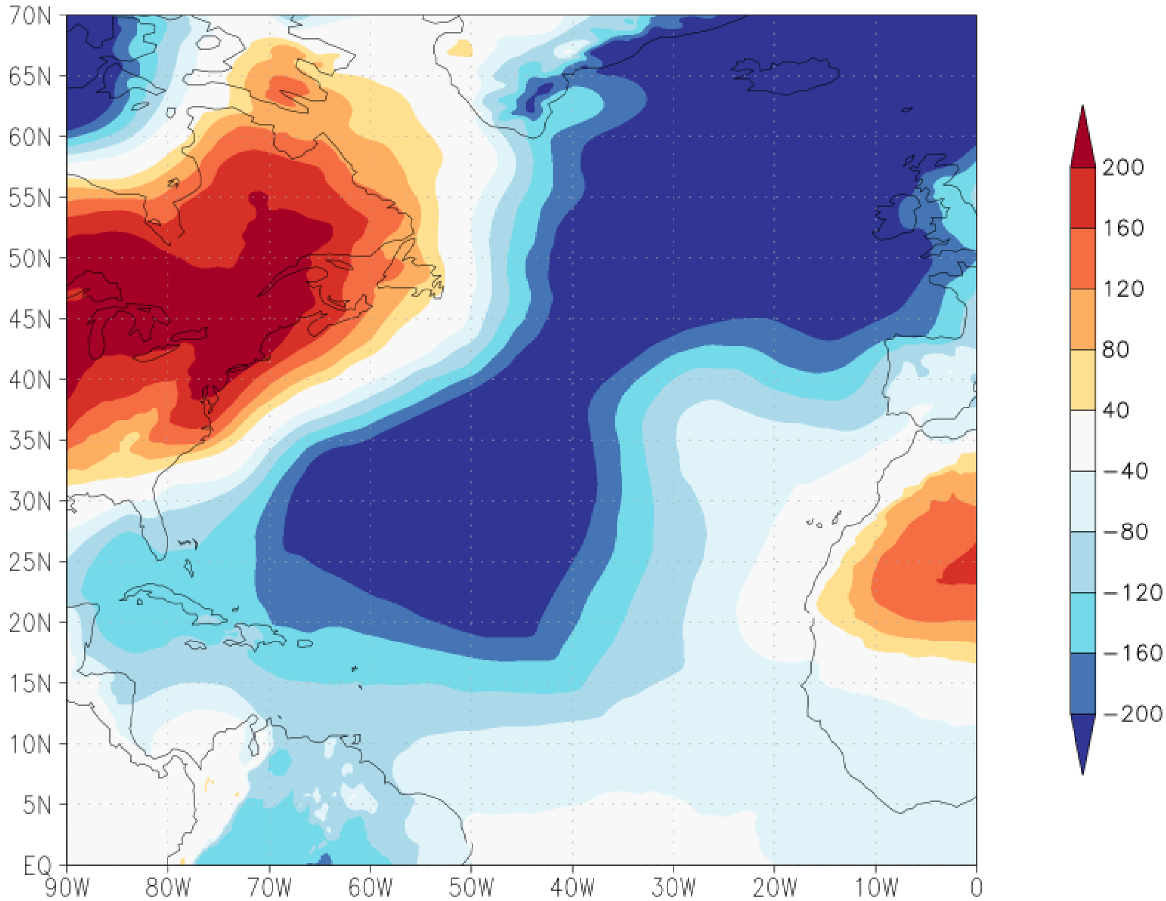



Figure 10: 2024 August–October-averaged mean sea level pressure anomalies. Note that units are in Pa. 1 Pa = 0.01 hPa = 0.01 mb.

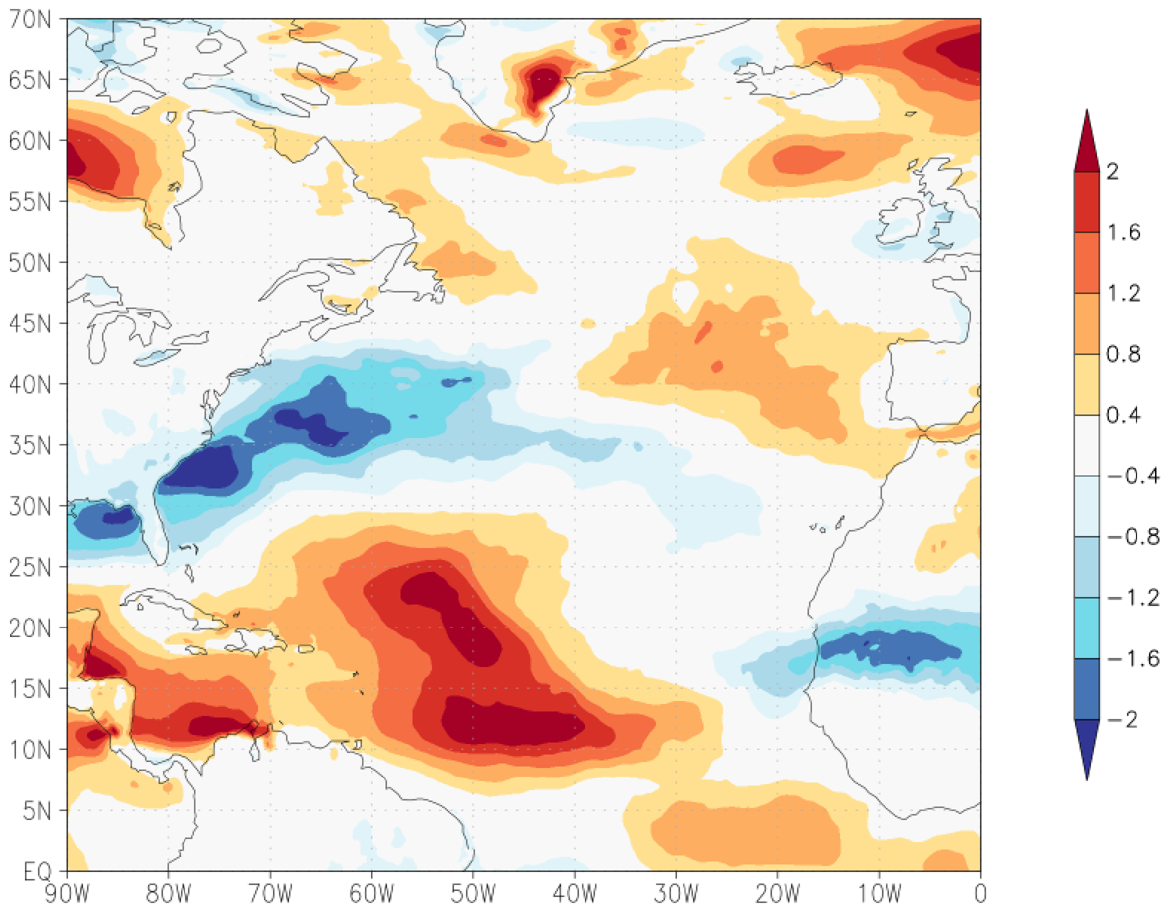



Figure 11: 2024 August–October-averaged 10 meter zonal wind anomalies.

### 6.5 Tropical Atlantic Vertical Wind Shear

During August through October, vertical wind shear anomalies were the lowest on record (since 1950) across the MDR (Figures 12, 13). This reduced shear was correctly anticipated by our seasonal forecasts. However, during the same three-month period, Atlantic ACE was only slightly above the long-term average. This relatively weak ACE-shear relationship in August–October 2024 is one of the primary reasons why we moderately over-forecast observed ACE this season (Figure 14). For example, had ACE in 2024 followed the best fit regression line based on the August–October ACE-shear relationship from 1950–2023, the three-month period would have generated ~70 more ACE than was observed. We know that additional parameters other than shear are critical for TC formation and intensification, but the relatively poor ACE-shear relationship in 2024 was somewhat surprising. We also note that vertical wind shear was quite high in the subtropics this season (Figure 12), which was likely a driving factor why only two named storms formed in the Atlantic north of 24°N (Isaac and Patty).

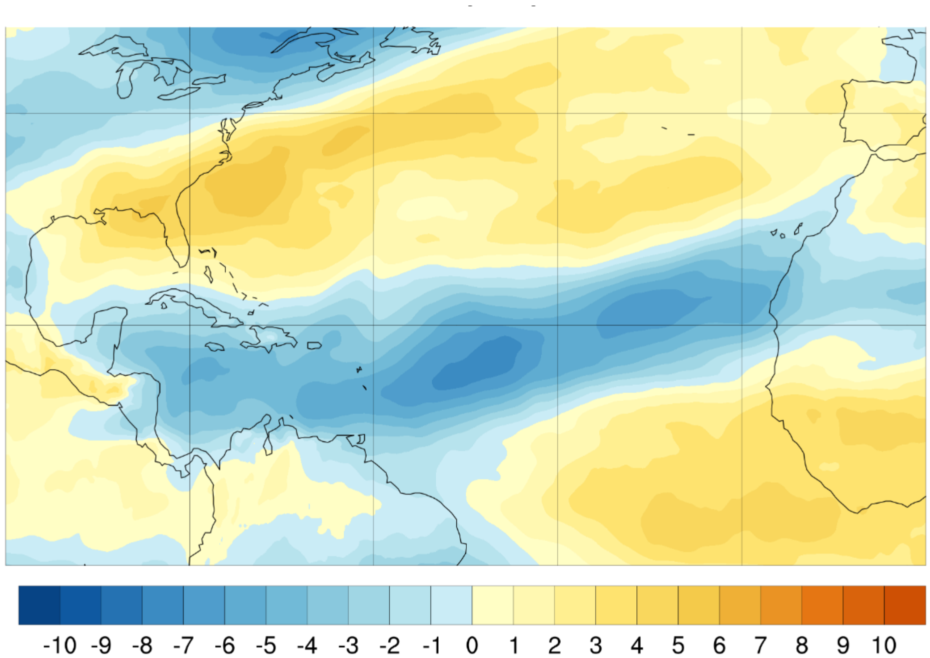



Figure 12: Anomalous North Atlantic vertical wind shear (m $s^{-1}$) from August–October 2024.

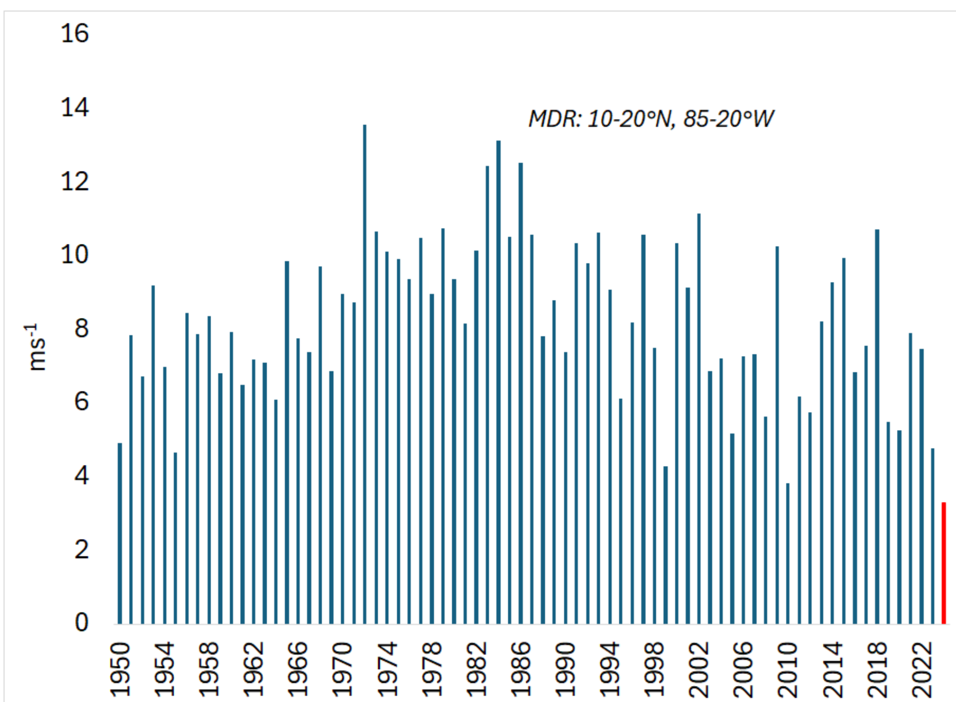



Figure 13: Timeseries of August–October-averaged MDR vertical wind shear from 1950–2024. The red column denotes the observed value in 2024 – the lowest shear on record for August–October.

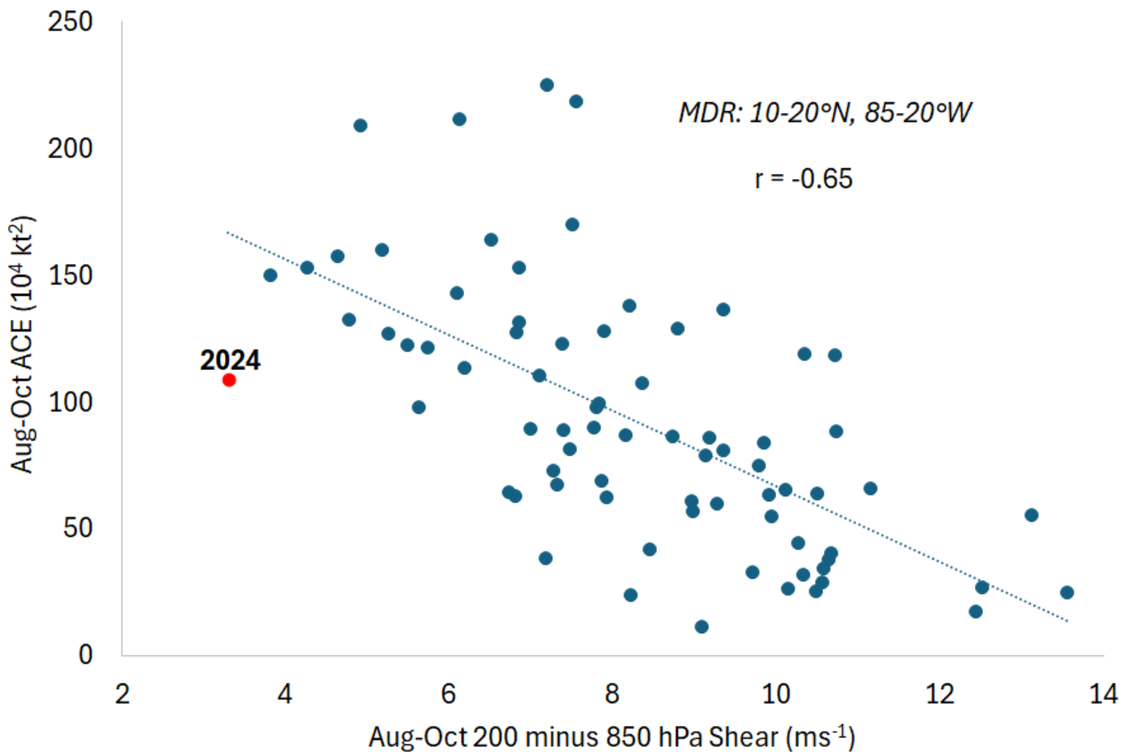



Figure 14: Relationship between August–October-averaged vertical wind shear and August–October-averaged Atlantic ACE.

## 7 Analysis of Mid-Season Lull and Hyperactive End to the Season

Here we briefly discuss four potential drivers of the mid-season lull that occurred from 20 August to 23 September as well as the hyperactive end to the 2024 hurricane season. We also wrote a discussion, posted on our website on 3 September, that discussed this mid-season lull. We are currently working with colleagues from several institutions to investigate the mid-season lull in more detail.

### 7.1 Mid-Season Lull

From 20 August to 23 September, the Atlantic generated just 7 ACE – the least amount of ACE during that period since 1994. This lull was especially surprising given how conducive large-scale conditions (e.g., extremely warm Atlantic, cool neutral ENSO, etc.) appeared to be for the season.

1) Northward-shifted monsoon trough

While normally a vigorous and northward-shifted monsoon trough favors an active Atlantic hurricane season, the monsoon trough shifted extremely far north during August (Figure 15). Low-level westerly zonal wind anomalies extended north to ~20°N, acting as a conduit for easterly wave tracks that emerged over the cold waters of the northeast Atlantic west of Mauritania. This far northerly track also brought down dry air from the subtropics, helping to squelch deep convection in the tropics (Figure 16). Mid-level relative humidity was generally below normal across the MDR in August (Figure 17). However, our preliminary analysis (discussed more later in this document) indicates that the easterly wave tracks shifted back towards a more climatological average position in September, so the northward shift in the tracks appears to have mostly suppressed TC activity during the latter part of August when the MJO would have broadly favored Atlantic TC activity.

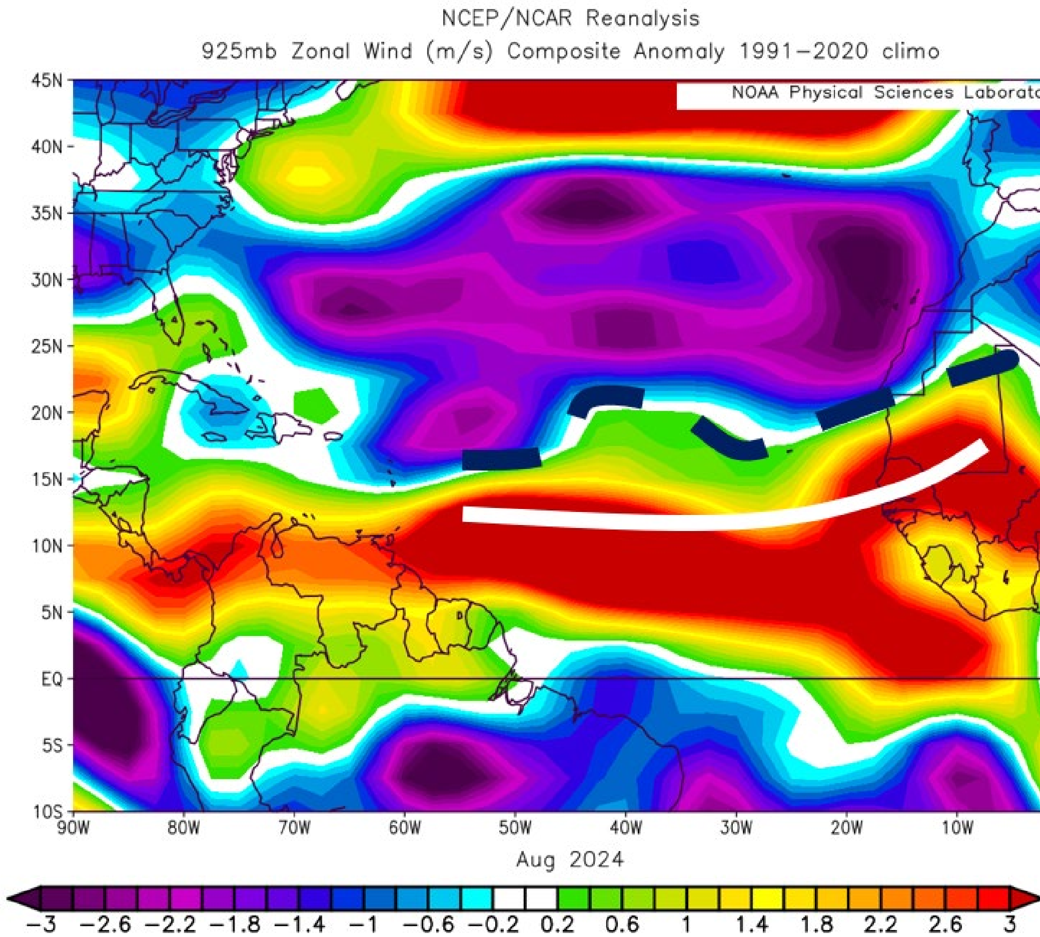



Figure 15: Observed August 925 hPa zonal winds across the tropical Atlantic along with an approximate placement of the monsoon trough in August 2024 (blue dashed line) relative to an estimated hurricane optimal line (white solid line).

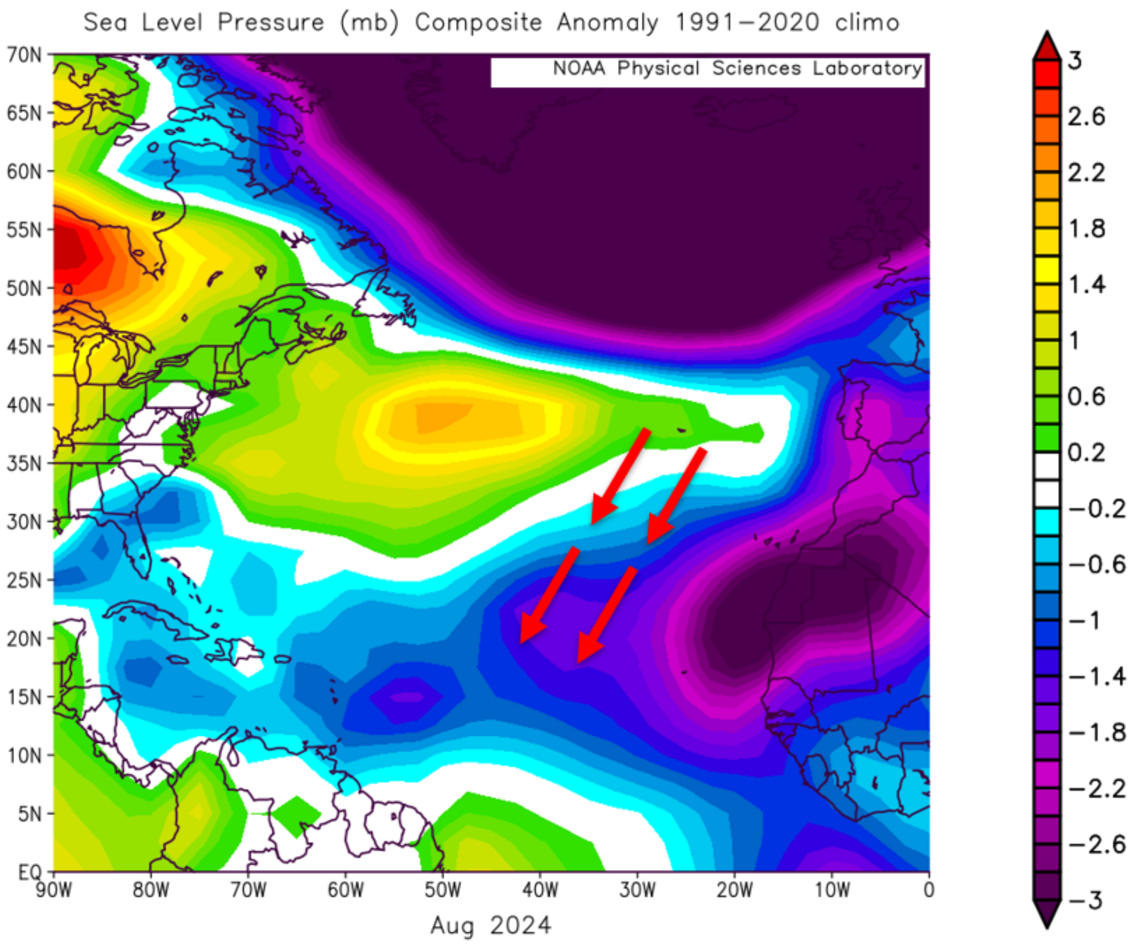



Figure 16: Observed sea level pressure anomalies in August 2024 and associated low-level wind flow across the eastern subtropical Atlantic.

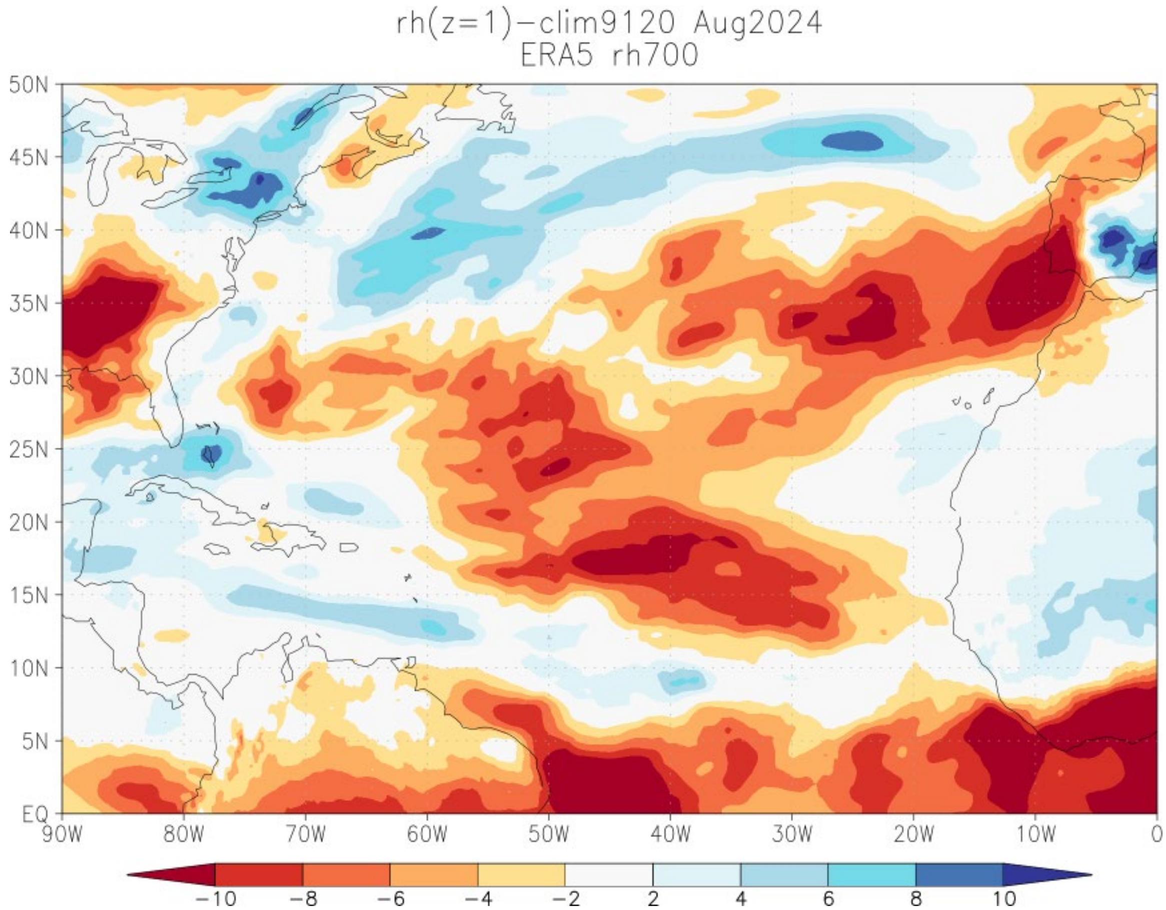



Figure 17: Observed 700 hPa relative humidity anomalies in August 2024.

2) Upper-tropospheric warming

While the Atlantic MDR was characterized by extremely warm SSTs in 2024, upper-level temperatures were also very warm during August. While SSTs in August 2023 and August 2024 were nearly equal when averaged across the MDR, upper-level temperatures were ~0.5-1°C warmer in August 2024 (Figure 18). This increase in upper-level temperatures was primary concentrated in the eastern and central Atlantic. Very little robust easterly wave activity in the eastern and central Atlantic occurred during the second half of August as well as the first part of September. This increase in upper-level temperatures results in increased atmospheric stability, suppressing deep convection.

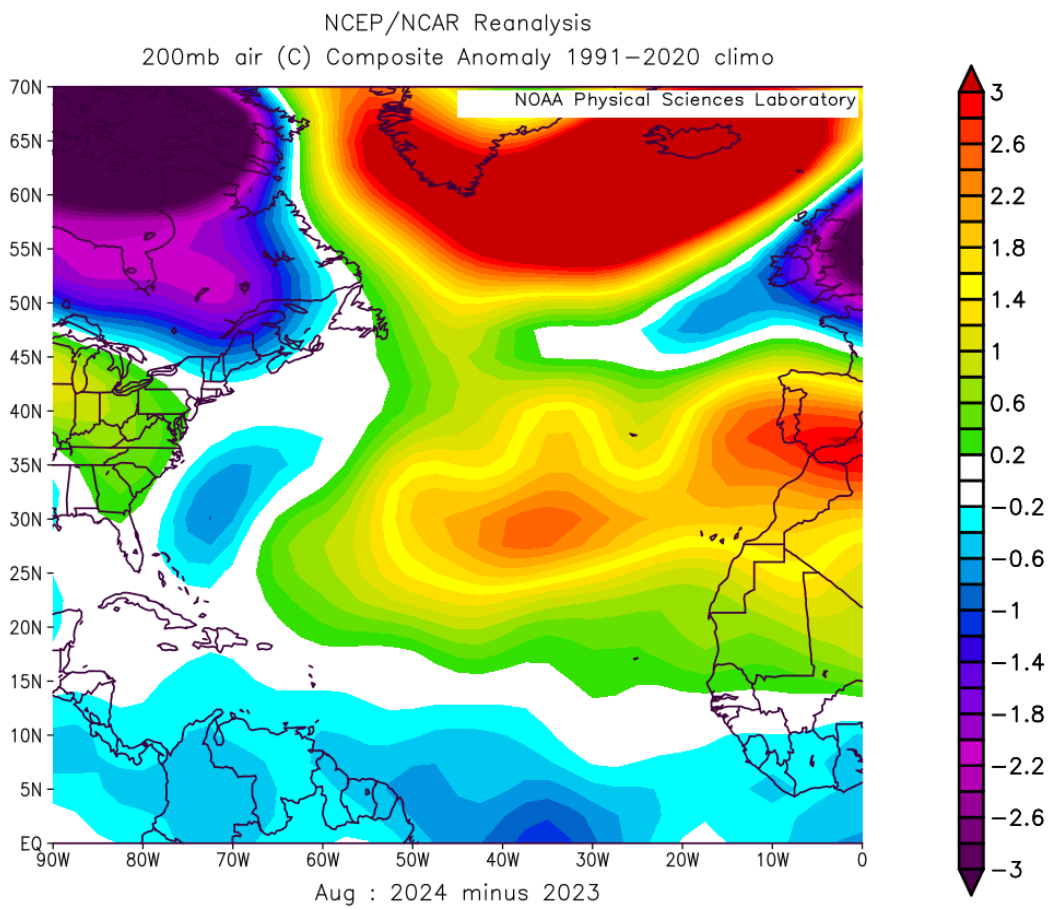



Figure 18: August 2024 minus August 2023 200 hPa temperatures.

3) Too much easterly shear in the eastern Atlantic

In August 2024, the entire tropical Atlantic was characterized by pronounced easterly upper-level zonal wind anomalies (Figure 19). These upper-level easterly anomalies extended all the way into Africa, indicative of an extremely vigorous African monsoon. While these upper-level easterly anomalies reduce shear in the western and central Atlantic (where the background shear in August is westerly), these upper-level easterly anomalies increase easterly shear in the eastern Atlantic (where the background shear in August is easterly) (Figure 20).

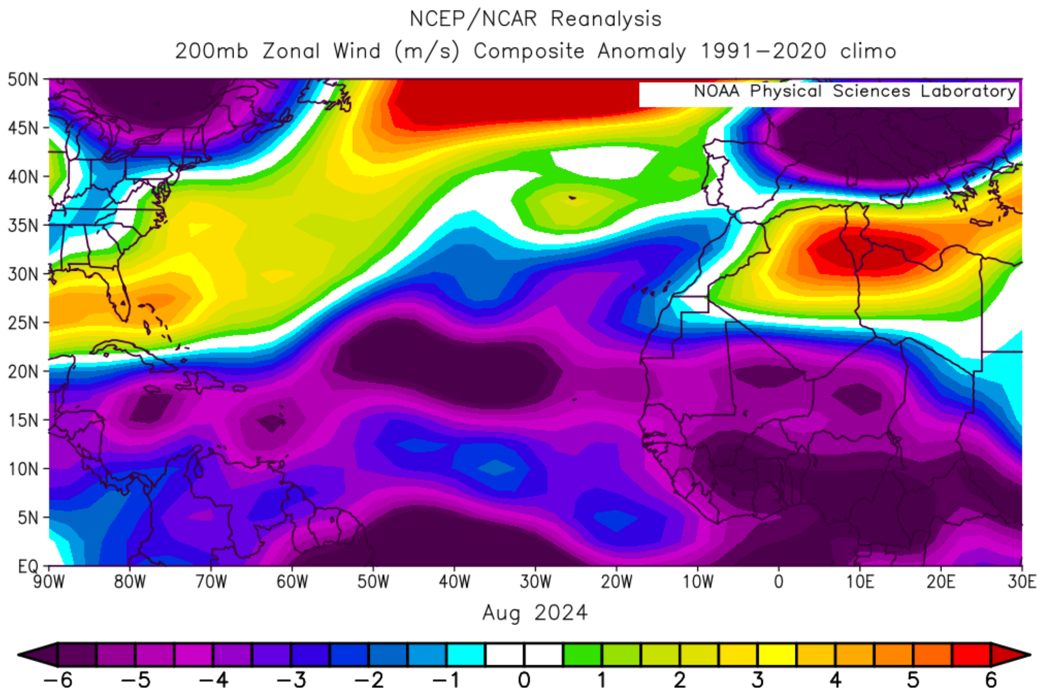



Figure 19: 200 hPa zonal wind anomalies during August 2024.

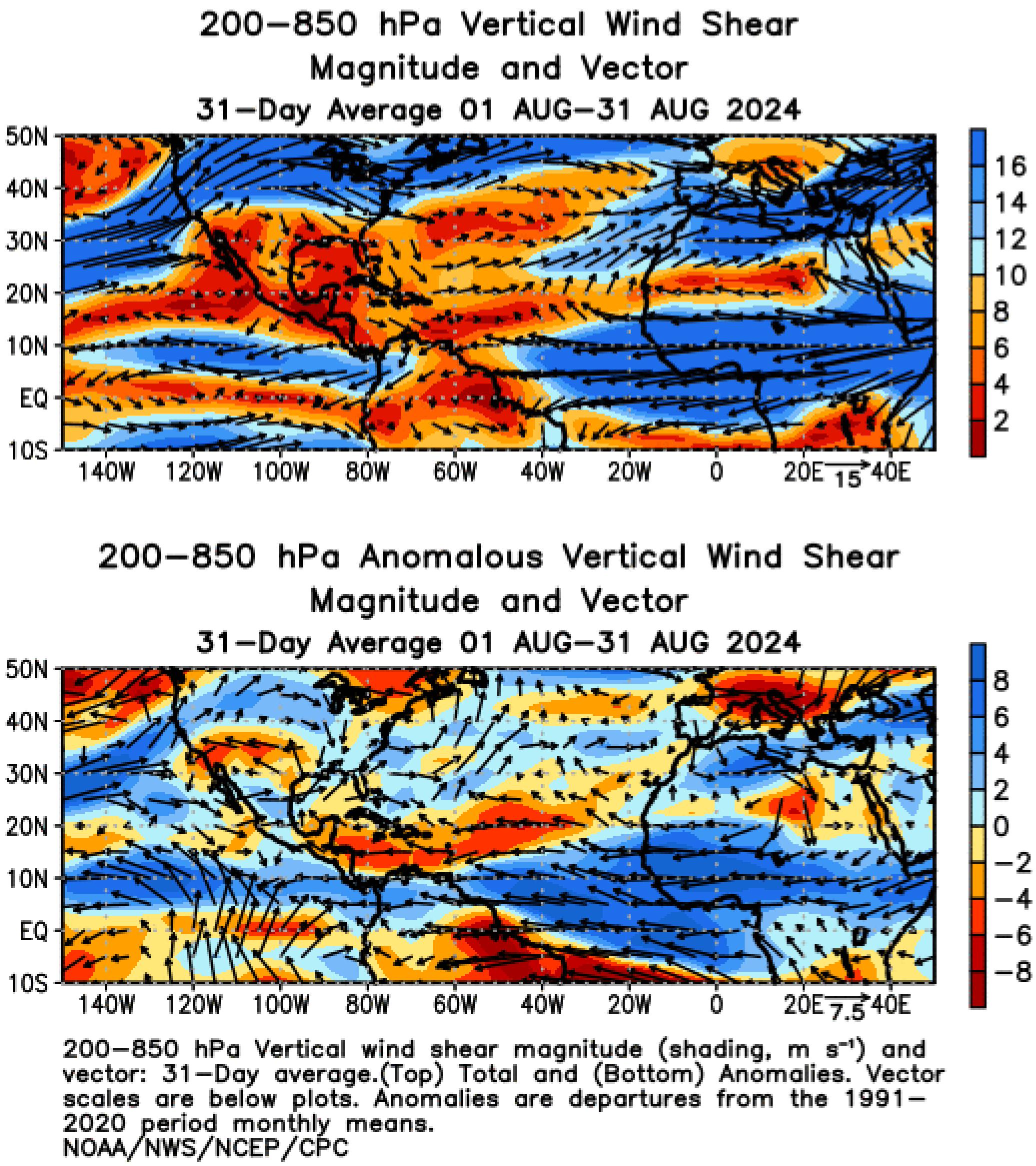



Figure 20: Observed vertical wind shear during August 2024. Figure courtesy of NOAA.

4) TC unfavorable large-scale conditions from the MJO

While the MJO was broadly favorable for Atlantic hurricane activity for most of August, it was in phases 4–7 from late August through the latter part of September (Figure 21). These phases of the MJO are associated with increased Atlantic subsidence (Figure 22) as well as increases in Atlantic vertical wind shear (Figure 23). While vertical wind shear was record low when averaged from August – October, it was briefly above normal during the first part of September (the climatological peak of the season). We also had an increase in tropical upper-tropospheric trough activity around this time. We believe that these unfavorable MJO phases during most of September were the primary reason why the Atlantic hurricane season lull was so prolonged.

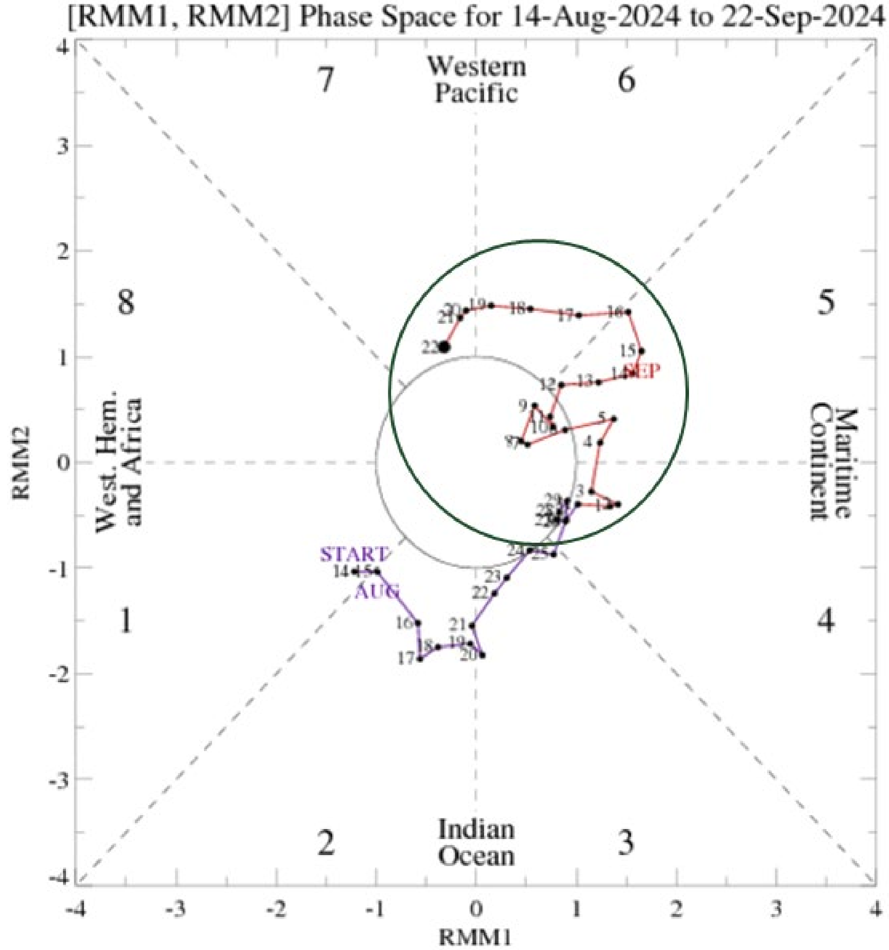



Figure 21: Observed propagation of the Madden-Julian oscillation from 14 August to 22 September. The green circle denotes the time when the MJO was in phases 4–7.

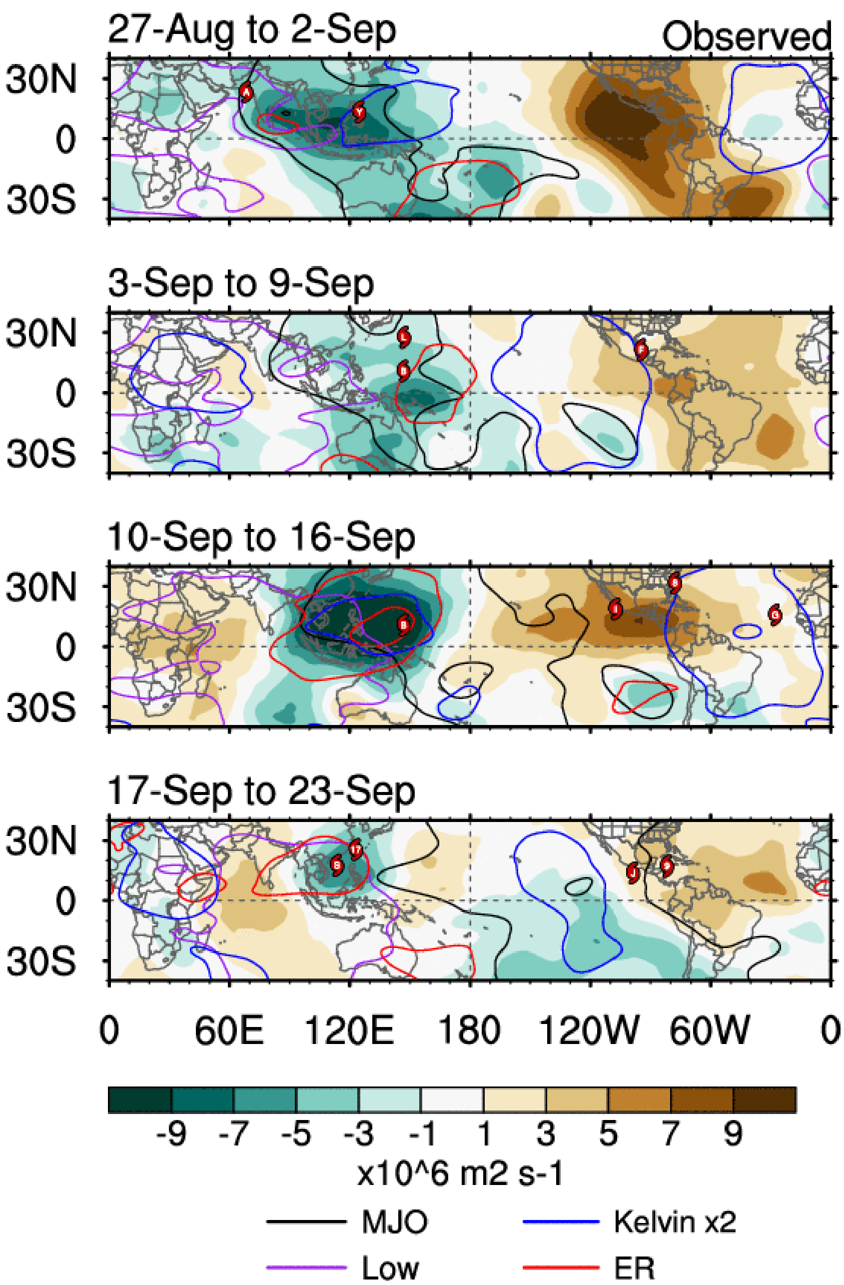



Figure 22: Observed 200 hPa velocity potential anomalies from 27 August to 23 September. Positive velocity potential anomalies indicate sinking motion. Figure courtesy of Carl Schreck.

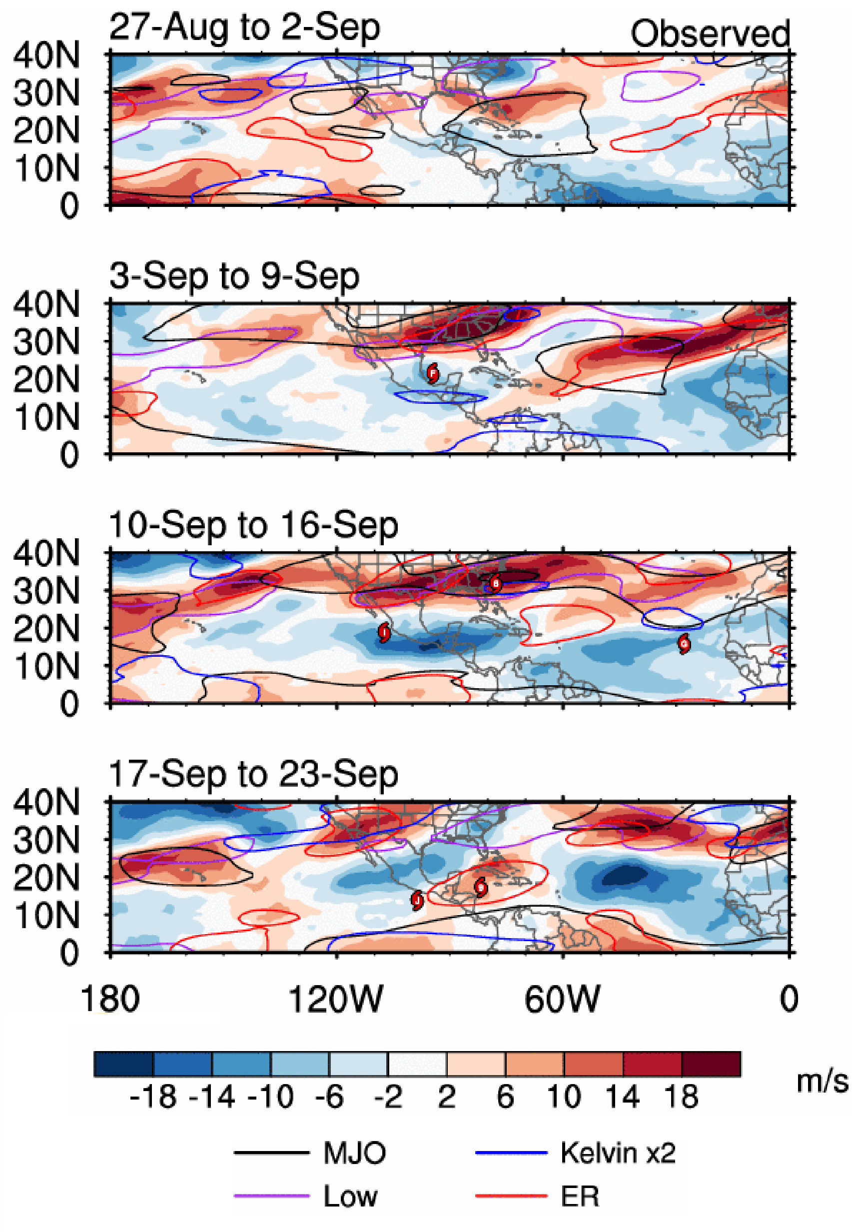



Figure 23: Observed 200 hPa zonal wind shear anomalies from 27 August to 23 September. Vertical wind shear was somewhat elevated across the western part of the MDR from 3–9 September and from 17–23 September. Figure courtesy of Carl Schreck.

### 7.2 Hyperactive End to the Season

Beginning on 24 September when Helene formed through the end of the season, the Atlantic was hyperactive. Seven hurricanes formed since 25 September – the most on record, while ACE generated since 24 September was the second most on record. Here we discuss the subseasonal drivers of the extremely active end to the season.

1) Monsoon trough shifts southward

Following its far northward shift in late August, the monsoon trough shifted back southward towards a more climatological position in September (Figure 24). In addition, the climatological position of the monsoon trough also shifts south from September – onwards, so the easterly wave track became more conducive for an active end to the season, especially when other conditions (e.g., shear, moisture, etc.) became more conducive.

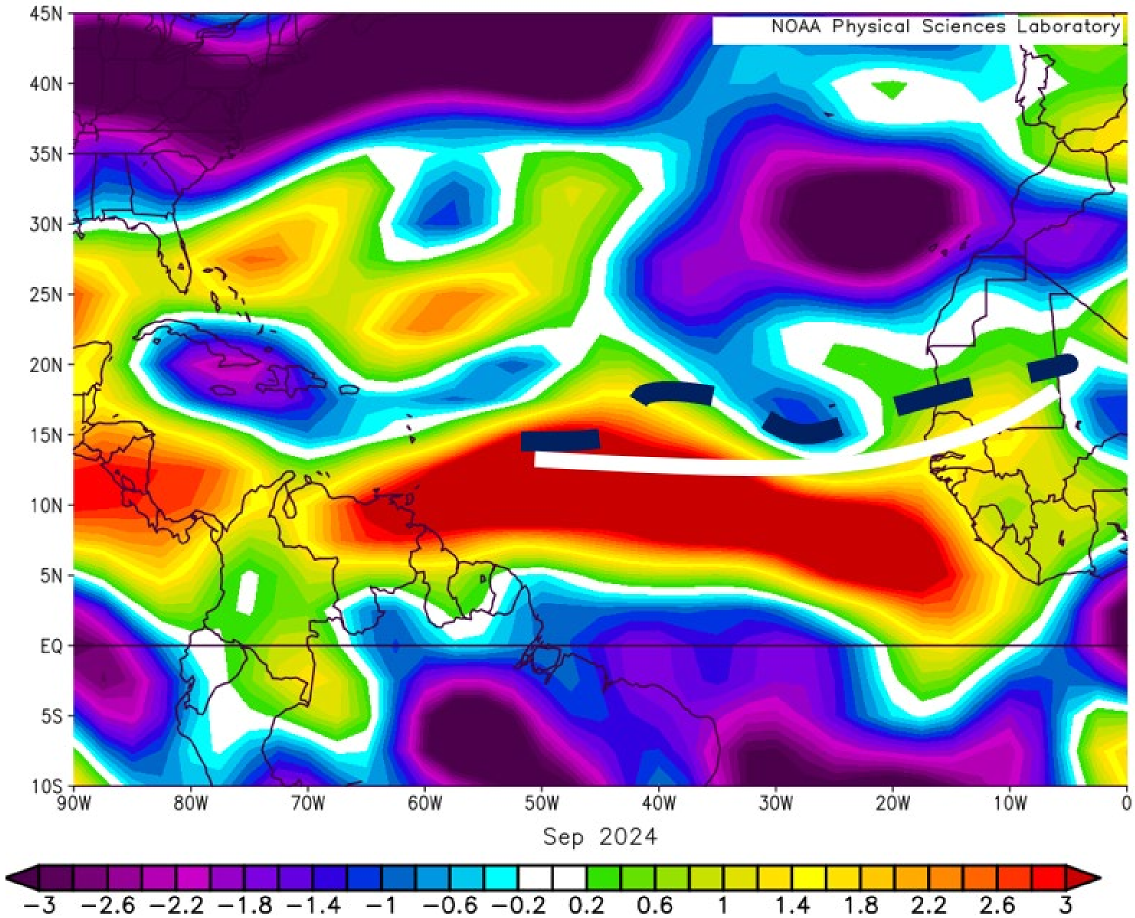



Figure 24: Observed September 925 hPa zonal winds across the tropical Atlantic along with an approximate placement of the monsoon trough in September 2024 (blue dashed line) relative to an estimated hurricane optimal line (white solid line).

2) Upper-tropospheric cooling

As we hypothesized in our early September discussion, we saw considerable cooling of the upper troposphere during the month (Figure 25), while SSTs and upper ocean heat content remained extremely warm (Figure 26). Consequently, the atmosphere in the MDR became more unstable as September progressed, setting the stage for a hyperactive end of the season.

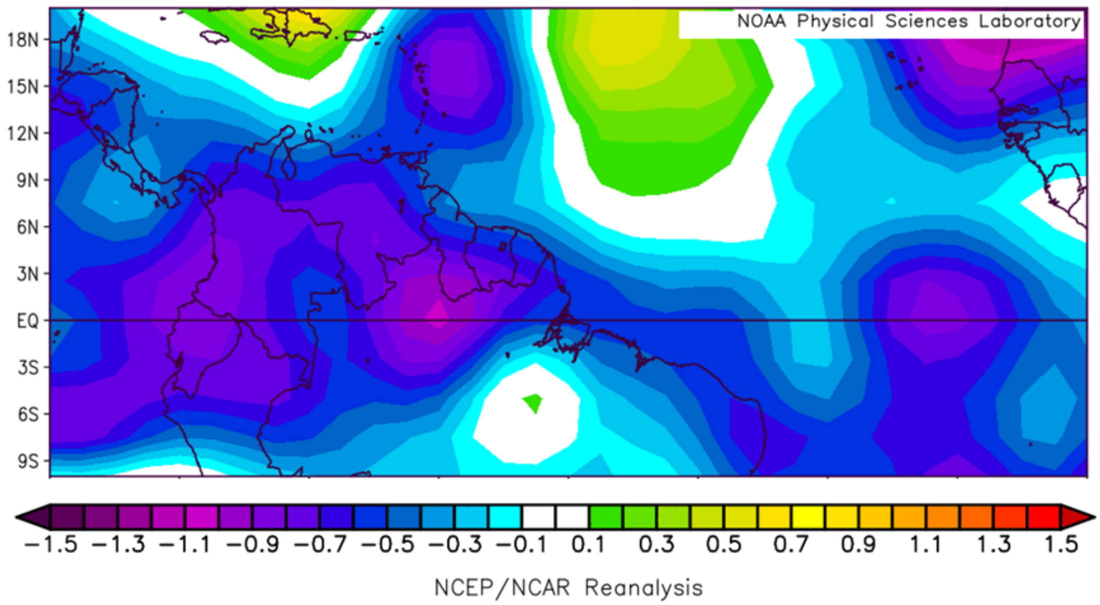



Figure 25: 21–30 September 2004 200 hPa temperatures minus 1–10 September 2004 200 hPa temperatures.

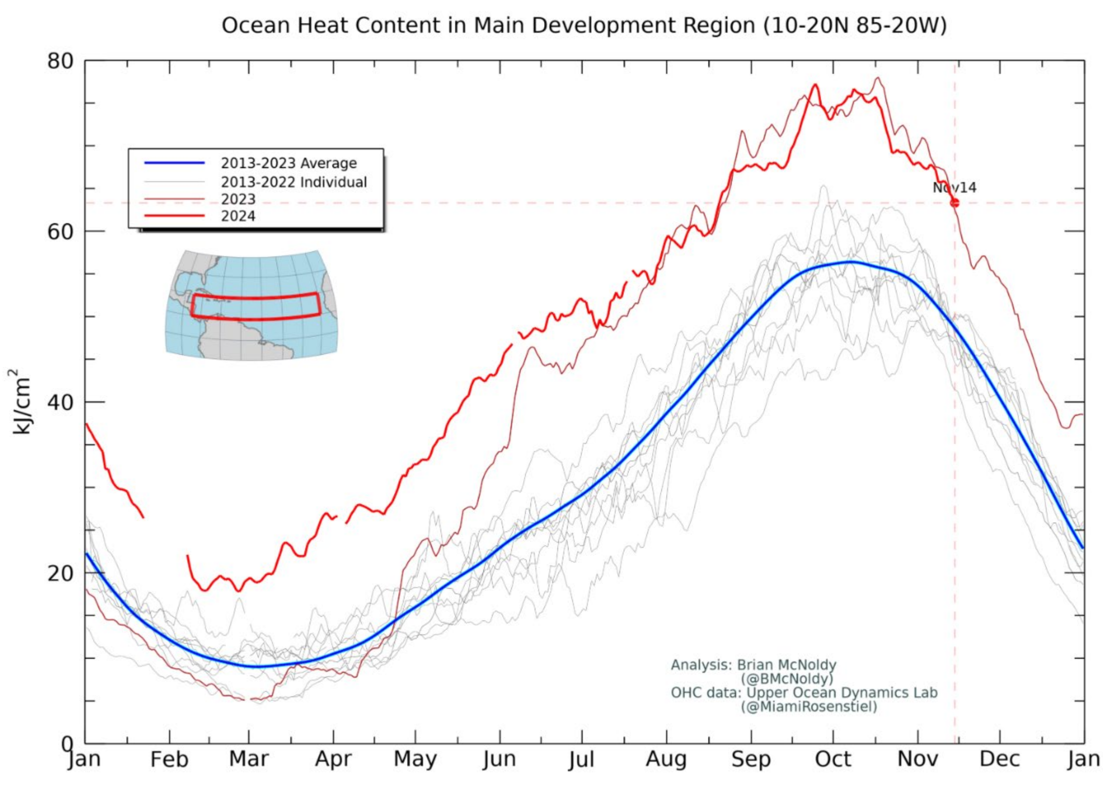



Figure 26: Observed MDR upper ocean heat content anomalies (dark red line), 2023 anomalies (light red line), individual years from 2013 to 2022 (dark gray lines) and the 2013–2023 average (blue line). Figure courtesy of Brian McNoldy (University of Miami).

3) TC favorable large-scale conditions from the MJO

The MJO moved into more favorable phases for Atlantic TC activity in late September (e.g., phases 8–3; Figure 27). These favorable phases persisted through the middle of October. During this time, the Atlantic was characterized by anomalously high precipitable water (Figure 28) and low shear (e.g., easterly shear anomalies; Figure 29). These conditions created a highly conducive dynamic and thermodynamic environment for TC activity. Following less favorable MJO phases in mid-to-late October, the MJO became favorable for Atlantic TCs once again in early November (Figure 30). Three storms formed during this time: Patty, Rafael and Sara. The ACE generated by these storms pushed seasonal ACE values to hyperactive levels.

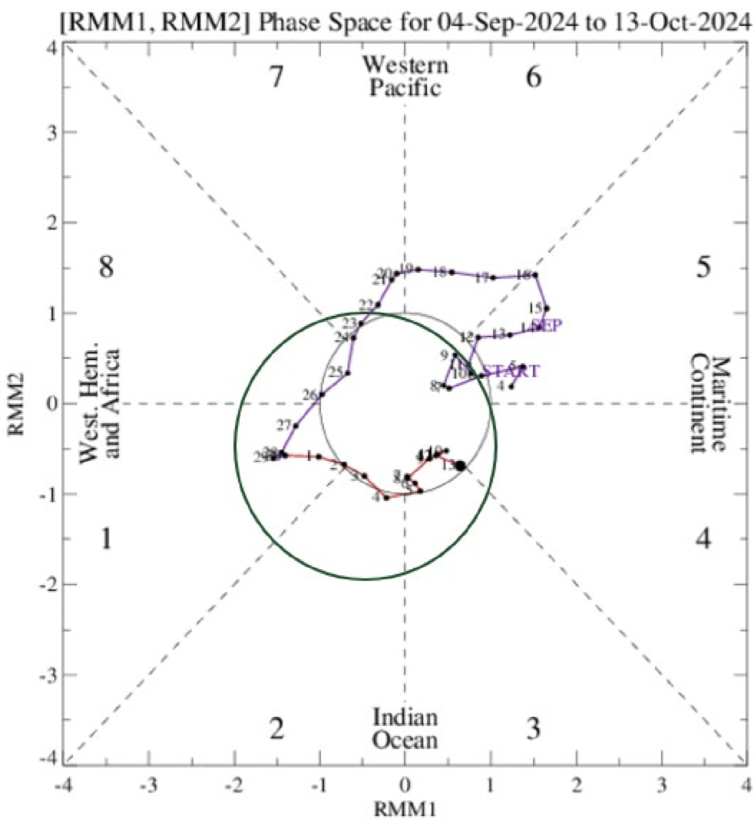



Figure 27: Observed propagation of the Madden-Julian oscillation from 4 September to 13 October. The green  circle denotes the time when the MJO was in phases 8–3.

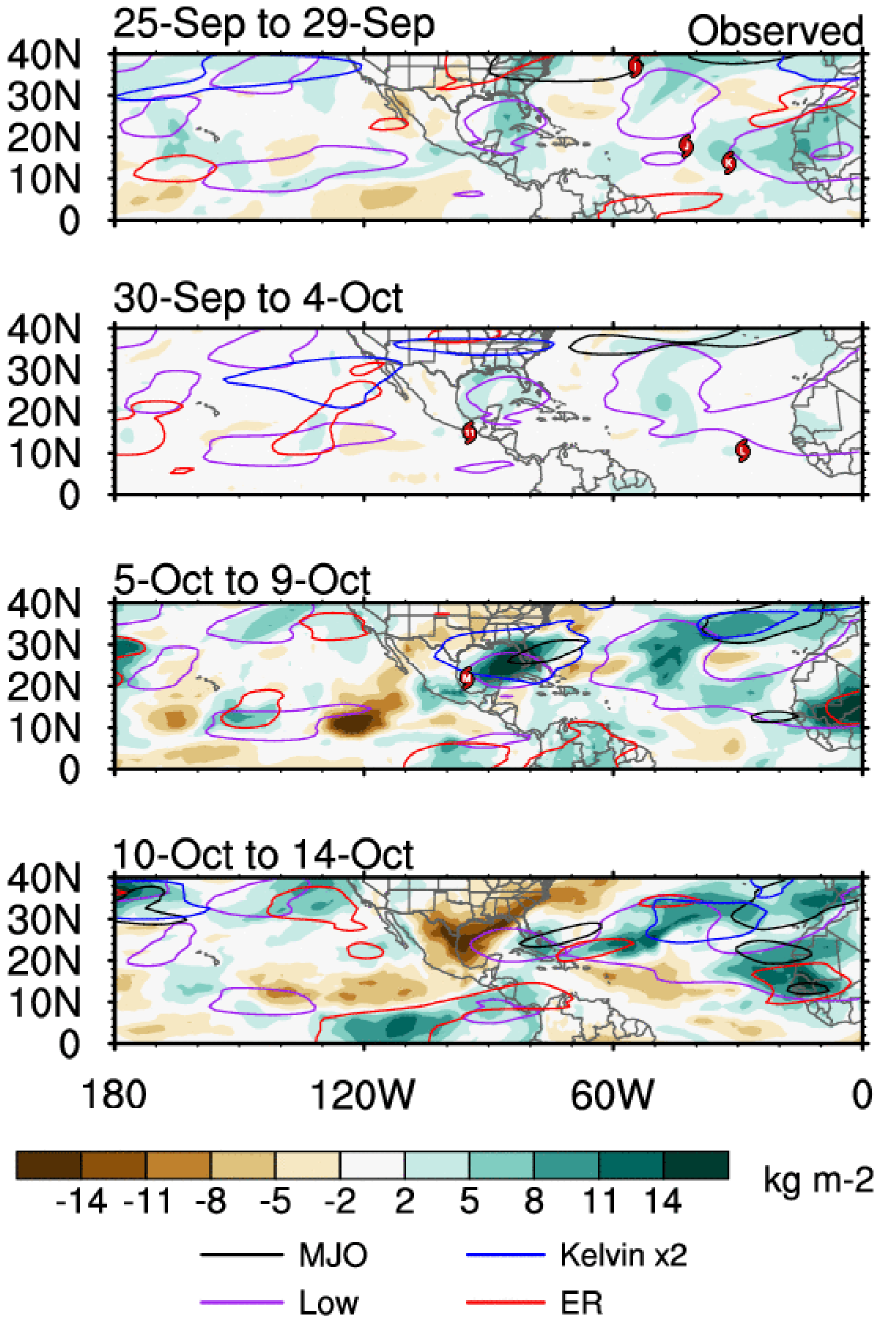



Figure 28: Observed precipitable water across the Western Hemisphere from 25 September–14 October. Figure courtesy of Carl Schreck.

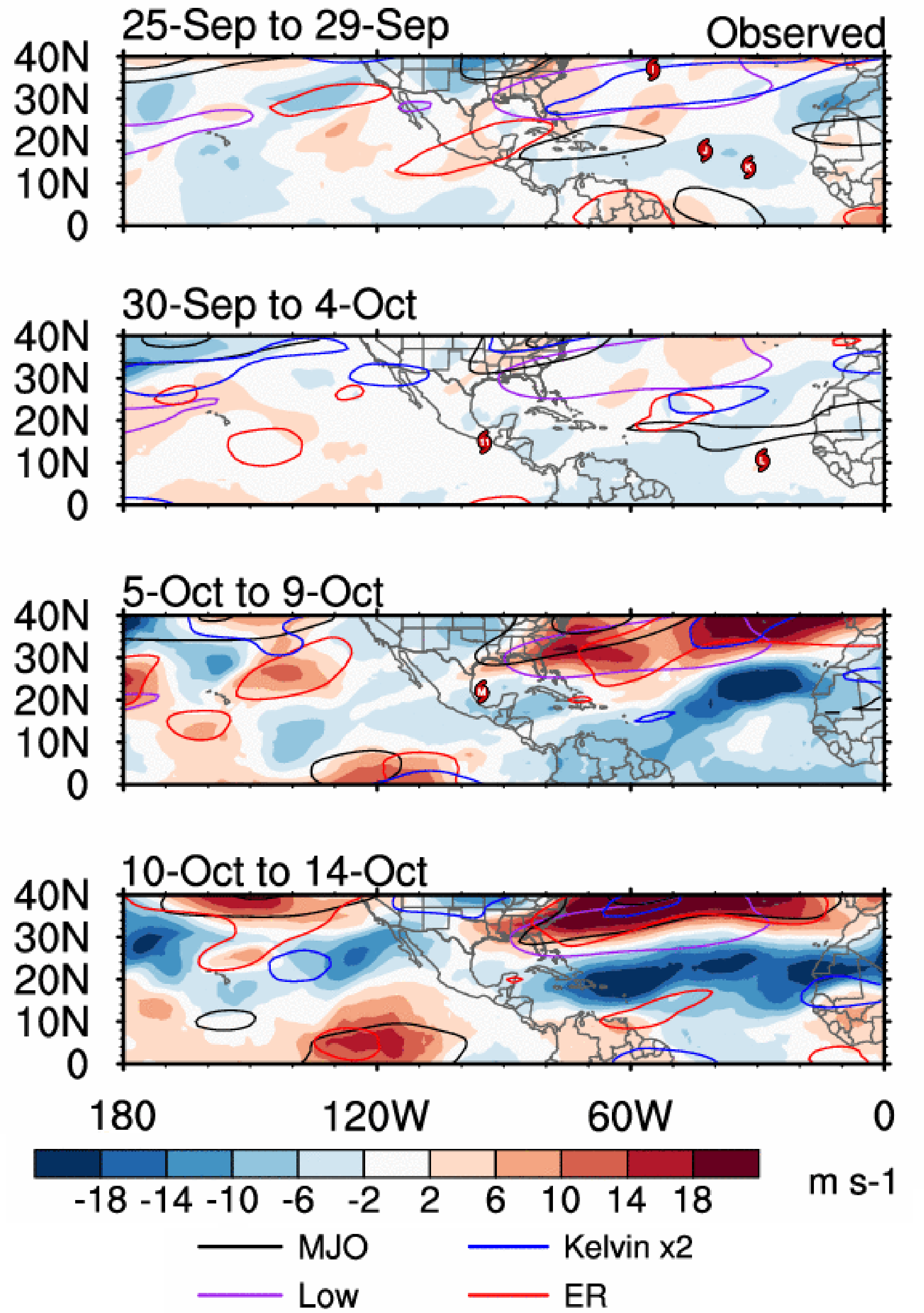



Figure 29: Observed 200 minus 850 hPa zonal shear anomalies across the Western Hemisphere from 25 September–14 October. Figure courtesy of Carl Schreck.

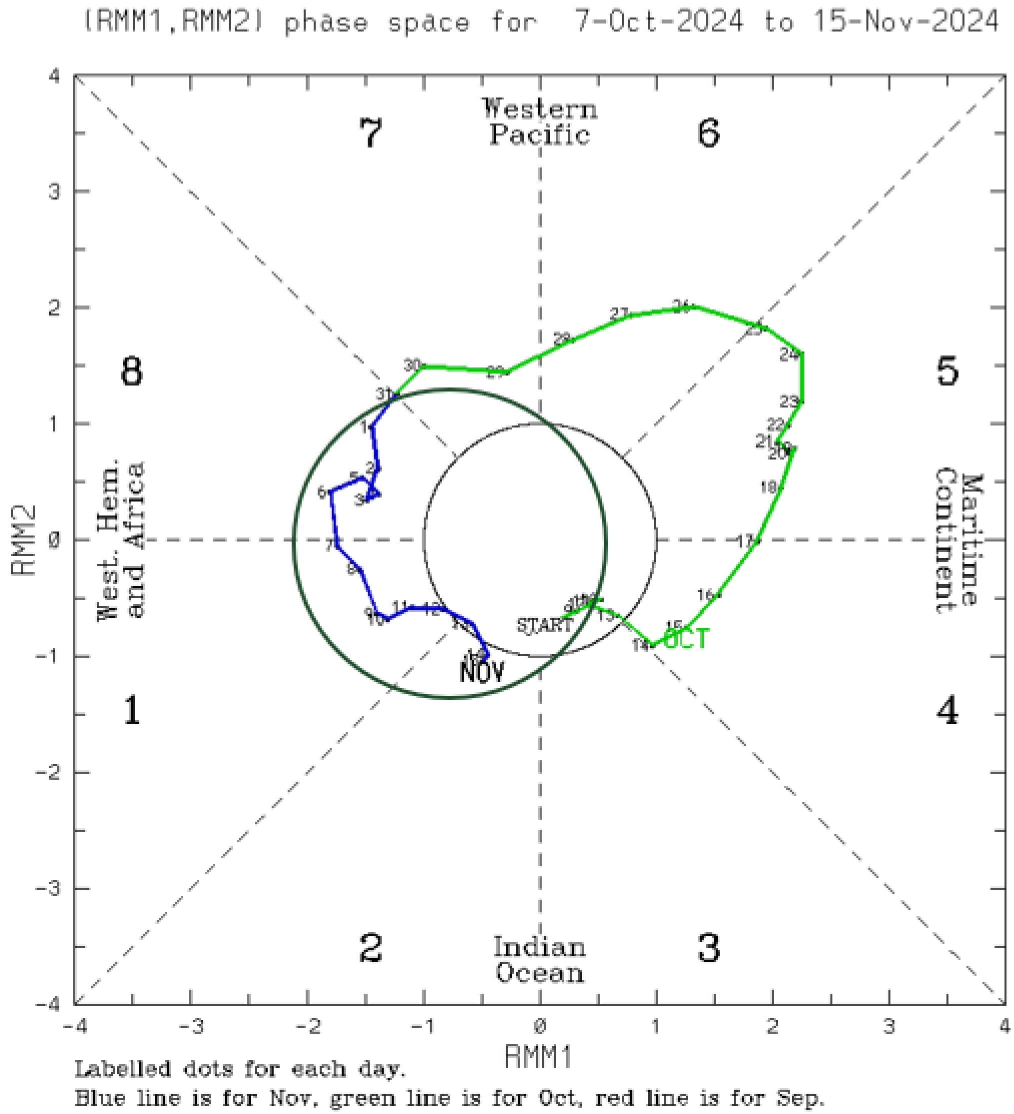



Figure 30: Observed propagation of the Madden-Julian oscillation from 7 October to 15 November. The green circle highlights the first half of November when the MJO was in phases 8–2.

## 8 Forecasts of 2025 Hurricane Activity

We will be issuing our first outlook for the 2025 hurricane season on Thursday, 3 April 2025. This April forecast will include the dates of all our updated 2025 forecasts. All these forecasts will be made available online.

## 8 Verification of Previous Forecasts

Figure 31 displays the observed versus predicted real-time CSU August hurricane forecasts from 1984–2024. The forecast correlates with observations at 0.68, indicating that CSU's August seasonal hurricane forecast can explain ~45% of the variance in observed Atlantic hurricane counts.

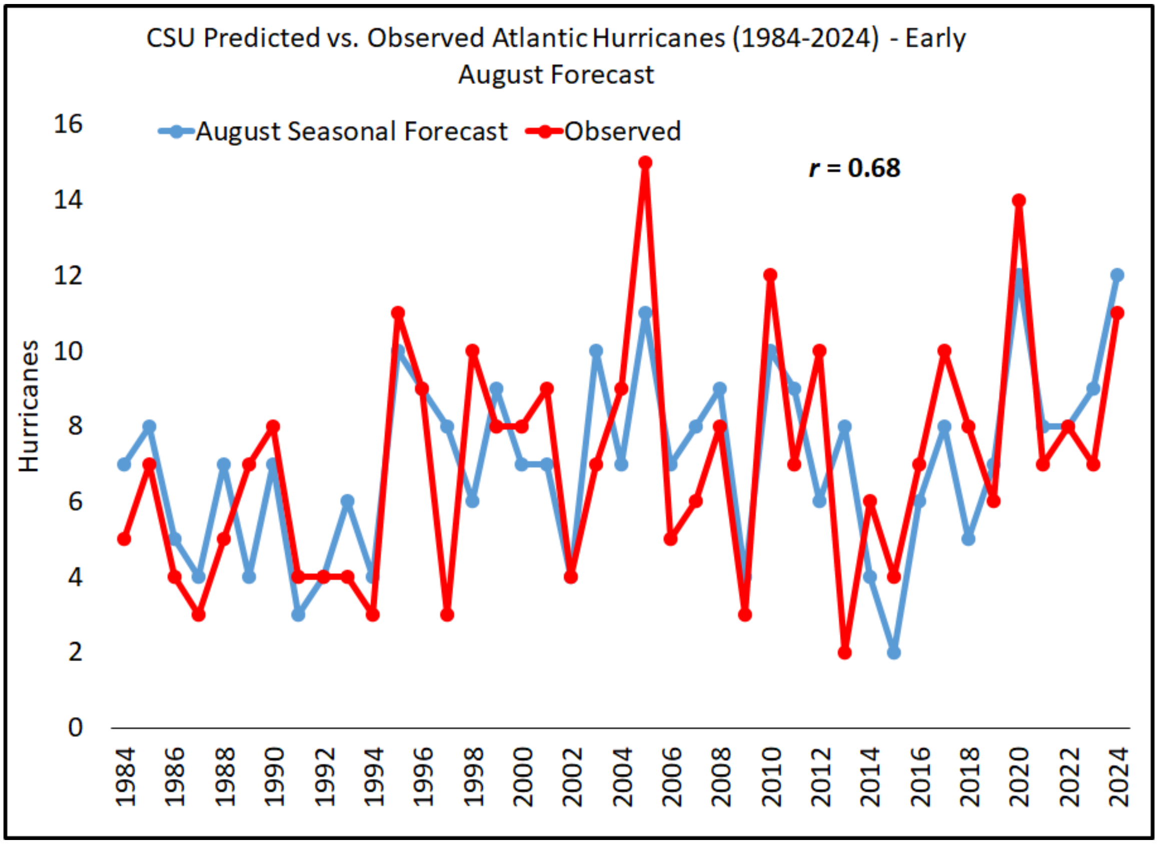



Figure 31: Observed versus predicted Atlantic named storms from 1984–2024.

CSU's seasonal hurricane forecasts have generally shown improvement in recent years, likely due to a combination of improved physical understanding, adoption of statistical/dynamical models and more reliable reanalysis products. Figure 32 displays correlations between observed and predicted Atlantic hurricanes from 1984–2013, from 2014–2024 and from 1984–2024, respectively. Correlation skill has improved at all lead times in recent years for hurricanes, with the most noticeable improvements at longer lead times. While eleven 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.

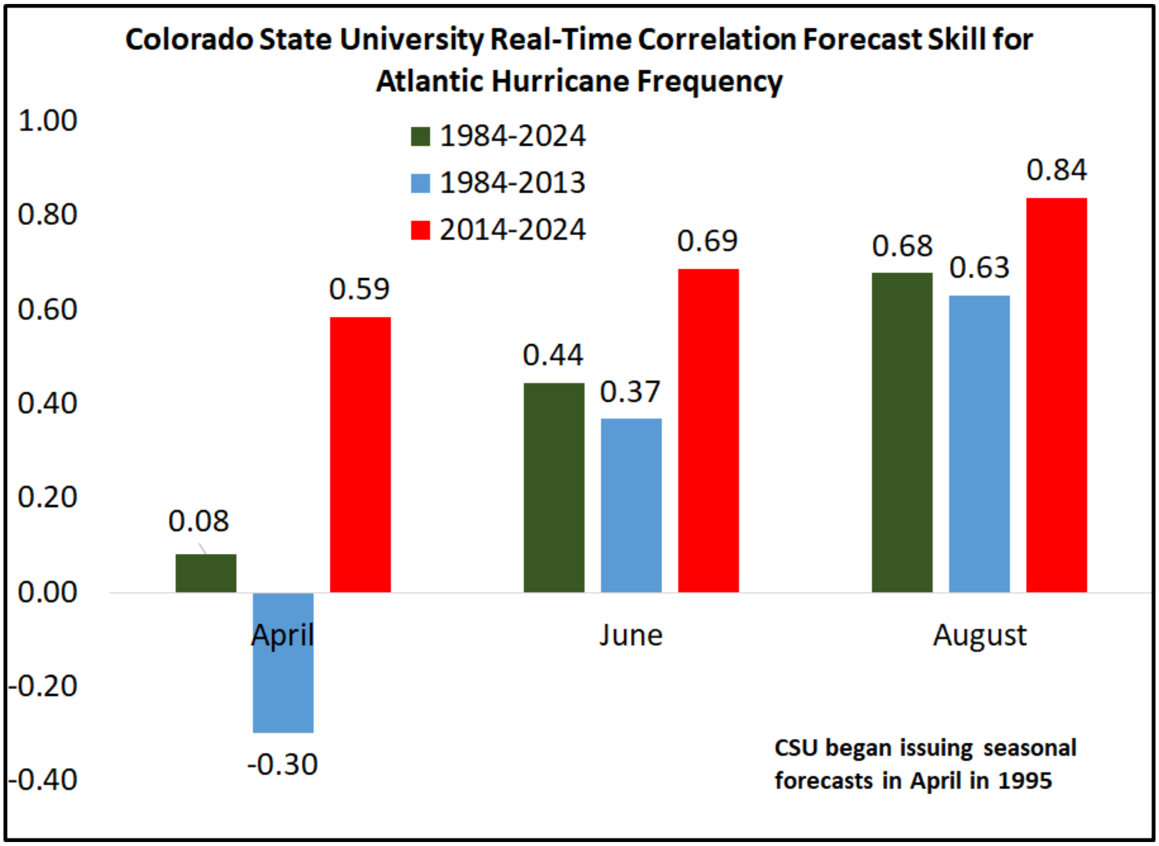



Figure 32: CSU's real-time forecast skill for Atlantic hurricanes using correlation as the skill metric. Correlation skills are displayed for three separate time periods: 1984–2013, 2014–2024 and 1984–2024, respectively.