SUMMARY OF 2022 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF AUTHORS' SEASONAL AND TWO-WEEK FORECASTS

The 2022 Atlantic hurricane season was a near-average season by most metrics, with slightly below-average levels of Accumulated Cyclone Energy. The seasonal hurricane forecasts issued in 2022 by the Tropical Meteorology Project predicted somewhat more activity than was observed. The season's most significant continental US storm was Hurricane Ian, which made landfall in southwest Florida as a Category 4 hurricane, bringing tremendous wind and storm surge damage to southwest Florida as well as significant flooding to large swaths of the state.

By Philip J. Klotzbach[1], Michael M. Bell[2] and Alexander J. DesRosiers[3]
In Memory of William M. Gray[4]

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

Jennifer Dimas, Colorado State University media representative, is coordinating media inquiries into this verification. She can be reached at 970-988-4265 or Jennifer.Dimas@colostate.edu

Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523
Email: philk@atmos.colostate.edu

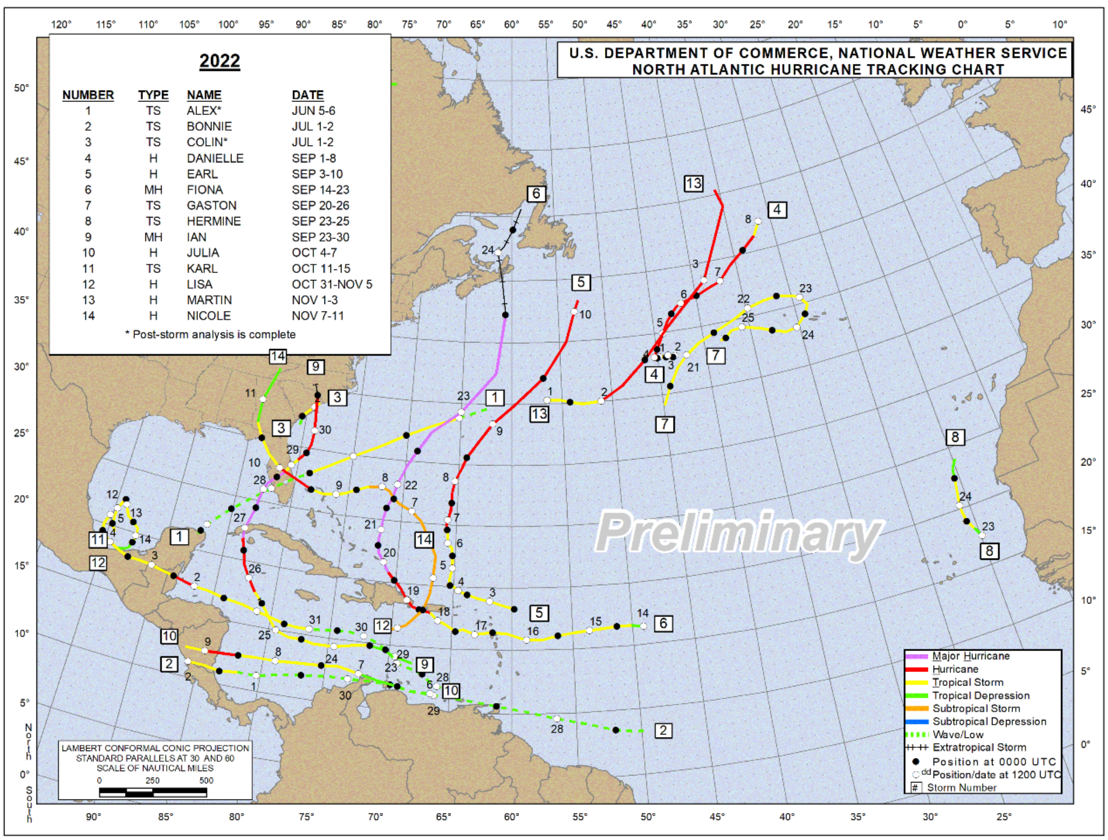
As of 28 November 2022

Project Sponsors:

[1] Senior Research Scientist
[2] Professor
[3] Graduate Research Assistant
[4] Professor Emeritus

ATLANTIC BASIN SEASONAL HURRICANE FORECASTS FOR 2022

Forecast Parameter and 1991-2020 Average (in parentheses)	Issue Date 7 April 2022	Issue Date 2 June 2022	Issue Date 7 July 2022	Issue Date 4 August 2022	**Observed 2022 Activity Thru 11/28**	% of 1991-2020 Average
Named Storms (NS) (14.4)	19	20	20	18	**14**	97%
Named Storm Days (NSD) (69.4)	90	95	95	85	**56.25**	81%
Hurricanes (H) (7.2)	9	10	10	8	**8**	111%
Hurricane Days (HD) (27.0)	35	40	40	30	**21.25**	79%
Major Hurricanes (MH) (3.2)	4	5	5	4	**2**	63%
Major Hurricane Days (MHD) (7.4)	9	11	11	8	**5.75**	78%
Accumulated Cyclone Energy (ACE) (123)	160	180	180	150	**95**	77%
Net Tropical Cyclone Activity (NTC) (135%)	170	195	195	160	**114**	84%



2022 Atlantic basin tropical cyclone tracks through November 28. 14 named storms, 8 hurricanes and 2 major hurricanes occurred. Figure courtesy of NOAA.

ABSTRACT

This report summarizes tropical cyclone (TC) activity which occurred in the Atlantic basin during 2022 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 somewhat over-estimated late-season Caribbean storm activity.

The first quantitative seasonal forecast for 2022 was issued on 7 April with updates on 2 June, 7 July and 4 August. These seasonal forecasts also contained estimates of the probability of US and Caribbean hurricane landfall during 2022.

The 2022 hurricane season was officially a near-normal hurricane season based on NOAA's Accumulated Cyclone Energy (ACE) definition (e.g., the middle tercile from 1951-2020; 73-126 ACE). Overall numbers of named storms and hurricanes were near their 1991-2020 averages, while integrated measures such as Net Tropical Cyclone (NTC) activity and Accumulated Cyclone Energy (ACE) were slightly below their 1991-2020 averages.

Our named storm number and major hurricane number forecasts were lower than what was observed, while our hurricane number forecasts verified well this year. Our seasonal forecasts of Accumulated Cyclone Energy (ACE) predicted more activity than was observed.

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 6 outlooks that were issued.

La Niña conditions prevailed throughout the 2022 Atlantic hurricane season. While La Niña typically decreases tropical Atlantic and Caribbean vertical wind shear, wind shear was elevated across the Caribbean in both August and October. The complete lack of activity in August 2022 was the biggest surprise of the 2022 season.

Tropical Atlantic sea surface temperatures were warmer than normal during the peak of the 2022 hurricane season. Anomalously cool sea surface temperatures in the subtropical Atlantic may have favored anomalously frequent wavebreaking and associated increases in vertical wind shear, especially during August.

The most impactful storm of the 2022 Atlantic hurricane season for the continental US was Hurricane Ian, which made landfall in southwest Florida at Category 4 intensity, causing ~130 fatalities and >50 billion dollars in damage. Hurricane Fiona caused significant damage in both Puerto Rico and Canada's Atlantic Provinces.

DEFINITIONS AND ACRONYMS

Accumulated Cyclone Energy (ACE) - A measure of a named storm's potential for wind and storm surge 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.

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.

Main Development Region (MDR) – An area in the tropical Atlantic where a majority of major hurricanes form, which we define as 7.5-22.5°N, 75-20°W.

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 1950-2000 average value of this parameter is 100.

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

Thermohaline Circulation (THC) – A large-scale circulation in the Atlantic Ocean that is driven by fluctuations in salinity and temperature. When the THC 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 a number of 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 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 Carl Schreck, Louis-Philippe Caron, Brian McNoldy, Paul Roundy, Jason Dunion, 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 from zero 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 a number of 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 a large number of 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 atmospheric input to our statistical models and the high resolution NOAA Optimum Interpolation sea surface temperature (SST) dataset as the SST 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 2022, these predictions used the current ECMWF climate model (SEAS5), Met Office climate model (GloSea6) and Japan Meteorological Agency (JMA) climate model to predict the large-scale conditions in July that underpin the early August statistical seasonal hurricane forecast model. The early August outlook incorporated forecasts of these three climate models of tropical Atlantic and Caribbean August-September vertical wind shear and SST. 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 and JMA.

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 there is a rather high (50-60 percent) degree of year-to-year hurricane forecast potential if one combines 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 3-4 other predictors.

In a four-predictor empirical forecast model, the contribution of each predictor to the net forecast skill can only be determined by the separate elimination of each parameter from the full four-predictor model while noting the hindcast skill degradation. When taken from the full set of predictors, one parameter may degrade the forecast skill by 25-30 percent, while another degrades the forecast skill by only 10-15 percent. An individual parameter that, through elimination from the forecast, degrades a forecast by as much as 25-30 percent may, in fact, by itself, show less direct correlation with the predictand. A direct correlation of a forecast parameter may not be the best measure of the importance of this predictor to the skill of a 3-4 parameter forecast model. This is the nature of the seasonal or climate forecast problem where one is dealing with a very complicated atmospheric-oceanic system that is highly non-linear. There is a maze of changing physical linkages between the many variables. These linkages can undergo unknown changes from weekly to decadal time scales. It is impossible to fully understand how all these processes interact with each other. Despite the complicated relationships that are involved, all of our statistical and statistical/dynamical models show considerable hindcast skill. We are confident that in applying these skillful hindcasts to future forecasts that appreciable real-time skill will continue to result.

2 Tropical Cyclone Activity for 2022

Figure 1 and Table 1 summarize Atlantic basin TC activity that occurred in 2022. Overall, the season had near-average activity, with near-average numbers of named storms and hurricanes and slightly below-average numbers of major hurricanes. Online entries from Wikipedia are available for in-depth discussions of each TC that occurred in 2022. The National Hurricane Center is also currently in the process of writing up extensive reports on all 2022 TCs.

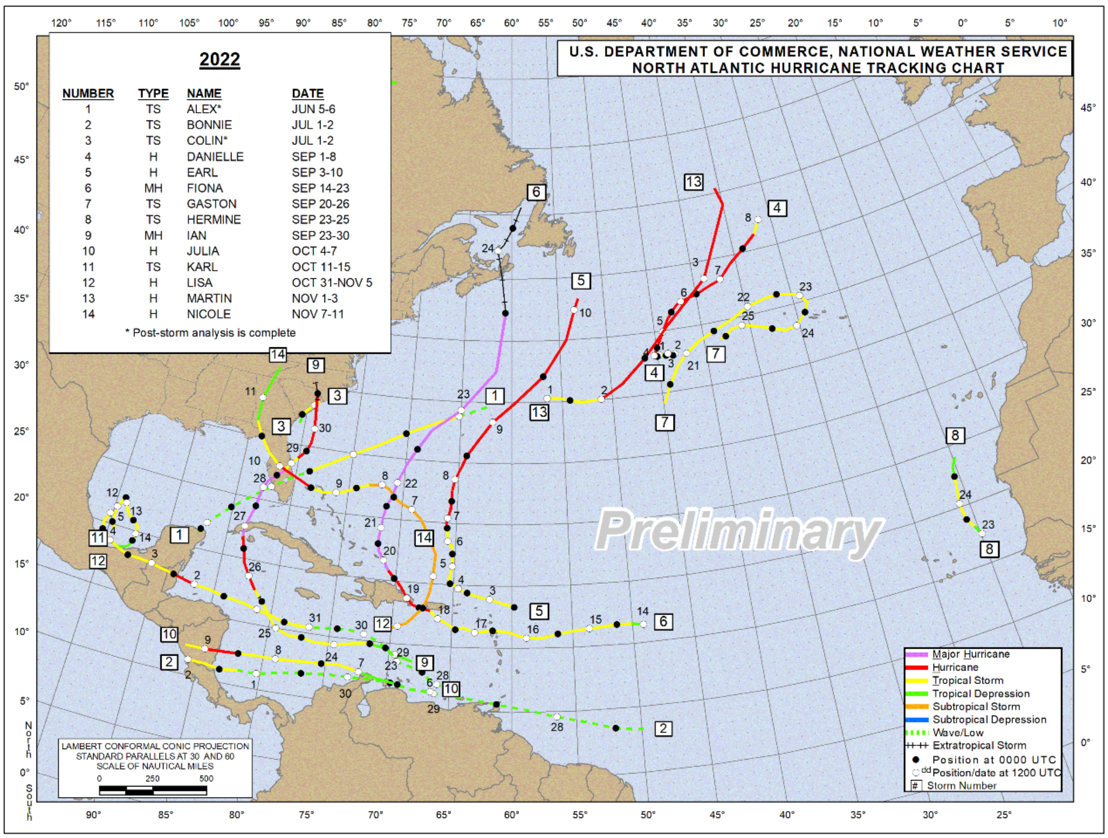


Figure 1: 2022 Atlantic basin TC tracks through November 28. 14 named storms, 8 hurricanes and 2 major hurricanes occurred. Figure courtesy of NOAA.

Table 1: Observed 2022 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 2022

Year	Storm#	Name	Dates TC Active	Max Wind (kts)	MSLP (mb)	Named Storm Days	Hurricane Days	Major Hurricane Days	Accumulated Cyclone Energy
2022	1	ALEX	6/5-6/6	60	984	1.50	0.00	0.00	1.8
2022	2	BONNIE	7/1-7/2	50	996	1.00	0.00	0.00	0.7
2022	3	COLIN	7/2-7/2	35	1012	0.75	0.00	0.00	0.4
2022	4	DANIELLE	9/1-9/8	80	972	7.25	5.00	0.00	12.5
2022	5	EARL	9/3-9/10	90	954	7.75	3.75	0.00	14.2
2022	6	FIONA	9/14-9/23	115	932	9.25	5.25	3.75	26.3
2022	7	GASTON	9/20-9/26	55	995	5.50	0.00	0.00	5.2
2022	8	IAN	9/24-9/30	135	937	7.00	4.25	2.00	17.4
2022	9	HERMINE	9/23-9/24	35	1002	1.25	0.00	0.00	0.6
2022	10	JULIA	10/7-10/9	75	982	2.50	0.75	0.00	2.9
2022	11	KARL	10/11-10/14	50	999	3.25	0.00	0.00	2.1
2022	12	LISA	10/31-11/3	70	988	3.00	0.50	0.00	3.3
2022	13	MARTIN	11/1-11/3	75	960	2.25	1.25	0.00	3.7
2022	14	NICOLE	11/7-11/11	65	980	4.00	0.50	0.00	4.0

3 Special Characteristics of the 2022 Hurricane Season

The 2022 hurricane season was classified as normal overall based on the NOAA ACE season type definition. Named storm and hurricane numbers were near average, while most aggregate indices including ACE were slightly below the 1991-2020 average.

Below is a selection of some of the notable statistics from the 2022 season:

Basinwide Statistics

- 14 named storms formed in the Atlantic this season. This is the 7th straight season where the Atlantic has had at least 14 named storm formations. The last season below the 1991-2020 average of 14 named storms was 2015 (when 11 named storms formed).

- 95 ACE was generated during 2022, making the 2022 Atlantic hurricane season a near-average season by the NOAA definition. This is the first Atlantic season not classified as above average (>126 ACE) since 2015.

- The Atlantic had no named storm activity between July 3 and August 31 – the 1st time since 1941 that the Atlantic had no named storm activity between those dates.

- 4 hurricanes (Danielle, Earl, Fiona and Ian) formed in the Atlantic between September 2 – 26 – the 7th time since the start of the active era (since 1995) that this has occurred. The other six years were: 1998, 2001, 2005, 2010, 2017, 2020.

- The Atlantic produced only 5 ACE during October 2022 – the lowest ACE generated during October since 2009.

- 3 hurricanes formed during November (Lisa, Martin and Nicole), tying 2022 with 2001 for the most November Atlantic hurricane formations on record.

Individual Storm/Landfall Statistics

- Hurricane Danielle generated ~13 ACE – the most by an Atlantic named storm forming north of 38°N on record.

- Hurricane Fiona, as a post-tropical cyclone, made landfall with an estimated central pressure of ~931 hPa in Nova Scotia – the lowest pressure recorded for a landfalling storm in Canada on record

- Hurricane Ian made landfall with maximum sustained winds of 130 kt. Ian is tied with five other hurricanes for the 5th strongest continental US hurricane landfall on record, trailing only the four landfalling Category 5 continental US hurricanes (Florida Keys-1935, Camille-1969, Andrew-1992, Michael-2018)

- Hurricanes Lisa and Martin had maximum sustained winds of 75 kt simultaneously in November – the first time that two hurricanes have had maximum sustained winds of 75+ kt in November simultaneously since 1932

- Hurricane Lisa made landfall on November 2 in Belize – the first landfalling hurricane in Belize in November since 1942

- Hurricane Nicole was the latest calendar year hurricane to make landfall along the east coast of Florida on record

4 Quantitative Verification of 2022 Atlantic Hurricane Forecasts

4.1 Verification of Seasonal Forecasts

Table 2 is a comparison of our forecasts for 2022 for four different lead times along with this year's observations. The 2022 Atlantic hurricane season ended up near average.

Table 2: Verification of our 2022 seasonal hurricane predictions.

Forecast Parameter and 1991-2020 Average (in parentheses)	Issue Date 7 April 2022	Issue Date 2 June 2022	Issue Date 7 July 2022	Issue Date 4 August 2022	Observed 2022 Activity Thru 11/28
Named Storms (NS) (14.4)	19	20	20	18	14
Named Storm Days (NSD) (69.4)	90	95	95	85	56.25
Hurricanes (H) (7.2)	9	10	10	8	8
Hurricane Days (HD) (27.0)	35	40	40	30	21.25
Major Hurricanes (MH) (3.2)	4	5	5	4	2
Major Hurricane Days (MHD) (7.4)	9	11	11	8	5.75
Accumulated Cyclone Energy (ACE) (123)	160	180	180	150	95
Net Tropical Cyclone Activity (NTC) (135%)	170	195	195	160	114

Table 3 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 25% of all forecast parameters fell within the 70% confidence interval in 2022. As noted earlier, our forecasts generally over-predicted Atlantic hurricane activity in 2022. Using the total number of parameters within the 70% confidence interval as a skill metric, this forecast was the least skillful overall forecast from CSU since 2017 (when we under-predicted the extremely active season).

Table 3: Verification of CSU's 2022 seasonal hurricane predictions with 70% confidence intervals.

Forecast Parameter and 1991-2020 Average (in parentheses)	Issue Date 7 April 2022	Issue Date 2 June 2022	Issue Date 7 July 2022	Issue Date 4 August 2022	Observed 2022 Activity Thru 11/28
Named Storms (NS) (14.4)	16-23	17-23	17-23	15-21	14
Named Storm Days (NSD) (69.4)	67-114	73-117	75-116	66-104	56.25
Hurricanes (H) (7.2)	**7-12**	**8-12**	**8-12**	**6-10**	8
Hurricane Days (HD) (27.0)	22-50	27-55	28-54	**20-42**	21.25
Major Hurricanes (MH) (3.2)	**2-6**	3-7	3-7	3-5	2
Major Hurricane Days (MHD) (7.4)	6-14	7-17	7-16	**5-12**	5.75
Accumulated Cyclone Energy (ACE) (123)	106-220	127-238	130-234	107-198	95
Net Tropical Cyclone Activity (NTC) (135%)	117-227	143-249	147-246	118-205	114

4.2 Verification of Two-Week Forecasts

This is the 14th 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 mid-August to mid-November. In general, the MJO was relatively favorable for Atlantic TC activity in the latter part of August, with convection enhanced over Africa and the Indian Ocean. This would typically favor a busy period for Atlantic hurricane activity. The MJO was generally quite weak during September. Over the past few weeks, the MJO has predominately been enhancing convection over the tropical Pacific. These phases tend to suppress Atlantic hurricane activity due to increases in vertical wind shear and may be somewhat responsible for the quiet October that was observed (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 1966-2021 and defining above-normal, normal and below-normal two-week periods based on terciles. Since there are 56 years from 1966-2021, 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 18 years are counted as the middle tercile. Forecasts are issued in probabilistic format for each tercile.

Table 4 displays the six two-week forecasts that were issued during the 2022 hurricane season and shows their verification. We assigned the highest probability to the correct category for three of the six two-week periods. Most surprising was the two-week period during late August (August 18-31) where no Atlantic named storms occurred. We assigned a 70% chance of normal TC activity occurring during that two-week period given relatively favorable MJO phases.

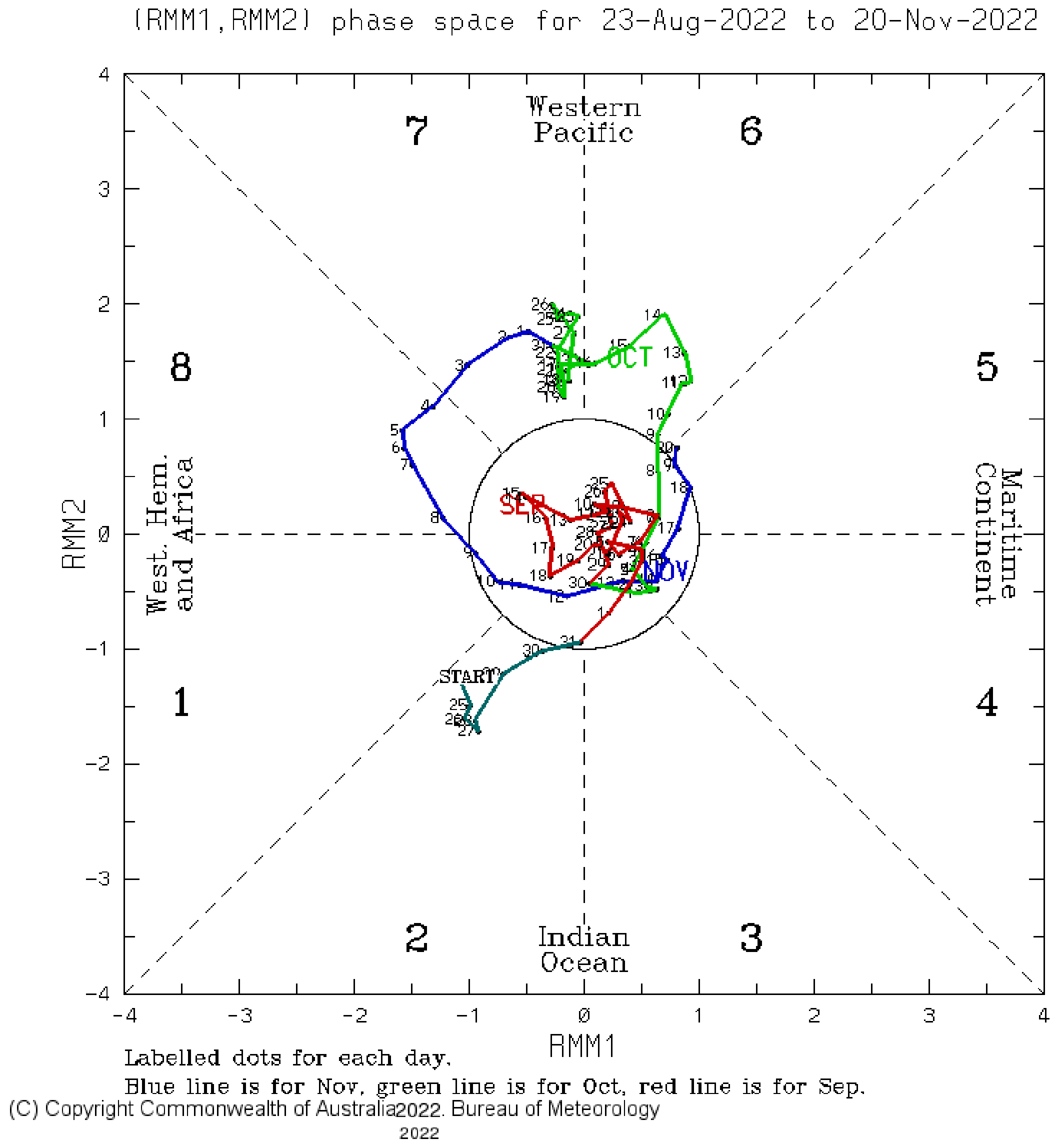


Figure 2: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 23 to November 20. The Maritime Continent refers to Indonesia and the surrounding islands. RMM stands for Real-Time Multivariate MJO. Figure courtesy of Bureau of Meteorology.

Table 4: Two-week Atlantic ACE forecast verification for 2022. Forecasts that verified in the correct category (or the category with the highest probability) are highlighted in blue, while forecasts that missed by one category are highlighted in green. 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
8/4 – 8/17	**Normal (2-5) (50%)**	**0 (40%)**
8/18 – 8/31	**Normal (7-21) (70%)**	**0 (15%)**
9/1 – 9/14	**Normal (12-32) (70%)**	**27 (70%)**
9/15 – 9/28	**Above-Normal (>26) (50%)**	**45 (50%)**
9/29 – 10/12	**Above-Normal (>12) (55%)**	**8 (40%)**
10/13 – 10/26	**Normal (1-9) (90%)**	**1 (90%)**

4.3 Verification of October-November Caribbean ACE Forecast

The October-November Caribbean ACE forecast for 2022 was somewhat of an over forecast. We define ACE generated in the region between 10-20°N, 88-60°W as Caribbean ACE. While the two-month period did generate two hurricanes in the Caribbean (Julia and Lisa), both of these storms did not reach hurricane strength until just before landfall in Central America. Consequently, they did not generate particularly large levels of ACE. The two-predictor model that comprises the Caribbean ACE forecast called for a well above-median two-month period, with 15 ACE predicted. The 1991-2020 mean Caribbean ACE is 8, and the median 1991-2020 Caribbean ACE is 2, highlighting the skewed distribution of late-season Caribbean ACE. 6 ACE were generated in the Caribbean during October-November 2022.

5 Landfall Analysis

The 2022 Atlantic hurricane season was near average for continental US landfall frequency, with three named storms (Colin, Ian and Nicole) and two hurricanes (Ian and Nicole) making landfall (Figure 3). 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. We do plot Ian's second landfall in South Carolina in Figure 3, given that this landfall was several hundred miles away from its first landfall in Florida. The most notable continental US hurricane landfall (Ian) was extremely intense (Category 4) and impactful, causing ~130 fatalities in the continental United States and over $50 billion USD in damage according to the National Centers for Environmental Information.

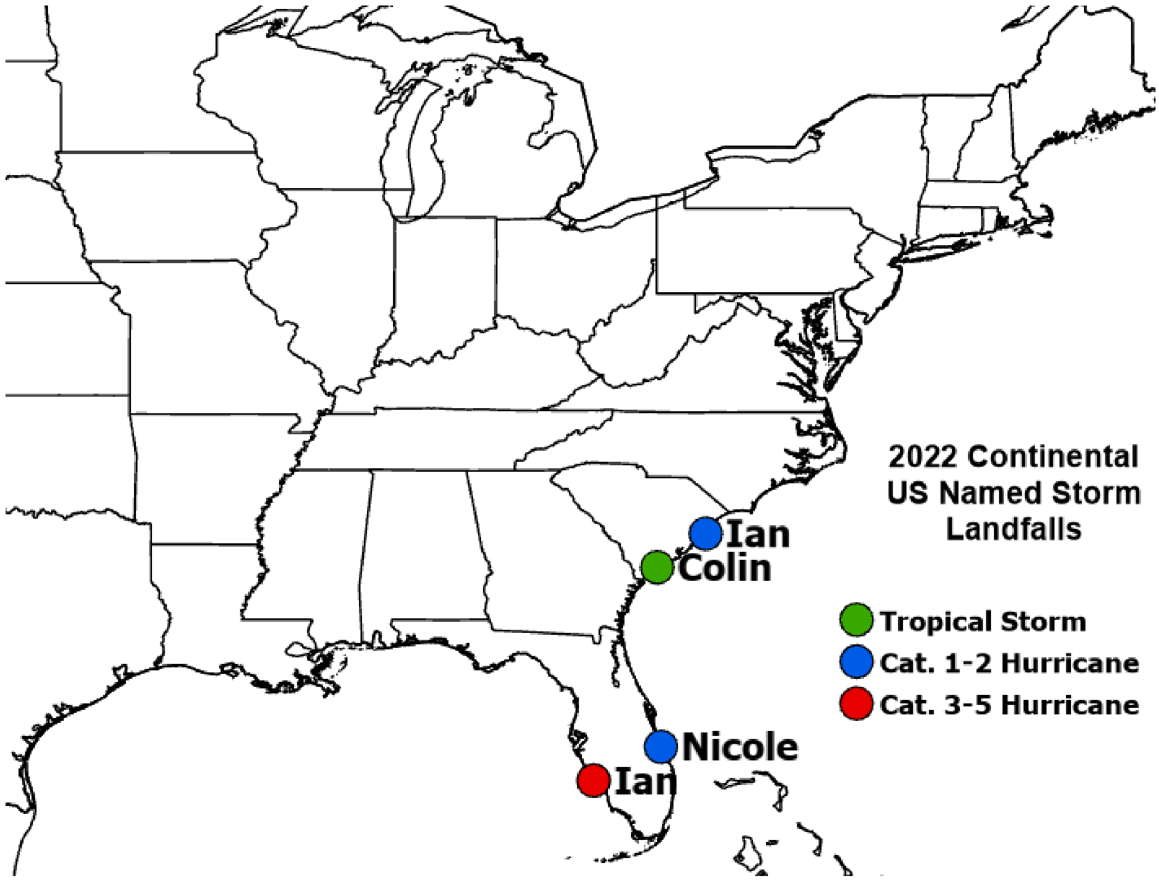


Figure 3: Location of the named storms making landfall in the continental US during the 2022 Atlantic hurricane season.

This year, we continued to calculate the impacts of tropical cyclones 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 tropical cyclones that may have made landfall in an immediately adjacent region to be counted for all regions that were in close proximity to 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.

Net landfall probability is shown to be linked to the overall Atlantic basin Net Tropical Cyclone activity (NTC; see Table 5). NTC is a combined measure of the year-to-year mean of six indices of hurricane activity, each expressed as a percentage difference from the 1950-2000 climatological average. Long-term statistics show that, on average, the more active the overall Atlantic basin hurricane season is, the greater the probability of U.S. hurricane landfall.

Table 5: NTC activity in any year consists of the seasonal total of the following six parameters expressed in terms of their long-term averages. A season with 10 NS, 50 NSD, 6 H, 25 HD, 3 MH, and 5 MHD would then be the sum of the following ratios: 10/9.6 = 104, 50/49.1 = 102, 6/5.9 = 102, 25/24.5 = 102, 3/2.3 = 130, 5/5.0 = 100, divided by six, yielding an NTC of 107.

	1950-2000 Average	
1)	Named Storms (NS)	9.6
2)	Named Storm Days (NSD)	49.1
3)	Hurricanes (H)	5.9
4)	Hurricane Days (HD)	24.5
5)	Major Hurricanes (MH)	2.3
6)	Major Hurricane Days (MHD)	5.0

Since the 2022 Atlantic hurricane season was predicted to be above-average, landfall probabilities at all lead times were elevated. As an example, Table 6 displays the landfall probabilities that were issued with the April 2022 outlook. As noted earlier, the 2022 Atlantic hurricane season had a near-average number of continental US named storm landfalls including one major hurricane landfall (Ian).

Table 6: 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 2022, based on the April CSU seasonal hurricane forecast.

		2022 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	77%	43%	13%	58%	28%	8%
Connecticut	34%	12%	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%	12%	53%	28%	8%
New Hampshire	29%	9%	2%	18%	6%	1%
New Jersey	35%	11%	1%	23%	7%	1%
New York	40%	16%	4%	26%	9%	2%
North Carolina	85%	56%	12%	68%	38%	8%
Rhode Island	32%	12%	2%	20%	8%	1%
South Carolina	76%	44%	13%	57%	29%	8%
Texas	80%	54%	25%	61%	36%	16%
Virginia	65%	31%	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 2022 Atlantic basin hurricane season.

6.1 ENSO

Using the Oceanic Nino Index to define ENSO events, La Niña conditions have been present since July-September of 2021. The Oceanic Niño Index is defined to be three-month-averaged SST anomalies averaged over the region 5°S-5°N, 170-120°W, also known as the Niño 3.4 region. From our early April forecast, we correctly predicted that El Niño was unlikely for the 2022 hurricane season. We anticipated that either cool neutral ENSO or La Niña conditions were likely to occur during the peak of the Atlantic hurricane season (August-October). The August-October-averaged Oceanic Niño Index was -1.0°C, which is the coldest August-October value for this index since 2010. Below are some quotes excerpted from our seasonal forecasts issued this year discussing our thoughts on the likely state of ENSO.

(7 April 2022) –

"We believe that the odds of a significant El Niño event for the 2022 Atlantic hurricane season are quite small."

(2 June 2022) –

"Based on the above information, our best estimate is that we will likely not have El Niño conditions for the peak of the Atlantic hurricane season."

(5 August 2022) –

"We favor the cooler model solutions (e.g., La Niña) given the current upwelling Kelvin wave and the forecast anomalously strong trade winds."

The dynamical and statistical models initialized during the late winter/early spring generally over-predicted ENSO SSTs during the peak of the Atlantic hurricane season. Figure 4 displays the ECMWF seasonal forecast for Niño 3.4 from 1 March, which is the forecast information that we had available for our early April seasonal forecast. The observed values were much lower than the ensemble average and lower than all ensemble members by May. The observed values remained lower than all ensemble members through September (when the 1 March forecast terminated). Figure 5 displays the March ENSO prediction plume from 24 statistical and dynamical models. The observed monthly ENSO values during the Atlantic hurricane season were cooler than most forecast models for the peak of the Atlantic hurricane season. The Community Climate System Model version 4 had the closest forecast to observations for August-October.

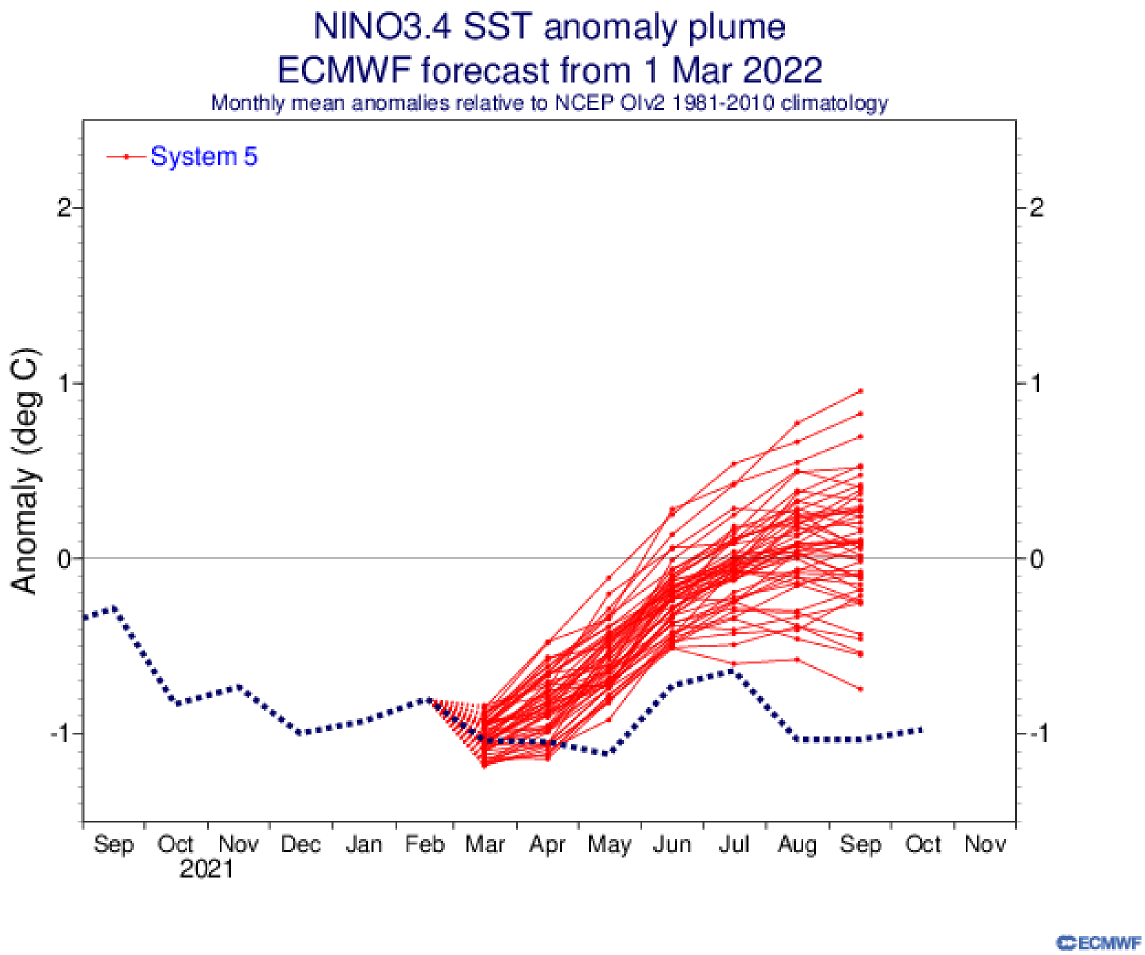


Figure 4: ECMWF ensemble prediction for Niño 3.4 from 1 March – the most recent information that we had available for our early April forecast in 2022. The blue dotted line represents the observed value.

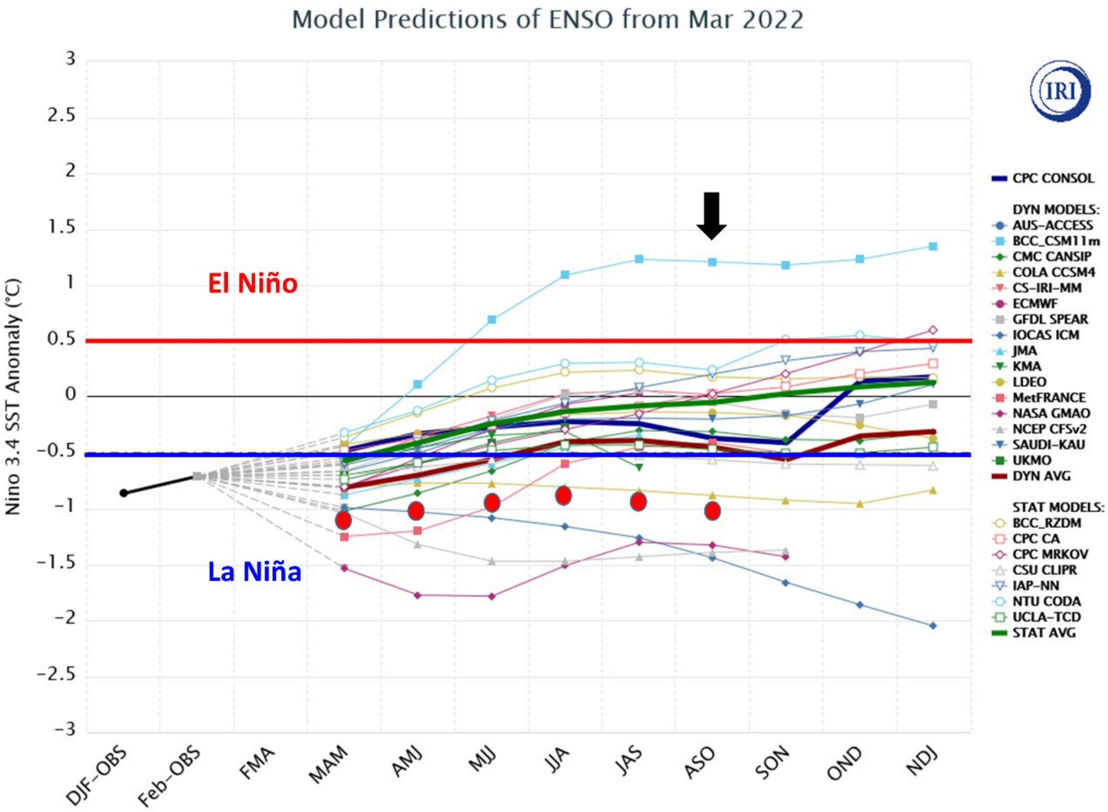


Figure 5: Ensemble prediction from 24 statistical and dynamical models for Niño 3.4 from mid-March. The black arrow highlights August-October – the peak three months of the Atlantic hurricane season. Red dots represent observed values for each three-month period. Figure adapted from International Research Institute website.

La Niña conditions have prevailed throughout 2022. There was some slight anomalous warming from the spring to the summer, but there has since been some anomalous cooling. Table 7 displays anomalies in the various Niño regions in January, April, July and October 2022, respectively.

Table 7: January 2022 anomalies, April 2022 anomalies, July 2022 anomalies, and October 2022 anomalies for the Niño 1+2, Niño 3, Niño 3.4 and Niño 4 regions. SST anomaly differences from January 2022 are in parentheses.

Region	January 2022 Anomaly (ºC)	April 2022 Anomaly (ºC)	July 2022 Anomaly (ºC)	October 2022 Anomaly (ºC)
Niño 1+2	-0.7	-1.4 (-0.7)	-1.2 (-0.5)	-1.8 (-1.1)
Niño 3	-1.2	-0.9 (+0.3)	-0.4 (+0.8)	-0.9 (+0.3)
Niño 3.4	-0.8	-1.0 (-0.2)	-0.7 (+0.1)	-0.9 (-0.1)
Niño 4	-0.2	-0.7 (-0.5)	-0.9 (-0.7)	-1.1 (-0.9)

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 6). Upper-ocean heat content anomalies were below-average through

December 2021, anomalously warmed quickly through early February, anomalously cooled through the middle of March, then slowly anomalously warmed through mid-June. A strong trade wind surge caused quick anomalous cooling through early August. Since that time, upper-ocean heat content anomalies have remained well below average. Current upper ocean heat content anomalies in the eastern and central tropical Pacific are typically associated with weak to moderate La Niña events.

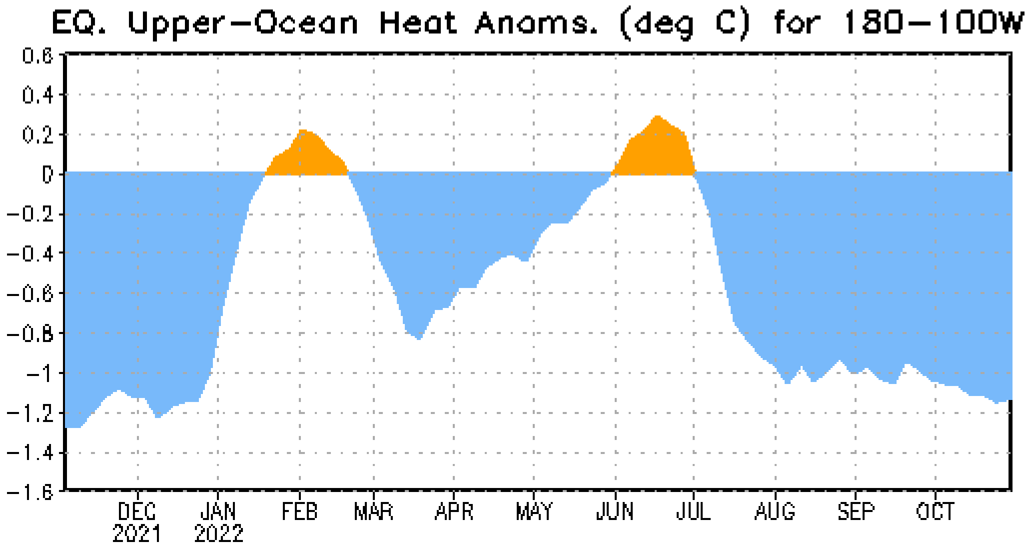


Figure 6: Upper ocean (0-300 meter) heat content anomalies in the eastern and central tropical Pacific from December 2021 – November 2022.

6.2 Intra-Seasonal Variability

The MJO was relatively weak during early August and then amplified over Africa and the Indian Ocean during the latter part of August, which normally would favor a busy period for Atlantic hurricane activity (Figure 7). During most of September, the MJO was quite weak. However, during October, the MJO persisted over the tropical Pacific, likely contributing to the increased vertical wind shear that was observed, especially in the Caribbean and the tropical Atlantic. Table 7 displays the historical relationship between MJO and Atlantic TC activity.

When looking at monthly ACE in 2022 compared with normal (Figure 8), the biggest surprise of the season was the lack of any named storm activity during August. June had near average activity, July was quiet, August had no activity, September was above the long-term average, and October was relatively quiet. November was quite busy. While some of the peaks/valleys of the 2022 Atlantic hurricane season were likely due to tropically-generated intraseasonal variability such as the MJO, the extremely quiet August likely had a significant mid-latitude component (discussed in detail in Section 7.1), given that the MJO and its associated tropical forcing would have favored a busy second half of August.

Table 8 displays the number of storms that were first named in each phase of the MJO over the course of the 2022 Atlantic hurricane season. Another surprise of the 2022 season was that no named storms formed in phases 1-2 of the MJO, which historically are the phases that favor the most Atlantic named storm formations. This also contrasts markedly with 2021, when 12 of the 21 Atlantic named storms formed in phases 1-2.

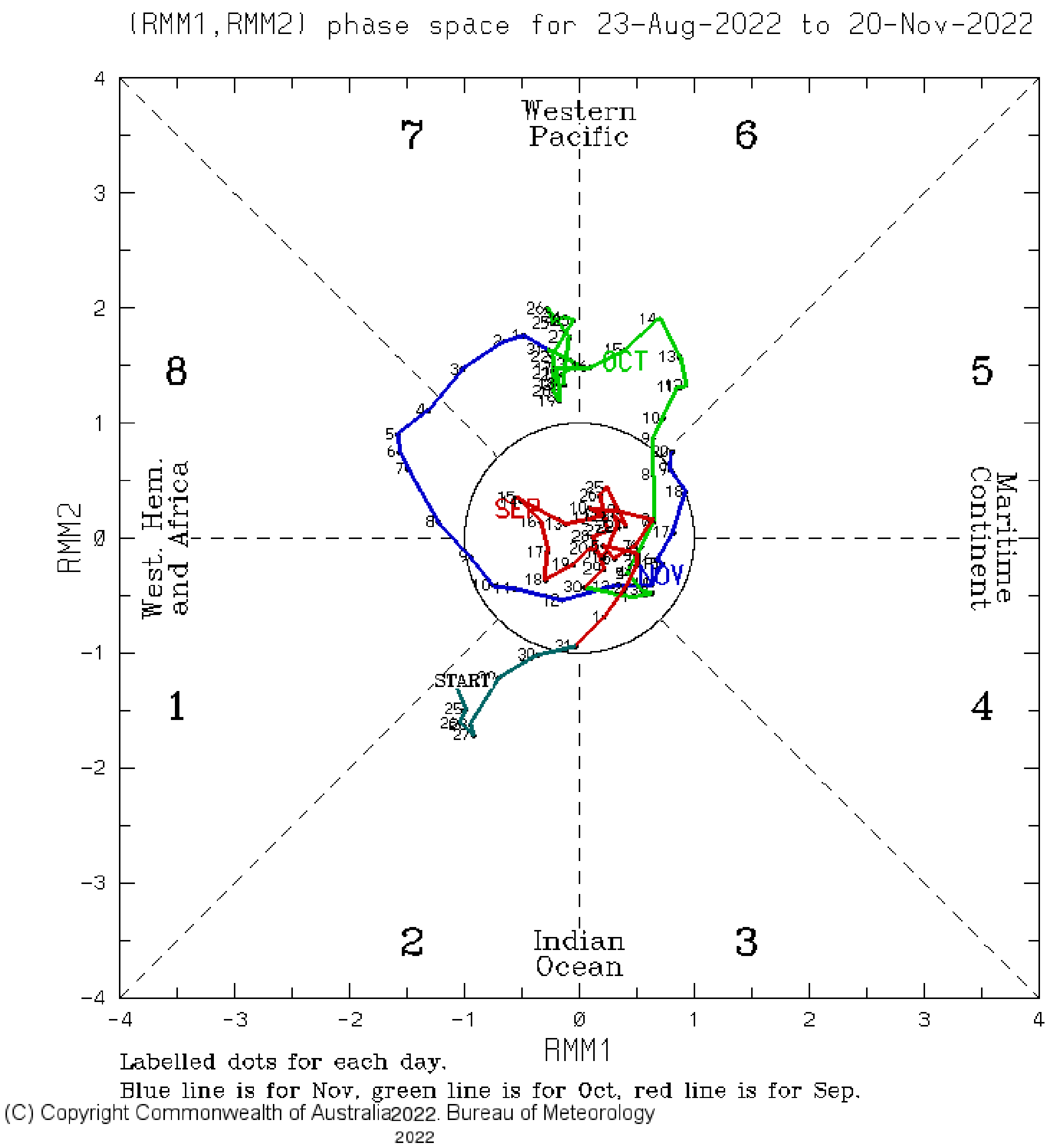


Figure 7: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 23 to November 20. Figure courtesy of [Bureau of Meteorology](#).

Table 7: Normalized values of named storms (NS), named storm days (NSD), hurricanes (H), hurricane days (HD), major hurricanes (MH), major hurricane days (MHD) and Accumulated Cyclone Energy (ACE) generated by all TCs forming in each phase of the MJO over the period from 1974-2007. Normalized values are calculated by dividing storm activity by the number of days spent in each phase and then multiplying by 100. This provides the level of TC activity that would be expected for 100 days given a particular MJO phase.

MJO Phase	NS	NSD	H	HD	MH	MHD	ACE
Phase 1	6.4	35.9	3.7	17.9	1.8	5.3	76.2
Phase 2	7.5	43.0	5.0	18.4	2.1	4.6	76.7
Phase 3	6.3	30.8	3.0	14.7	1.4	2.8	56.0
Phase 4	5.1	25.5	3.5	12.3	1.0	2.8	49.4
Phase 5	5.1	22.6	2.9	9.5	1.2	2.1	40.0
Phase 6	5.3	24.4	3.2	7.8	0.8	1.1	35.7
Phase 7	3.6	18.1	1.8	7.2	1.1	2.0	33.2
Phase 8	6.2	27.0	3.3	10.4	0.9	2.6	46.8
Phase 1-2	7.0	39.4	4.3	18.1	1.9	4.9	76.5
Phase 6-7	4.5	21.5	2.5	7.5	1.0	1.5	34.6
Phase 1-2 / Phase 6-7	1.6	1.8	1.7	2.4	2.0	3.2	2.2

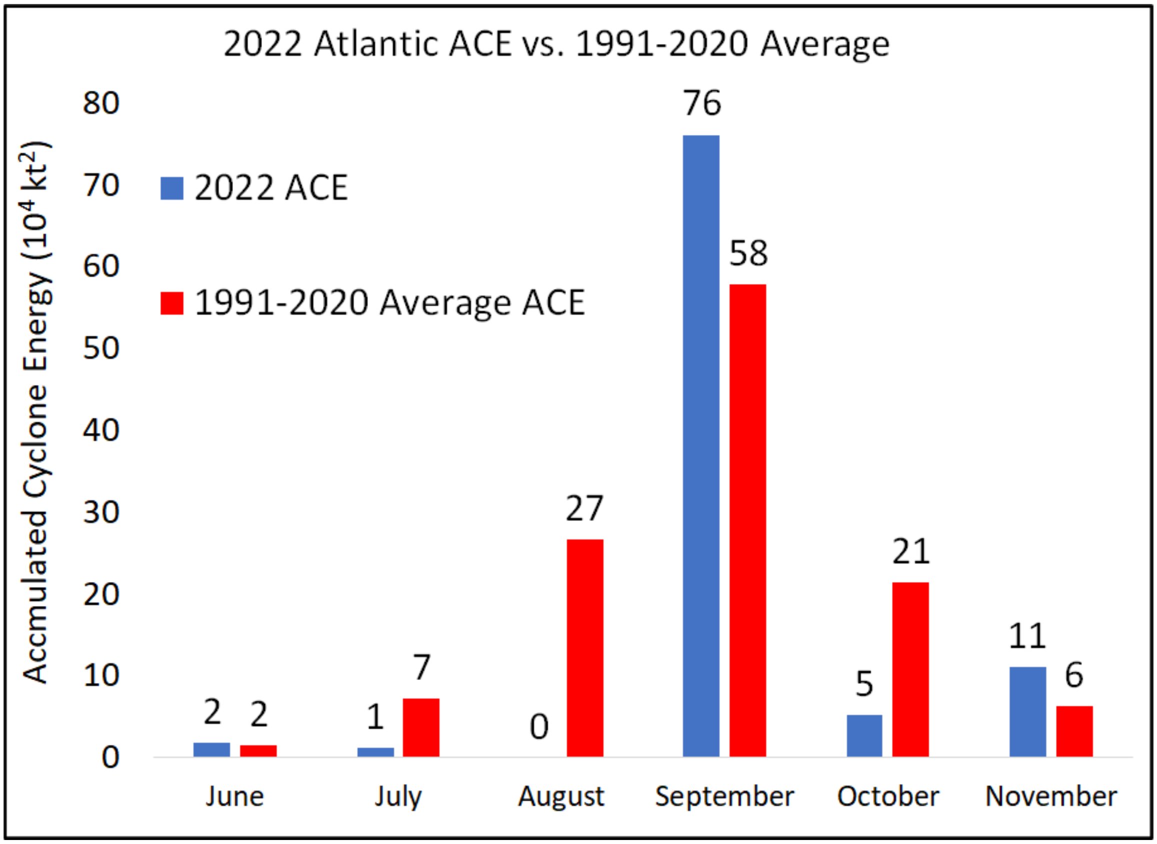


Figure 8: Atlantic Accumulated Cyclone Energy generated by month during 2022 (blue columns) compared with the 1991-2020 average (red columns)

Table 8: TC formations by MJO phase during the 2022 Atlantic hurricane season.

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

6.3 Atlantic SST

The early April seasonal Atlantic hurricane forecast called for an above-normal season, due in part to warm water anomalies across the eastern subtropical Atlantic (Figure 9). While the tropical Atlantic had near-average SST anomalies in March, anomalous warmth in the eastern subtropical Atlantic during the early spring has a stronger correlation with Atlantic TC activity.

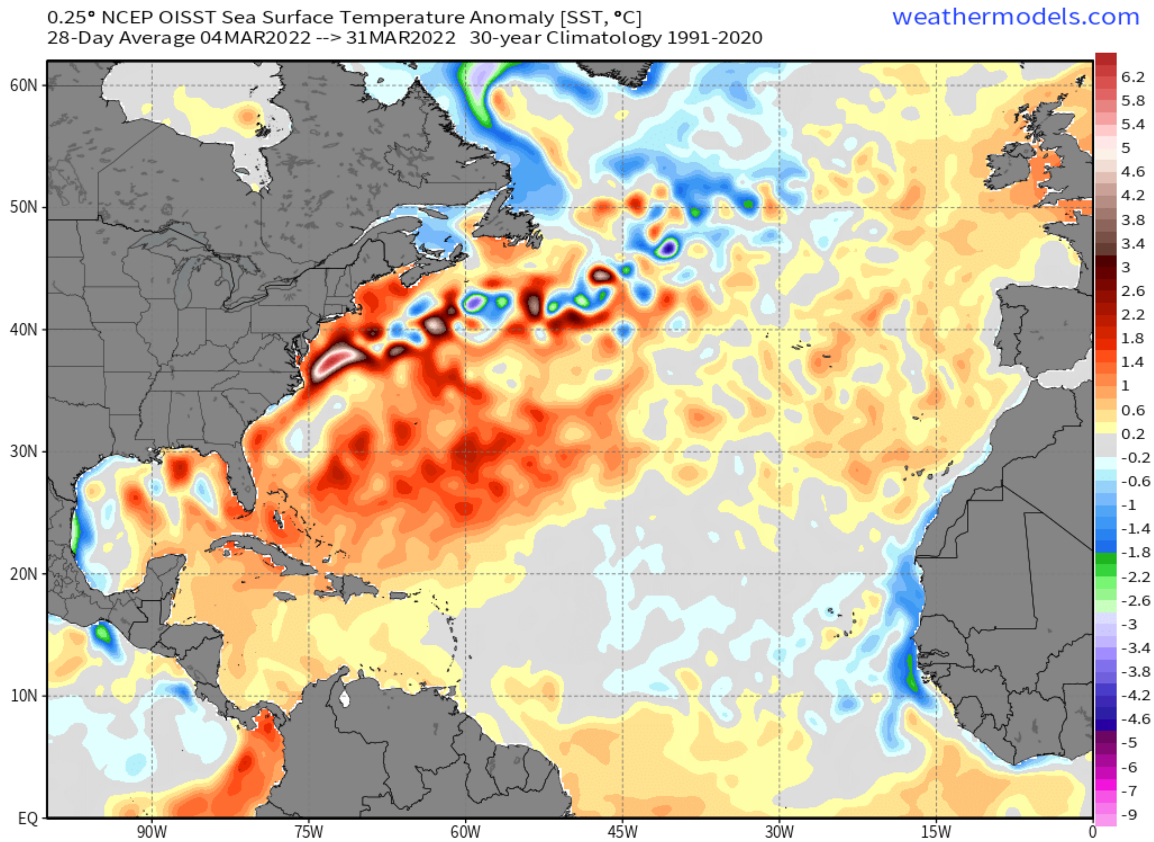


Figure 9: 28-day-averaged SST anomalies ending on March 31, 2022.

Both the tropical Atlantic and subtropical eastern Atlantic anomalously warmed from March to May (Figure 10). The considerable anomalous warmth across the North Atlantic was one of the primary reasons why we raised our seasonal hurricane forecast with our June outlook.

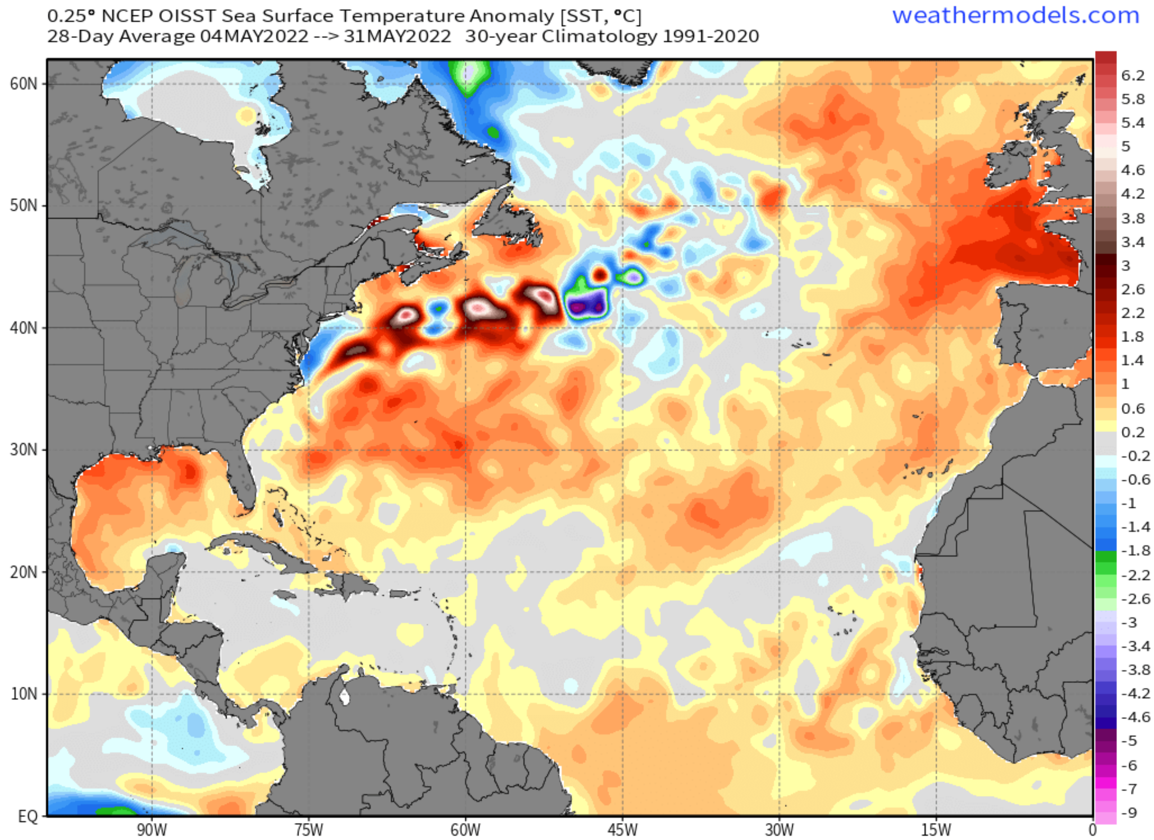


Figure 10: 28-day-averaged SST anomalies ending on May 31, 2022.

While tropical Atlantic SSTs remained anomalously warm by the end of July, considerable anomalous cooling took place across the subtropical eastern Atlantic (Figure 11). We noted this cooling as one of the reasons why we reduced our forecast somewhat with our early August outlook, as a stronger tropical-subtropical SST gradient can lead to enhanced baroclinicity and associated wavebreaking (discussed in detail in Section 7.1).

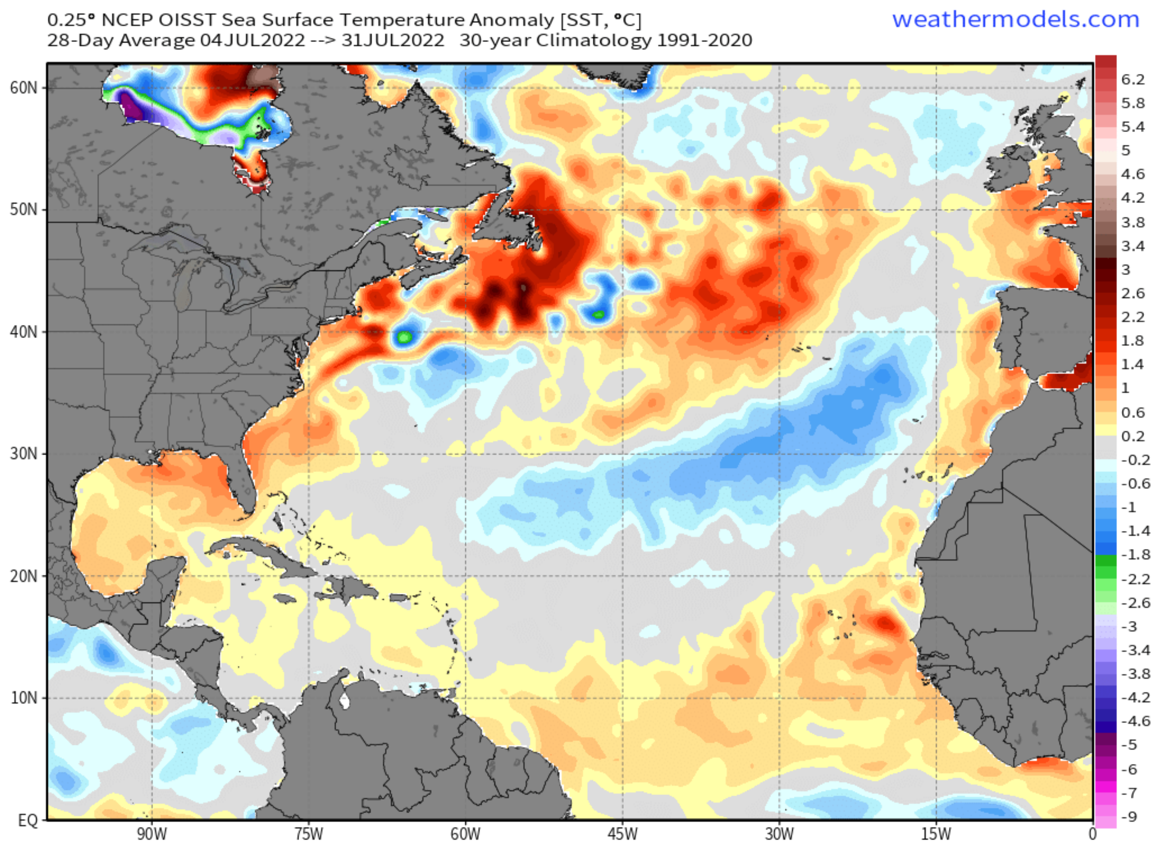


Figure 11: 28-day-averaged SST anomalies ending on July 31, 2022.

Relatively weak trade winds across most of the tropical and subtropical Atlantic during August-September of 2022 led to anomalous warming across these areas, leading to a warmer-than-normal Atlantic by the end of September (Figure 12). The considerable anomalous warmth in the mid-latitude Atlantic helped fuel relatively high latitude hurricanes such as Danielle and Martin.

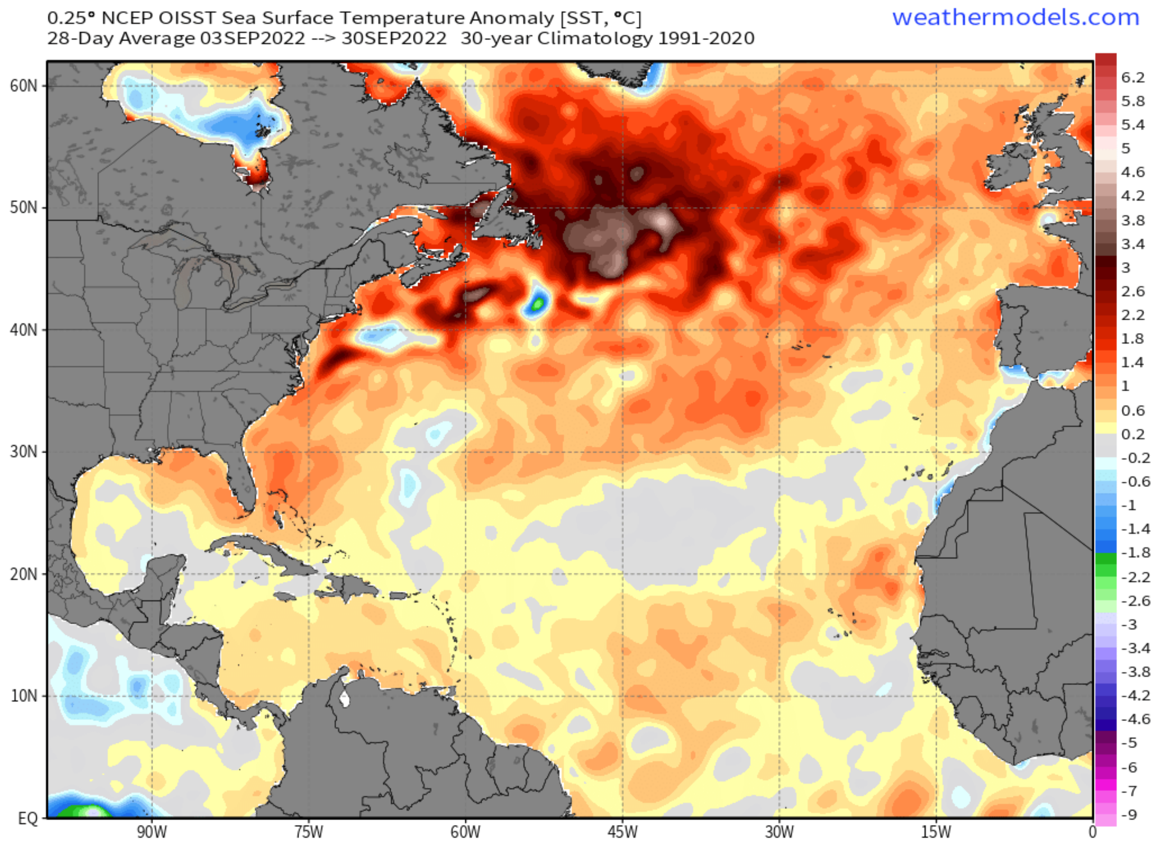


Figure 12: 28-day-averaged SST anomalies ending on September 30, 2022.

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. The August-October portion of the 2022 Atlantic hurricane season was characterized by slightly below-normal sea level pressures across most of the tropical Atlantic (Figure 13). This sea level pressure anomaly pattern would have indicated more activity in 2022 than was observed.

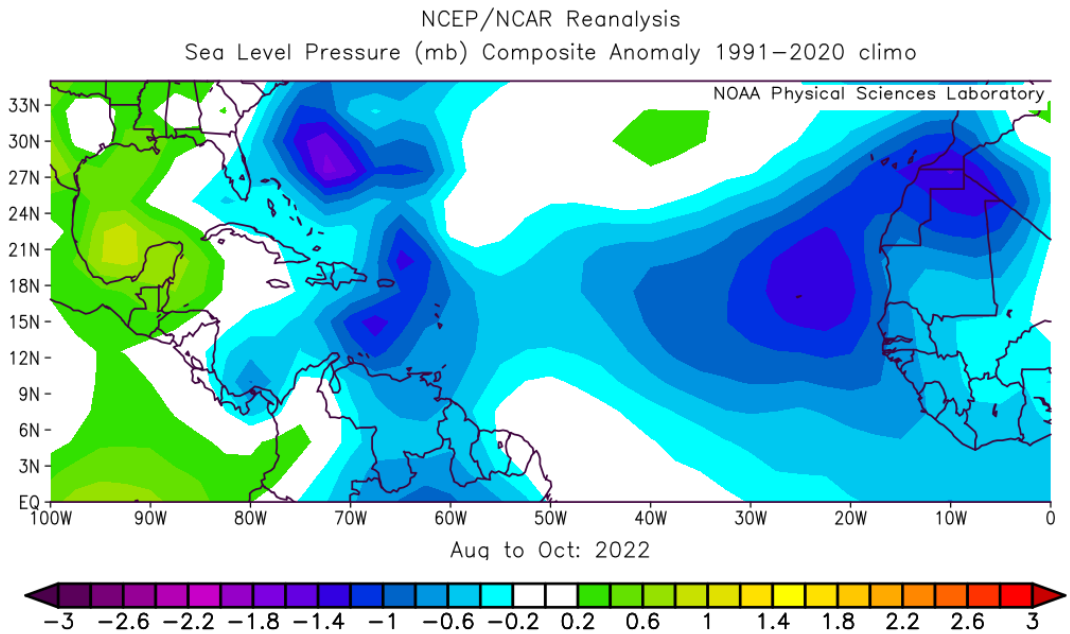


Figure 13: August-October 2022 tropical and sub-tropical North Atlantic sea level pressure anomalies.

6.5 Tropical Atlantic Vertical Wind Shear

During August through October, wind shear anomalies were higher than what would be expected in a La Niña year (Figure 14). Typically La Niña reduces vertical wind shear, especially in the Caribbean, while in 2022, vertical wind shear averaged above-normal across most of the Caribbean. However, these three-month averages do not tell the whole story of the 2022 season. In the next section, we will look at the peak three months of the 2022 Atlantic hurricane season (August-October) individually, as August and October had zero and well below-average TC activity, respectively, while September had above-average TC activity. Vertical wind shear anomalies during these three months likely played a significant role in why the months were as quiet (or active) as they were.

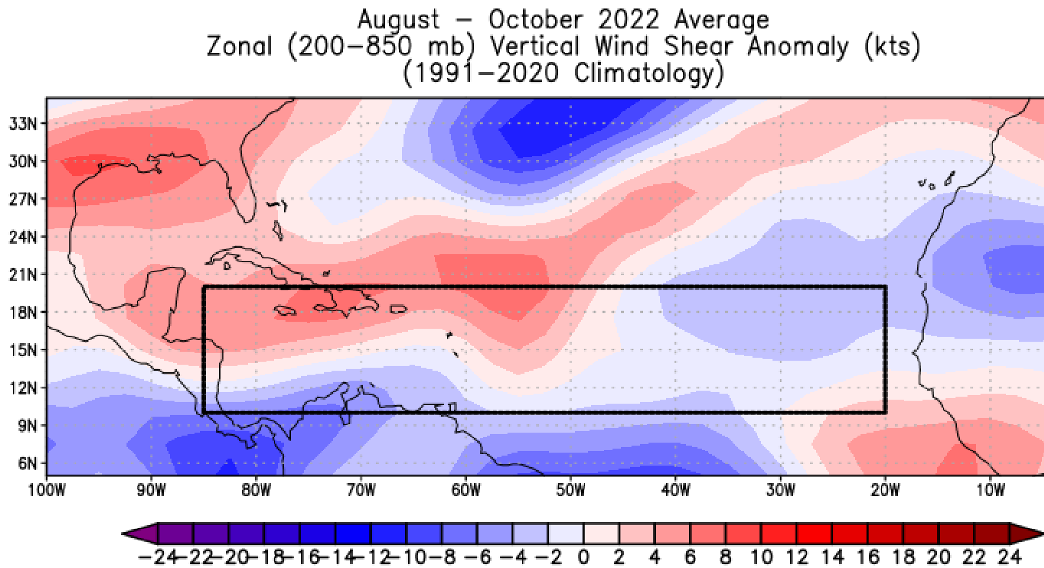


Figure 14: Anomalous vertical wind shear observed across the Atlantic from August to October 2022. The black box highlights the Main Development Region for Atlantic TCs, defined to be 10-20°N, 85-20°W.

7 Brief Analysis of August, September and October 2022 Large-Scale Conditions

Here we analyze the peak three months of the Atlantic hurricane season (August-October) individually to better understand why TC activity in each of these months differed significantly from climatology.

7.1 August 2022 Analysis

The biggest surprise of the 2022 Atlantic hurricane season was that August had no named storm activity. This is the first time that August had no named storm activity since 1997. What made this especially surprising was that this occurred during a La Niña year, when Atlantic TC activity is typically heightened. Figure 15 displays August vertical wind shear anomalies. The month was characterized by well above-average shear along a southwest to northeast oriented axis from the Caribbean to the subtropical eastern Atlantic.

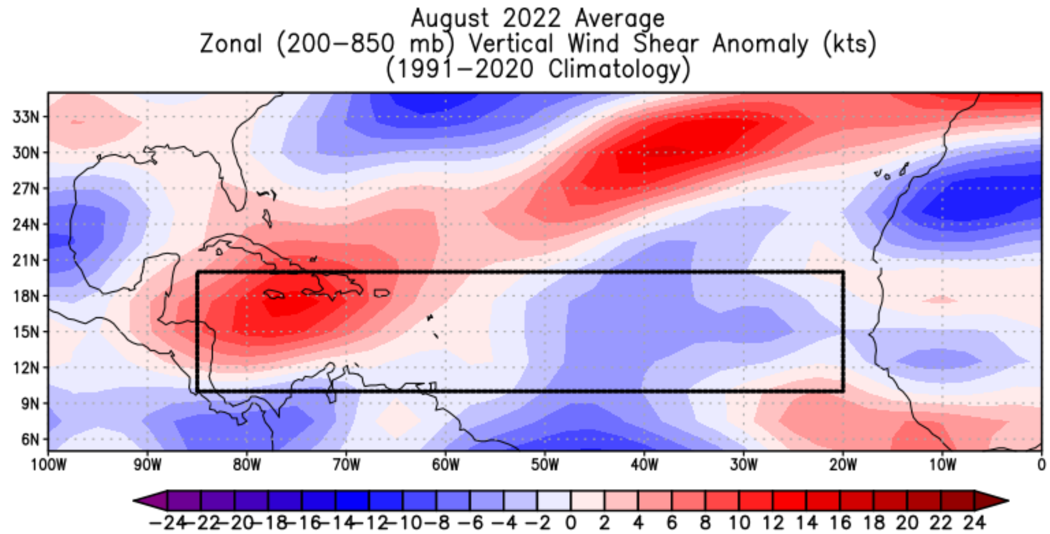


Figure 15: Anomalous vertical wind shear observed across the Atlantic in August 2022. The black box highlights the Main Development Region for Atlantic TCs, defined to be 10-20°N, 85-20°W.

This vertical wind shear anomaly pattern is a classic signal of an anomalously strong tropical upper-tropospheric trough (TUTT), which is characterized by low heights in the upper troposphere (Figure 16). This strong TUTT favors anticyclonic wave breaking from the mid-latitudes which advects dry mid-latitude air and increases vertical wind shear in the tropics.

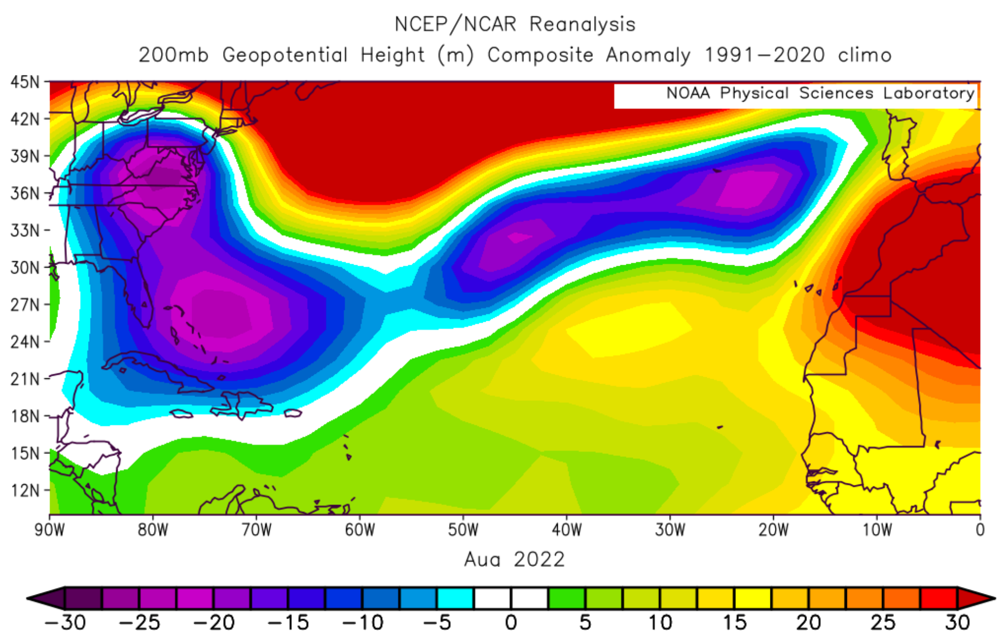


Figure 16: Anomalous 200 hPa geopotential height anomalies observed across the Atlantic in August 2022.

We did note in our early August 2022 outlook that the potential for increased wavebreaking and TUTT activity was possible, due to a stronger-than-normal SST gradient between the tropical and subtropical Atlantic (Figure 17). However, this stronger-than-normal SST gradient is not a guarantee of anomalous wavebreaking. Analysis done by Jhordanne Jones, PhD graduate from our research group, highlights some predictability on seasonal timescales for wavebreaking. However, there tends to be less predictability of wavebreaking given its mid-latitude sources than other seasonal TC predictors that have tropical origins.

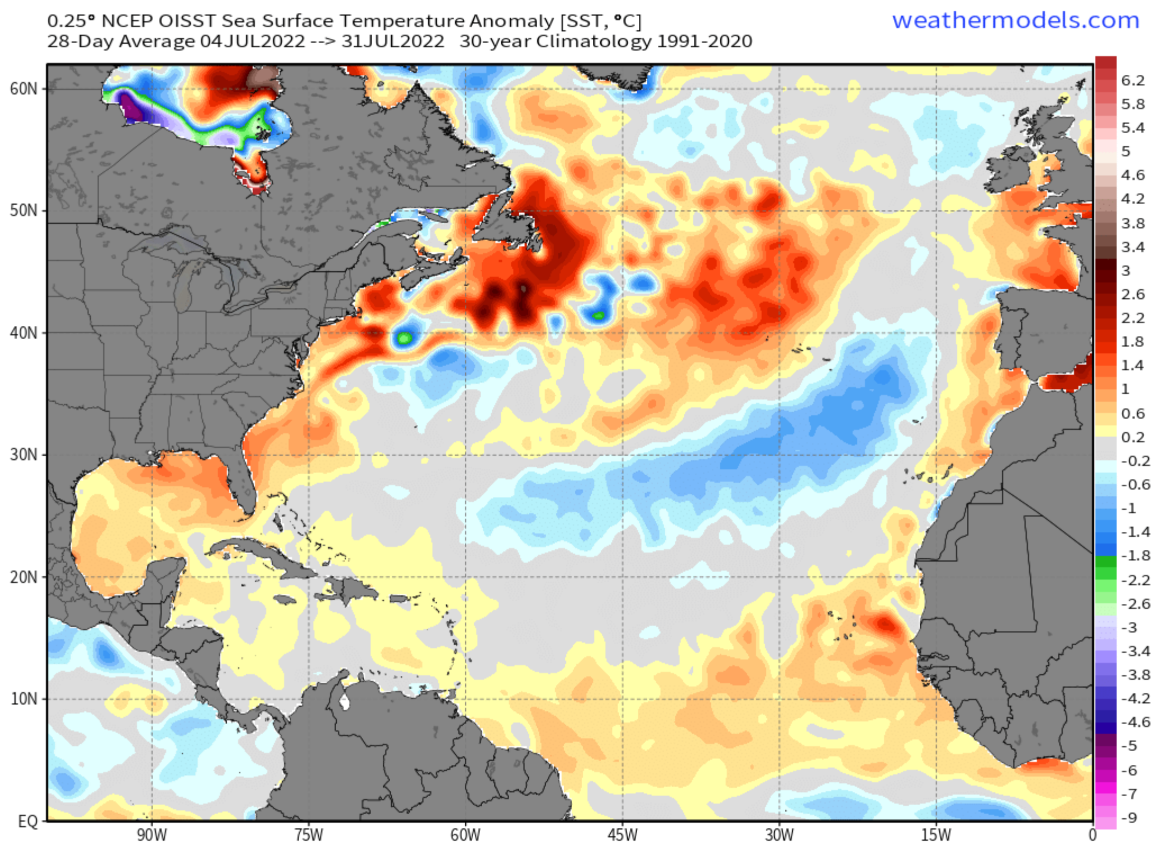


Figure 17: 28-day-averaged SST anomalies ending on July 31, 2022.

We will have more discussion of August 2022 in a forthcoming manuscript.

7.2 September 2022 Analysis

September 2022 had above-average Atlantic TC activity, with six named storms, four hurricanes and two major hurricanes occurring. ACE was also above average during September (Figure 8). As would be expected given the above-average activity, vertical wind shear was well below-average across the tropical Atlantic during September (Figure 18).

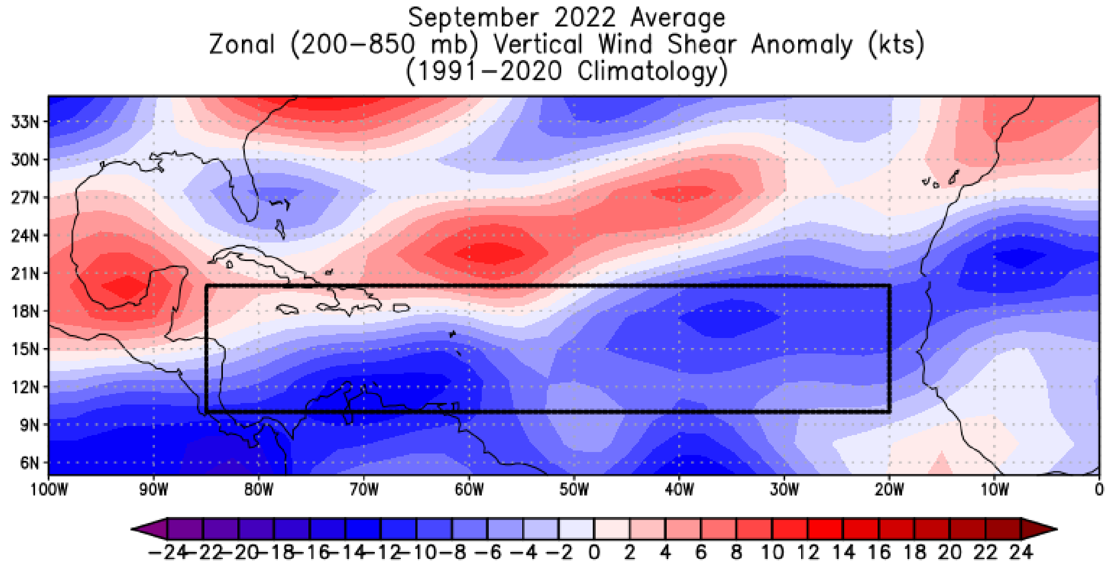


Figure 18: Anomalous vertical wind shear observed across the Atlantic in September 2022. The black box highlights the Main Development Region for Atlantic TCs, defined to be 10-20°N, 85-20°W.

Vertical motion during September (as inferred from upper-level velocity potential) was broadly characterized by rising motion over Africa and the Indian Ocean with suppressed motion over the eastern and central Pacific. The large-scale circulation associated with this anomalous vertical motion pattern drives anomalous upper-level easterly flow across the tropical Atlantic and Caribbean, reducing westerly vertical wind shear that typically prevails across the basin (Figure 19).

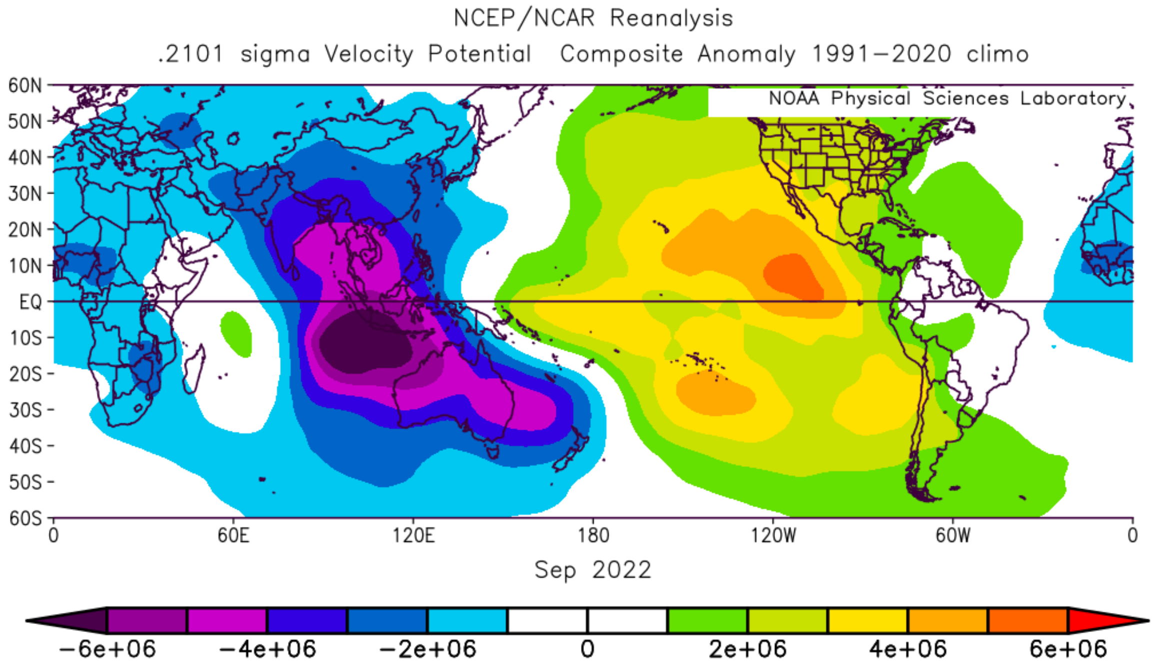


Figure 19: Anomalous ~200 hPa velocity potential anomalies in September 2022. Negative upper-level velocity potential anomalies indicate upward motion.

7.3 October 2022 Analysis

October 2022 was relatively quiet, with three named storms and one hurricane occurring during the month. Accumulated Cyclone Energy was only ~25% of normal. Vertical wind shear was well above average during October (Figure 20), which was quite surprising given an anomalously warm tropical Atlantic and La Niña conditions.

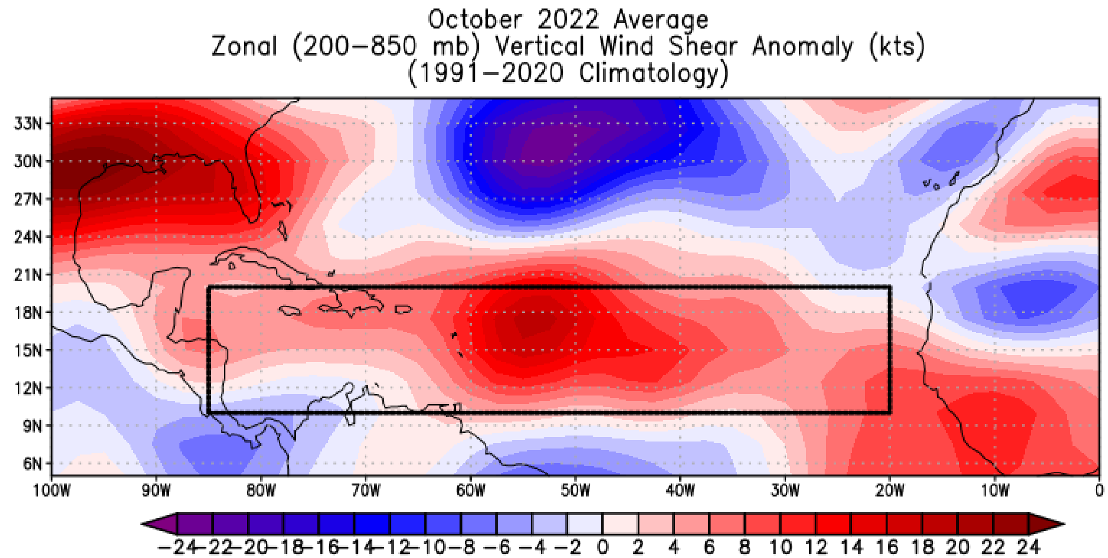


Figure 20: Anomalous vertical wind shear observed across the Atlantic in October 2022. The black box highlights the Main Development Region for Atlantic TCs, defined to be 10-20°N, 85-20°W.

The likely driver of the anomalously high shear experienced during October was Atlantic TC-unfavorable phases of the MJO (phases 6 and 7) (Figure 21). When the MJO is enhancing convection over the tropical Pacific, it tends to increase vertical wind shear over the Caribbean and tropical Atlantic.

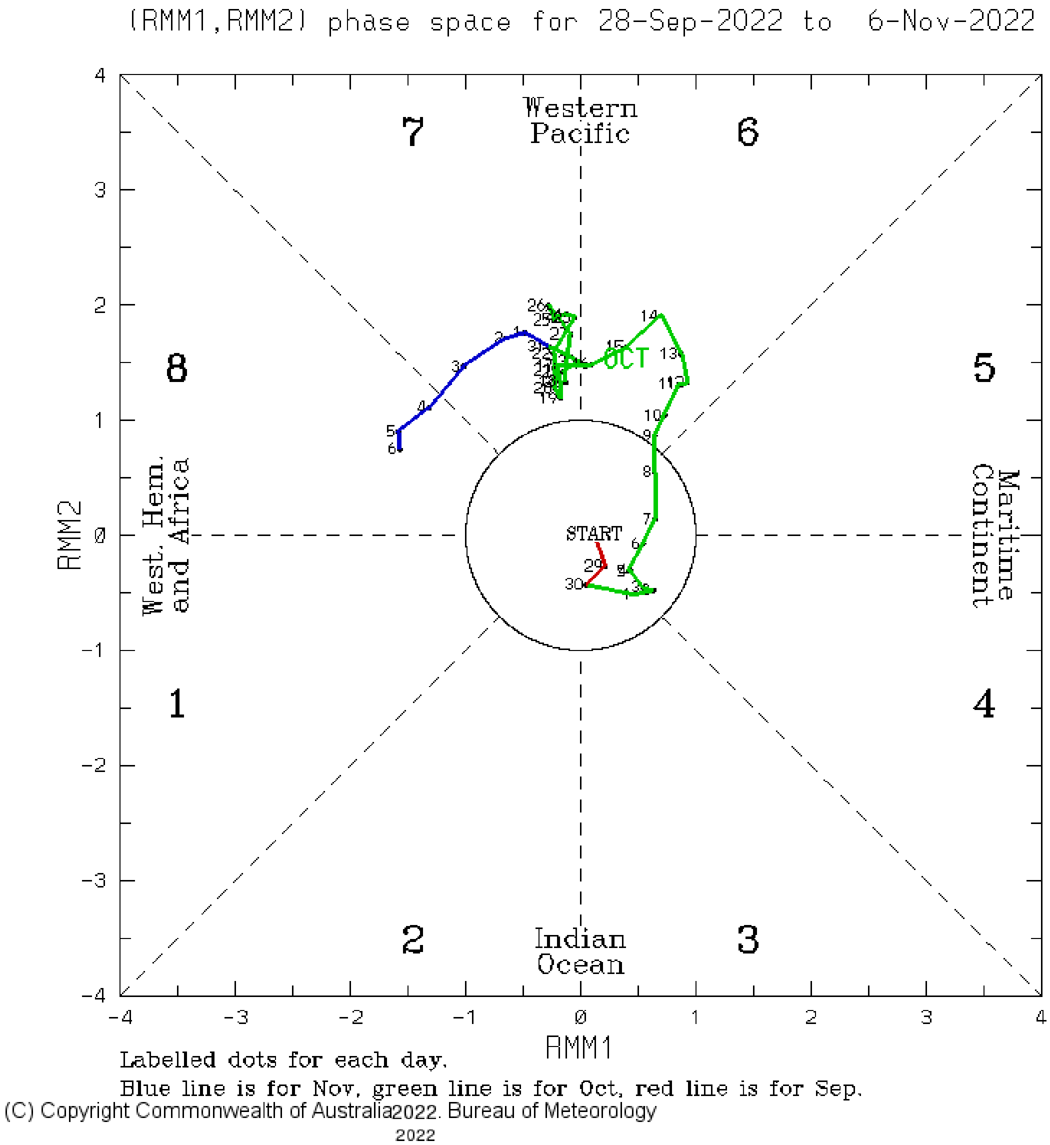


Figure 21: MJO propagation as measured by the Wheeler-Hendon MJO index from late September through early November.

8 Forecasts of 2023 Hurricane Activity

We will be issuing our first outlook for the 2023 hurricane season on Thursday, 13 April 2023. This April forecast will include the dates of all of our updated 2023 forecasts. All of these forecasts will be made available online. We have suspended our December forecasts given the lack of skill at seasonal predictions at that long-range lead time.

8 Verification of Previous Forecasts

Figure 22 displays the observed versus predicted real-time CSU August seasonal named storm forecasts from 1984-2022. 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 activity.

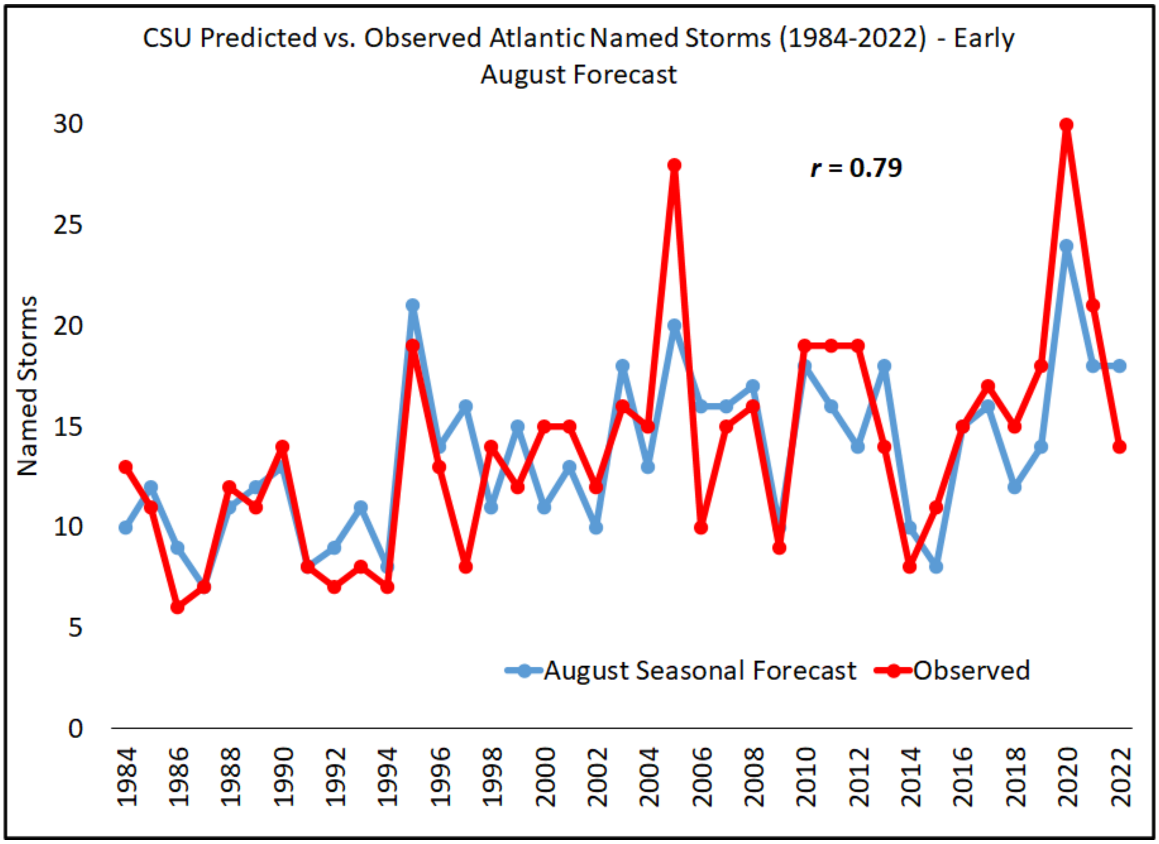


Figure 22: Observed versus predicted Atlantic named storms from 1984-2022.

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. Figure 23 displays correlations between observed and predicted Atlantic hurricanes from 1984-2013, from 2014-2022 and from 1984-2022, respectively. Correlation skill has improved at all lead times in recent years, with the most noticeable improvements at longer lead times. While nine 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.

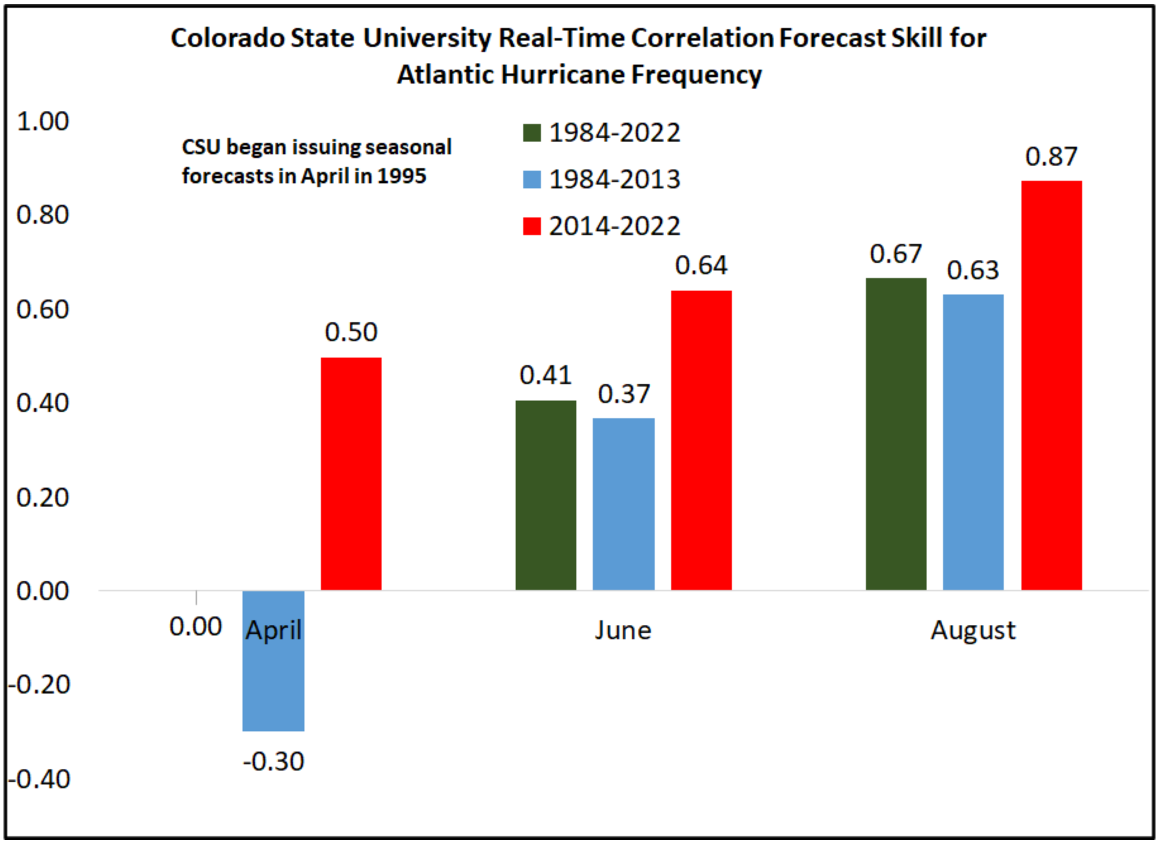


Figure 23: CSU's real-time forecast skill for Atlantic hurricanes using correlation as the skill metric. Correlation skills are displayed for three separate time periods: 1984-2013, 2014-2022 and 1984-2022, respectively.