SUMMARY OF 2021 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF AUTHORS' SEASONAL AND TWO-WEEK FORECASTS

The 2021 Atlantic hurricane season was another above-normal season with an extremely high number of named storms (21) and above-normal levels for most other tropical cyclone metrics including Accumulated Cyclone Energy. The seasonal hurricane forecasts issued in 2021 by the Tropical Meteorology Project verified quite well. The season's most significant hurricane was Hurricane Ida, which made landfall in central Louisiana as a Category 4 hurricane, bringing tremendous wind and storm surge damage to the central Gulf Coast as well as significant inland flooding to the mid-Atlantic.

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In Memory of William M. Gray[3]

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

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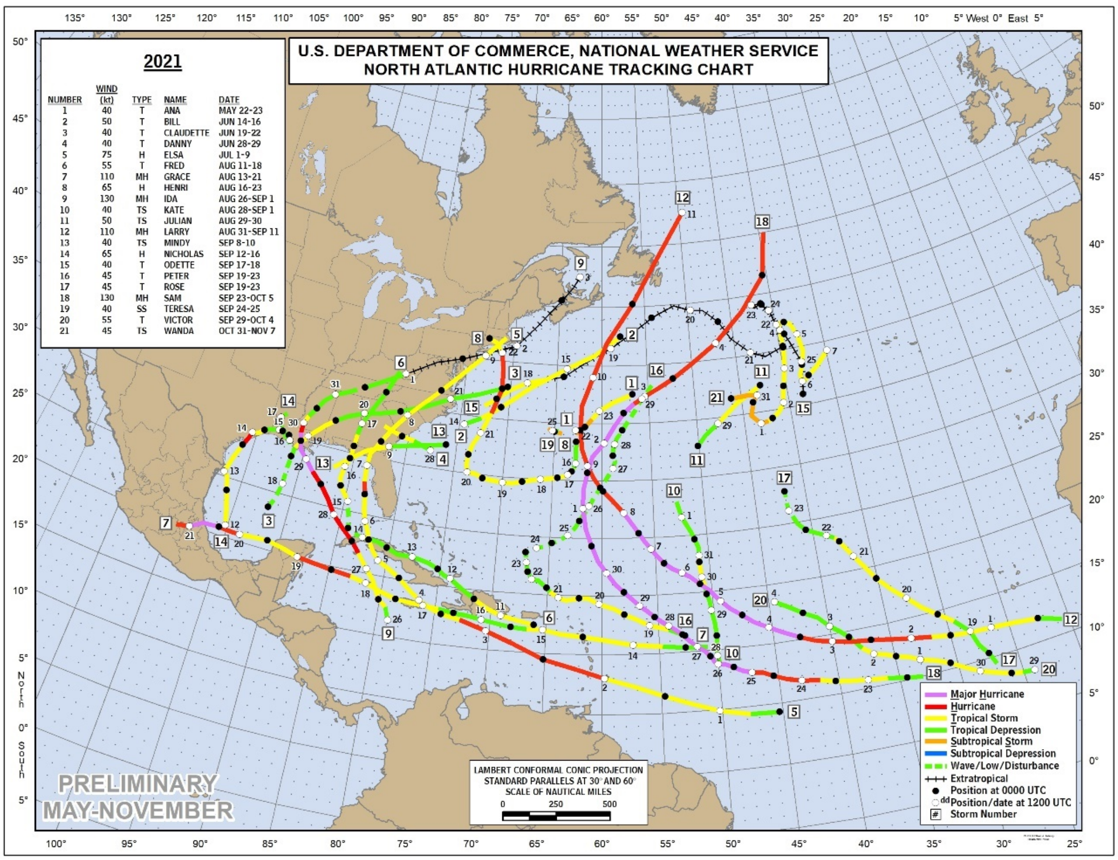
ATLANTIC BASIN SEASONAL HURRICANE FORECASTS FOR 2021

Forecast Parameter and 1991-2020 Average (in parentheses)	Issue Date 8 April 2021	Issue Date 3 June 2021	Issue Date 8 July 2021	Issue Date 5 August 2021	**Observed 2021 Activity Thru 11/30**	% of 1991-2020 Average
Named Storms (NS) (14.4)	17	18	20	18	**21**	146%
Named Storm Days (NSD) (69.4)	80	80	90	80	**78**	112%
Hurricanes (H) (7.2)	8	8	9	8	**7**	97%
Hurricane Days (HD) (27.0)	35	35	40	35	**27.5**	102%
Major Hurricanes (MH) (3.2)	4	4	4	4	**4**	125%
Major Hurricane Days (MHD) (7.4)	9	9	9	9	**13.75**	186%
Accumulated Cyclone Energy (ACE) (123)	150	150	160	150	**145**	118%
Net Tropical Cyclone Activity (NTC) (135%)	160	160	170	160	**176**	130%



2021 Atlantic basin tropical cyclone tracks through November 30. 21 named storms, 7 hurricanes and 4 major hurricanes occurred. Figure courtesy of Ethan Gibney (NOAA).

ABSTRACT

This report summarizes tropical cyclone (TC) activity which occurred in the Atlantic basin during 2021 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 2021 was issued on 8 April with updates on 3 June, 8 July and 5 August. These seasonal forecasts also contained estimates of the probability of US and Caribbean hurricane landfall during 2021.

The 2021 hurricane season was above normal. The season had 21 named storms, trailing only the 2020 (30 named storms) and 2005 (28 named storms) seasons for most named storms in a single season on record. The season had a near-normal number of hurricanes and a slightly above-normal number of major hurricanes. Integrated measures such as Net Tropical Cyclone (NTC) activity and Accumulated Cyclone Energy (ACE) were above average.

Our seasonal forecasts of Accumulated Cyclone Energy (ACE) verified quite well. Our storm number forecasts were generally quite good this year, with a slight under-prediction of named storms and slight over-prediction of hurricanes. All of our seasonal outlooks correctly predicted the number of major hurricanes that occurred. Almost all TC metrics forecast by our group at various lead times verified in our 70% confidence interval.

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 correct tercile or the tercile with the highest probability in 3 out of 6 outlooks that were issued.

The season transitioned from cool neutral ENSO conditions to La Niña conditions during the peak of the season. August and September generated above-normal ACE, while October produced near-normal ACE. The season was surprisingly quiet after early October, given that La Niña typically favors late season Atlantic hurricane activity.

Tropical Atlantic sea surface temperatures were warmer than normal during the peak of the 2021 hurricane season. Vertical wind shear was generally below average during August and September across the tropical Atlantic but above average in October, especially in the Caribbean.

The most impactful storm of the 2021 Atlantic hurricane season was Hurricane Ida, which made landfall along the central Louisiana coast as a Category 4 hurricane with

a 930 hPa central pressure – the second strongest hurricane on record for Louisiana by minimum sea level pressure, trailing only Katrina (2005 – 920 hPa). Ida's remnants also brought catastrophic flooding to portions of the mid-Atlantic.

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 30-70 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.

Multivariate ENSO Index (MEI) – An index defining ENSO that considers tropical Pacific sea surface temperatures, sea level pressures, zonal and meridional winds and cloudiness.

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 North Atlantic (TNA) index – A measure of sea surface temperatures in the area from 5.5-23.5°N, 57.5-15°W.

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.

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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 would like to acknowledge assistance from 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 2021, these predictions used the current ECMWF climate model (SEAS5) and Met Office climate model (GloSea6) to predict the large-scale conditions in July that underpin the early August statistical seasonal hurricane forecast model. The early August outlook incorporated SEAS5 and GloSea6 forecasts 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 generally called for an above-average Atlantic hurricane season in 2021.

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 relations 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 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 2021

Figure 1 and Table 1 summarize Atlantic basin TC activity that occurred in 2021. Overall, the season was active with a high level of named storm activity, near-average level of hurricane activity and above-average major hurricane activity. Online entries from [Wikipedia](#) are available for in-depth discussions of each TC that occurred in 2021. The National Hurricane Center is also currently in the process of writing up extensive [reports](#) on all 2021 TCs.

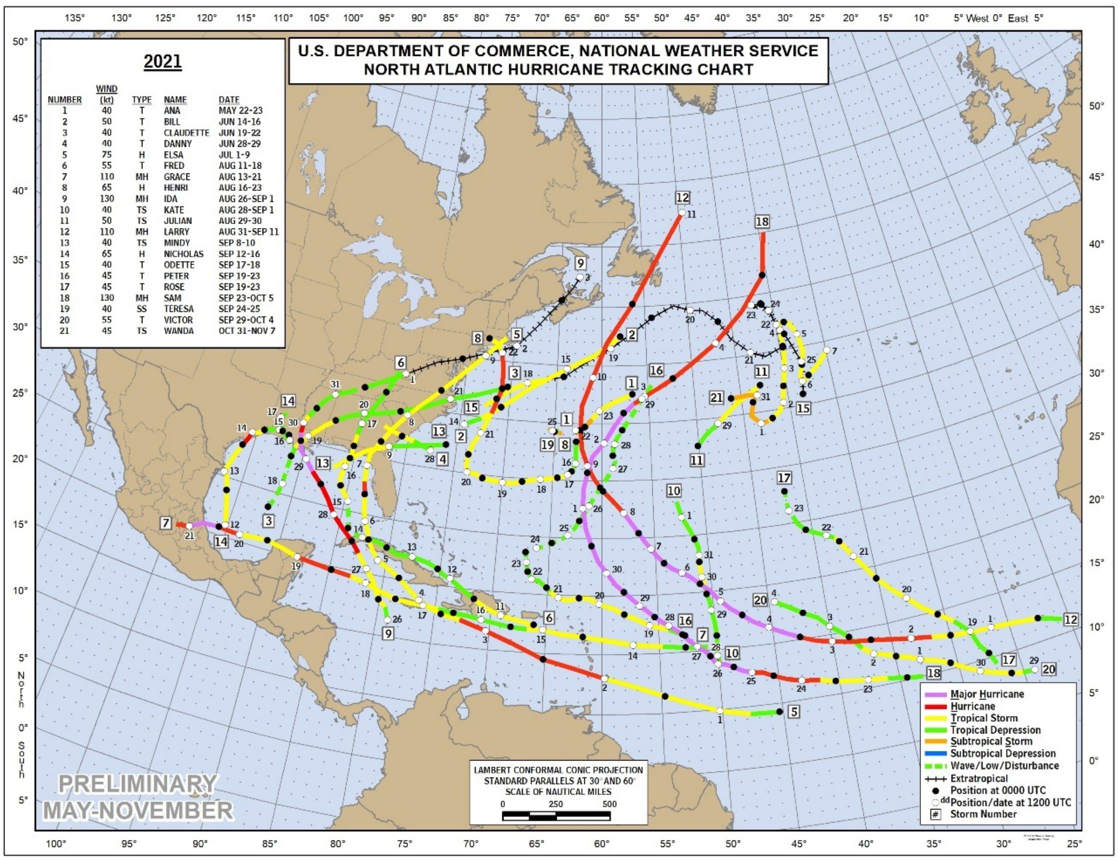

Figure 1: 2021 Atlantic basin TC tracks through November 30. 21 named storms, 7 hurricanes and 4 major hurricanes occurred. Figure courtesy of Ethan Gibney (NOAA).

Table 1: Observed 2021 Atlantic basin TC activity through November 30. 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 2021

Year	Storm#	Name	Dates TC Active	Max Wind (kts)	MSLP (mb)	Named Storm Days	Hurricane Days	Major Hurricane Days	Accumulated Cyclone Energy
2021	1	ANA	5/22-5/23	40	1006	1.75	0.00	0.00	1.0
2021	2	BILL	6/14-6/15	50	998	1.25	0.00	0.00	1.0
2021	3	CLAUDETTE	6/19-6/22	40	1004	1.75	0.00	0.00	1.0
2021	4	DANNY	6/28-6/29	35	1011	0.50	0.00	0.00	0.2
2021	5	ELSA	7/1-7/9	75	991	8.50	1.50	0.00	9.5
2021	6	FRED	8/11-8/17	55	993	3.00	0.00	0.00	2.1
2021	7	GRACE	8/14-8/21	110	962	6.00	2.00	0.50	9.1
2021	8	HENRI	8/16-8/22	65	986	6.25	0.75	0.00	7.7
2021	9	IDA	8/26-8/30	130	929	4.25	2.75	1.00	10.8
2021	10	KATE	8/30-8/31	40	1004	1.25	0.00	0.00	0.7
2021	11	JULIAN	8/29-8/29	50	995	0.50	0.00	0.00	0.5
2021	12	LARRY	9/1-9/11	110	955	10.50	9.25	4.50	32.8
2021	13	MINDY	9/8-9/9	40	1004	0.75	0.00	0.00	0.4
2021	14	NICHOLAS	9/12-9/14	65	991	2.50	0.25	0.00	2.4
2021	15	ODETTE	9/17-9/18	40	1002	1.00	0.00	0.00	0.6
2021	16	PETER	9/19-9/21	45	1005	2.50	0.00	0.00	1.7
2021	17	ROSE	9/19-9/22	45	1004	2.50	0.00	0.00	1.4
2021	18	SAM	9/23-10/5	135	929	12.00	11.00	7.75	53.8
2021	19	TERESA	9/24-9/25	40	1008	0.75	0.00	0.00	0.4
2021	20	VICTOR	9/29-10/2	55	997	3.00	0.00	0.00	2.4
2021	21	WANDA	10/31-11/7	45	987	7.50	0.00	0.00	5.7

3 Special Characteristics of the 2021 Hurricane Season

The 2021 hurricane season was above-normal, with the 3rd-most named storms in a single season on record. The number of major hurricane days (due mostly to Larry and Sam) was also extremely high this year. Most other TC metrics in 2021 were slightly to somewhat above-normal. Accumulated Cyclone Energy was elevated in August and September but suppressed after early October.

Below is a selection of some of the notable statistics from the 2021 season:

Basinwide Statistics

- 21 named storms formed in the Atlantic this season. This is the 3rd most in a single Atlantic season on record, trailing 2020 (30 named storms) and 2005 (28 named storms).

- 13.75 major hurricane days occurred in the Atlantic this year – the 6th most in the satellite era (since 1966), trailing in order from most major hurricane days: 2004, 2017, 2005, 2003, and 1999.

- The Atlantic had no named storm activity between July 10 and August 10 – the 3rd time in the most recent active Atlantic hurricane era (since 1995) where July 10 – August 10 had no named storm activity. The other two years were 1999 and 2009.

- 4 hurricanes (Grace, Henri, Ida and Larry) formed in the Atlantic between August 18 – September 2 – the first time on record that more than 3 hurricanes have formed between these two dates.

- The Atlantic had no named storm activity between October 3 and October 30 – the first time since 2006 that the Atlantic had no named storm activity between these two dates.

Individual Storm/Landfall Statistics

- Elsa was the earliest 5th Atlantic named storm formation on record (named on 1 July). Elsa broke the old earliest 5th Atlantic named storm formation record set by Edouard (on 6 July 2020).

- Elsa became a hurricane at 59.8°W on 2 July – the farthest east that a hurricane had formed this early in the calendar year in the tropics (south of 23.5°N) since 1933

- Tropical Storm Henri became the first named storm to make landfall in Rhode Island since Hurricane Bob in 1991

- Hurricane Ida made landfall with maximum sustained winds of 150 mph – tied with the Last Island Hurricane of 1856 and Hurricane Laura (2020) for strongest winds for a Louisiana hurricane on record.

- Hurricane Ida made landfall with a central pressure of 930 hPa – the 2nd strongest hurricane to make landfall in Louisiana on record by central pressure. The strongest Louisiana hurricane landfall by central pressure was Katrina (2005, 920 hPa).

- Hurricane Nicholas was the first hurricane to make landfall in Texas in September since Ike in 2008.

- Hurricane Sam was a major hurricane for 7.75 days, tied with Hurricane Edouard (1996) for the 4th most consecutive days at major hurricane strength in the satellite era (1966 onwards).

- Hurricane Sam generated the 5th-most Accumulated Cyclone Energy for a single Atlantic named storm in the satellite era.

- Sam, Teresa and Victor were the 2nd earliest 18th to 20th Atlantic named storm formations on record, trailing Sally, Teddy and Vicky, respectively (from 2020).

- 9 named storms lasted <=2 days (e.g., shorties) this season. 2021 tied the record set in 2007 for the most shorties in a single season on record.

4 Verification of Individual 2021 Lead Time Forecasts

Table 2 is a comparison of our forecasts for 2021 for four different lead times along with this year's observations. The 2021 Atlantic hurricane season was above average.

Table 2: Verification of our 2021 seasonal hurricane predictions.

Forecast Parameter and 1991-2020 Average (in parentheses)	Issue Date 8 April 2021	Issue Date 3 June 2021	Issue Date 8 July 2021	Issue Date 5 August 2021	**Observed 2021 Activity**
Named Storms (NS) (14.4)	17	18	20	18	**21**
Named Storm Days (NSD) (69.4)	80	80	90	80	**78**
Hurricanes (H) (7.2)	8	8	9	8	**7**
Hurricane Days (HD) (27.0)	35	35	40	35	**27.5**
Major Hurricanes (MH) (3.2)	4	4	4	4	**4**
Major Hurricane Days (MHD) (7.4)	9	9	9	9	**13.75**
Accumulated Cyclone Energy (ACE) (123)	150	150	160	150	**145**
Net Tropical Cyclone Activity (NTC) (135%)	160	160	170	160	**176**

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. All but the April forecast for named storms, the July forecast for hurricane days and the August forecast for major hurricane days fell within the 70% confidence interval.

Table 3: Verification of CSU's 2021 seasonal hurricane predictions with 70% confidence intervals.

Forecast Parameter and 1991-2020 Average (in parentheses)	8 April 2021	Update 3 June 2021	Update 8 July 2021	Update 5 August 2021	Observed 2021 Total
Named Storms (NS) (14.4)	14-20	**15-21**	**17-23**	**15-21**	21
Named Storm Days (NSD) (69.4)	**57-104**	**59-102**	**70-111**	**61-99**	78
Hurricanes (H) (7.2)	**6-10**	**6-10**	**7-11**	**6-10**	7
Hurricane Days (HD) (27.0)	**22-50**	**23-49**	28-54	**24-47**	27.5
Major Hurricanes (MH) (3.2)	**2-6**	**2-6**	**3-6**	**3-5**	4
Major Hurricane Days (MHD) (7.4)	**6-14**	**6-14**	**6-14**	6-13	13.75
Accumulated Cyclone Energy (ACE) (123)	**97-209**	**100-205**	**112-212**	**107-198**	145
Net Tropical Cyclone Activity (NTC) (135%)	**108-216**	**111-213**	**124-220**	**118-205**	176

4.1 Verification of Statistical-Dynamical Model Forecasts

We have issued statistical-dynamical model forecasts for the Atlantic basin hurricane season since 2019. This model, developed in partnership with Louis-Philippe Caron and the data team at the Barcelona Supercomputing Centre, uses output from both the ECMWF SEAS5 model and the GloSea6 model to forecast the input to our early August statistical forecast model. This forecast is issued during early April, June and July. Due to data acquisition issues, the GloSea6 model output was not available for the early April forecast in 2021.

This year, we also incorporated a prediction of August-September zonal wind shear and sea surface temperatures that we used in our early August forecast. Table 4 displays the statistical-dynamical model input to our seasonal hurricane forecast scheme in early April, early June, early July and early August from the ECMWF SEAS5 model. Table 5 displays the same input from the GloSea6 model. Both statistical-dynamical models called for near to above-normal Atlantic hurricane activity at all lead times.

Table 4: Statistical-dynamical model forecast input from ECMWF SEAS5 for the 2021 Atlantic basin seasonal hurricane forecasts.

Forecast Parameter and 1991-2020 Average (in parentheses)	Issue Date 8 April 2021	Issue Date 3 June 2021	Issue Date 8 July 2021	Issue Date 5 August 2021	**Observed 2021 Activity**
Named Storms (NS) (14.4)	16.9	16.3	16.7	18.8	**21**
Named Storm Days (NSD) (69.4)	92.0	82.6	85.5	79.2	**78**
Hurricanes (H) (7.2)	9.6	8.5	8.9	7.7	**7**
Hurricane Days (HD) (27.0)	41.0	34.2	35.8	26.3	**27.5**
Major Hurricanes (MH) (3.2)	4.6	4.0	4.2	2.9	**4**
Major Hurricane Days (MHD) (7.4)	12.2	10.0	10.5	6.6	**13.75**
Accumulated Cyclone Energy (ACE) (123)	180	154	161	126	**145**
Net Tropical Cyclone Activity (NTC) (135%)	189	166	173	142	**176**

Table 5: Statistical-dynamical model forecast input from the UK Met Office GloSea6 model for the 2021 Atlantic basin seasonal hurricane forecasts.

Forecast Parameter and 1991-2020 Average (in parentheses)	Issue Date 3 June 2021	Issue Date 8 July 2021	Issue Date 5 August 2021	**Observed 2021 Activity**
Named Storms (NS) (14.4)	17.3	17.6	19.7	**21**
Named Storm Days (NSD) (69.4)	89.7	91.4	85.0	**78**
Hurricanes (H) (7.2)	9.3	9.5	8.4	**7**
Hurricane Days (HD) (27.0)	38.1	39.0	29.5	**27.5**
Major Hurricanes (MH) (3.2)	4.5	4.6	3.3	**4**
Major Hurricane Days (MHD) (7.4)	11.4	11.7	7.7	**13.75**
Accumulated Cyclone Energy (ACE) (123)	171	175	140	**145**
Net Tropical Cyclone Activity (NTC) (135%)	183	187	156	**176**

4.2 Verification of Two-Week Forecasts

This is the 13th 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 predominately enhancing convection over the Indian Ocean and Maritime Continent, which typically increases Atlantic hurricane activity. The lack of MJO activity in phases 7-8 may be due to the transition towards a La Niña event that occurred during the season. The Wheeler-Hendon MJO index (used here) removes the previous 120-day mean in its calculation, and a rapid transition towards La Niña can occasionally skew the index.

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 is defined by ranking observed activity in the satellite era from 1966-2019 and defining above-normal, normal and below-normal two-week periods based on terciles. Since there are 54 years from 1966-2019, each tercile is composed of 18 years. The 18 years with the most active ACE periods are classified as the upper tercile, the 18 years with the least active ACE periods are classified as the lower tercile, while the remaining 18 years are classified as the middle tercile. Beginning this year with our 3rd two-week forecast and going forward, all forecasts will be issued probabilistically, with each tercile being assigned a category likelihood of occurring.

Table 6 displays the six two-week forecasts that were issued during the 2021 hurricane season and shows their verification. We correctly predicted (or assigned the highest probability) to three of the six two-week periods. Most surprisingly was the last two-week period of the season where no Atlantic named storm activity occurred. We assigned a 60% chance of normal TC activity occurring during that two-week period.

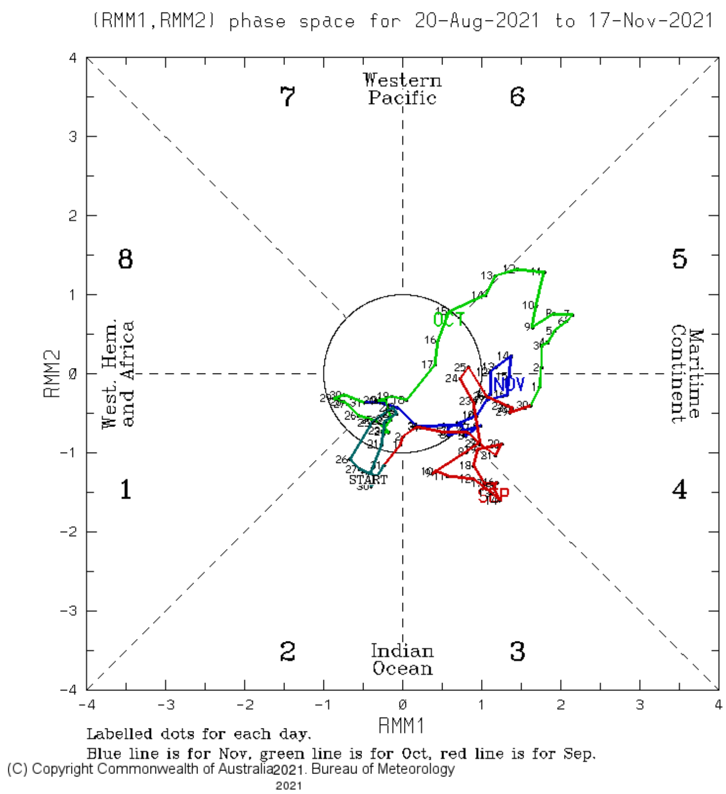

Figure 2: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 20 to November 17. The Maritime Continent refers to Indonesia and the surrounding islands. RMM stands for Real-Time Multivariate MJO. Figure courtesy of Bureau of Meteorology.

Table 6: Two-week Atlantic ACE forecast verification for 2021. 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	Predicted ACE (or Category with Highest Probability)	Observed ACE
8/5 – 8/18	**Above-Normal (>6)**	**7**
8/19 – 9/1	**Normal (11-22)**	**24**
9/2 – 9/15	**Above-Normal (>34) (90%)**	**35 (90%)**
9/16 – 9/29	**Normal (6-23) (50%)**	**33 (40%)**
9/30 – 10/13	**Above-Normal (>9) (>99%)**	**27 (>99%)**
10/14 – 10/27	**Normal (1-7) (60%)**	**0 (20%)**

4.3 Verification of October-November Caribbean ACE Forecast

The October-November Caribbean ACE forecast for 2021 did not verify well. The two-predictor model that comprises the Caribbean ACE forecast called for a well above-median two-month period, with 9 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.

Surprisingly given the anomalously warm Caribbean and La Niña conditions in the tropical Pacific, no TC activity occurred in the Caribbean in October-November. Additional discussion of why the October-November portion of the 2021 Atlantic hurricane season was so quiet is included later in this document.

5 Landfall Analysis

The 2021 Atlantic hurricane season was quite active for continental US hurricane landfalls, with seven named storms (Danny, Elsa, Fred, Henri, Ida, Mindy and Nicholas) making landfall, of which two were at hurricane strength (Ida and Nicholas) at the time of 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.

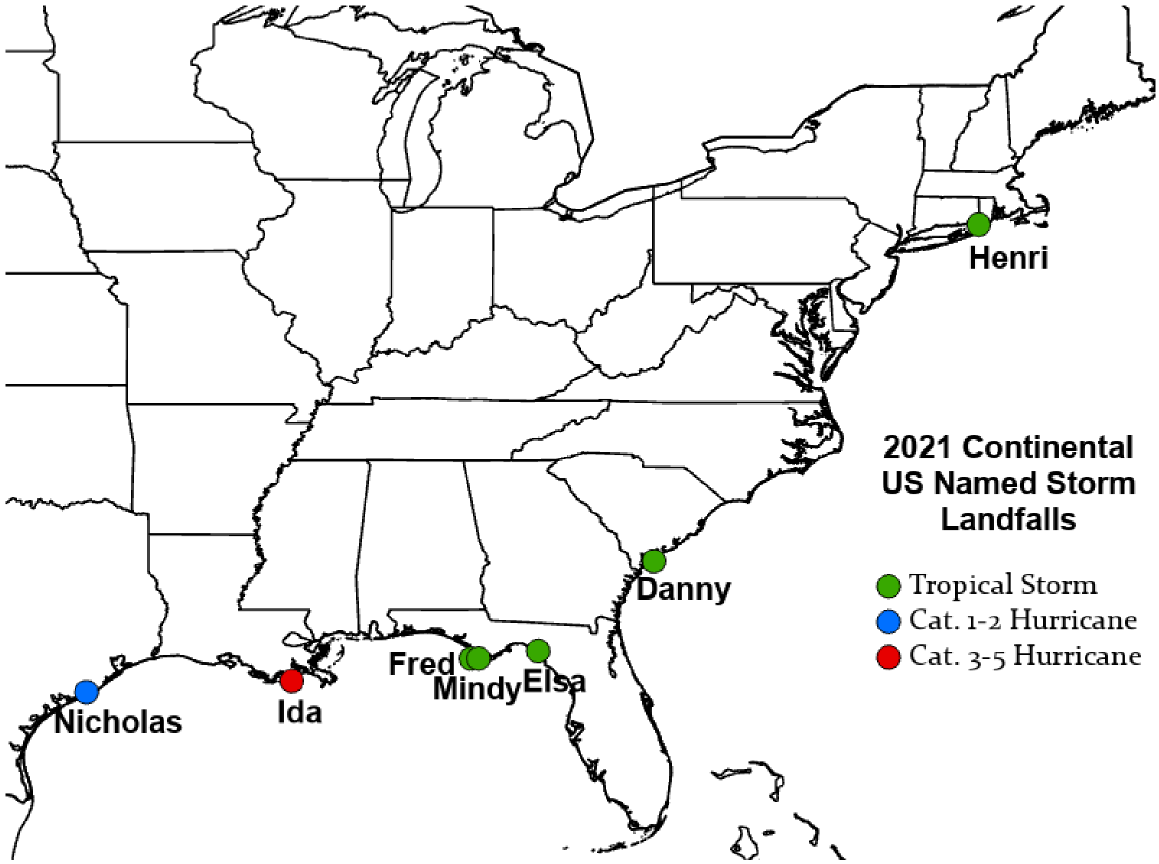

Figure 3: Location of the named storms making landfall in the continental US during the 2021 Atlantic hurricane season.

This year, we debuted a new methodology for calculating 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 1851-2019. 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 7). 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 7: 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 2021 Atlantic hurricane season was predicted (and observed) to be above-average, landfall probabilities at all lead times were elevated. As noted earlier, the 2021 Atlantic hurricane season had an above-average number of continental US named storm and hurricane landfalls. As an example, Table 8 displays the landfall probabilities that were issued with the June 2021 outlook.

Table 8: 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 1851–2019 climatological average as well as the probability for 2021, based on the June CSU seasonal hurricane forecast.

		2021 Probability				**Climatology**	
	Probability >=1	**event within**	**50 miles**		**Probability >=1**	**event within**	**50 miles**
State	Named Storm	Hurricane	Major Hurricane		Named Storm	Hurricane	Major Hurricane
Texas	75%	49%	21%		58%	35%	14%
Louisiana	80%	53%	23%		63%	37%	15%
Mississippi	69%	39%	12%		52%	26%	8%
Alabama	75%	41%	14%		58%	28%	9%
Florida	96%	75%	41%		86%	58%	28%
Georgia	79%	45%	11%		63%	31%	7%
South Carolina	73%	41%	12%		56%	28%	7%
North Carolina	84%	52%	11%		68%	37%	7%
Virginia	63%	28%	3%		46%	19%	2%
Maryland	47%	16%	2%		33%	11%	1%
Delaware	33%	8%	<1%		22%	5%	<1%
New Jersey	34%	11%	1%		23%	7%	1%
New York	40%	15%	4%		27%	10%	2%
Connecticut	33%	13%	3%		22%	8%	2%
Rhode Island	33%	13%	4%		22%	8%	2%
Massachusetts	49%	23%	6%		34%	15%	3%
New Hampshire	28%	10%	3%		18%	6%	2%
Maine	34%	12%	3%		23%	8%	2%

6 Summary of Atmospheric/Oceanic Conditions

In this section, we go into more detail discussing large-scale conditions that we believe significantly impacted the 2021 Atlantic basin hurricane season.

6.1 ENSO

Weak to moderate La Niña conditions were present during the winter of 2020/2021 and then transitioned to neutral ENSO conditions during the spring of 2021. From our early April forecast, we correctly predicted that El Niño was unlikely for the 2021 hurricane season. We anticipated that either cool neutral ENSO or weak La Niña conditions were likely to occur during the peak of the Atlantic hurricane season (August-October). The August-October-averaged Oceanic Nino Index was -0.7°C, which is classified as weak La Niña conditions. Below are some quotes excerpted from our seasonal forecasts issued this year discussing our thoughts on the likely state of ENSO.

(8 April 2021) –

"We believe that the odds of a significant El Niño event for the 2021 Atlantic hurricane season are quite small."

(3 June 2021) –

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

(5 August 2021) –

"We believe that we will likely have either cool neutral ENSO or weak La Niña for the peak of the Atlantic hurricane season (August-October)."

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 Nino 3.4 from 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 almost all members by August. 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 somewhat cooler than most forecast models for the peak of the Atlantic hurricane season. The Climate Prediction Center Markov model had the closest forecast to observations for August-October.

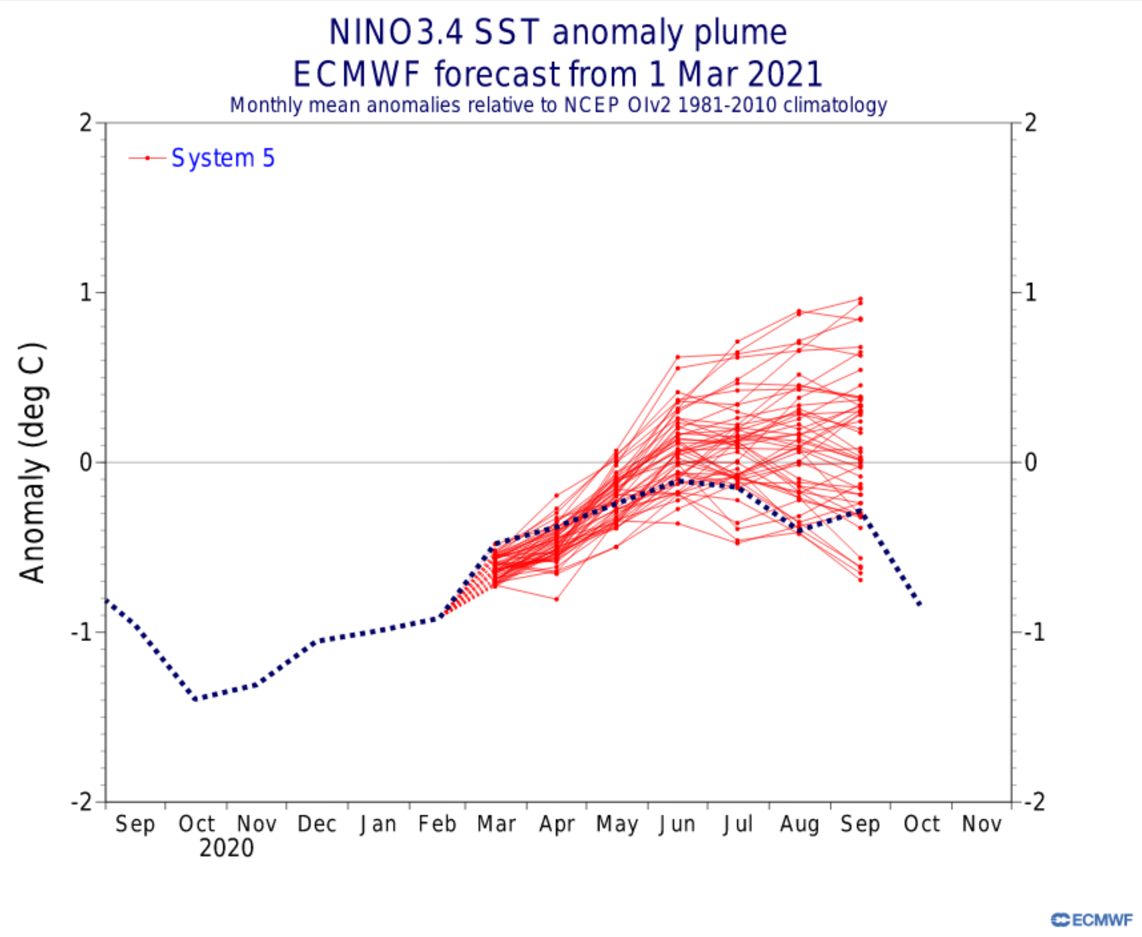

Figure 4: ECMWF ensemble prediction for Nino 3.4 from 1 March – the most recent information that we had available for our early April forecast in 2021. The blue dotted line represents the observed value.

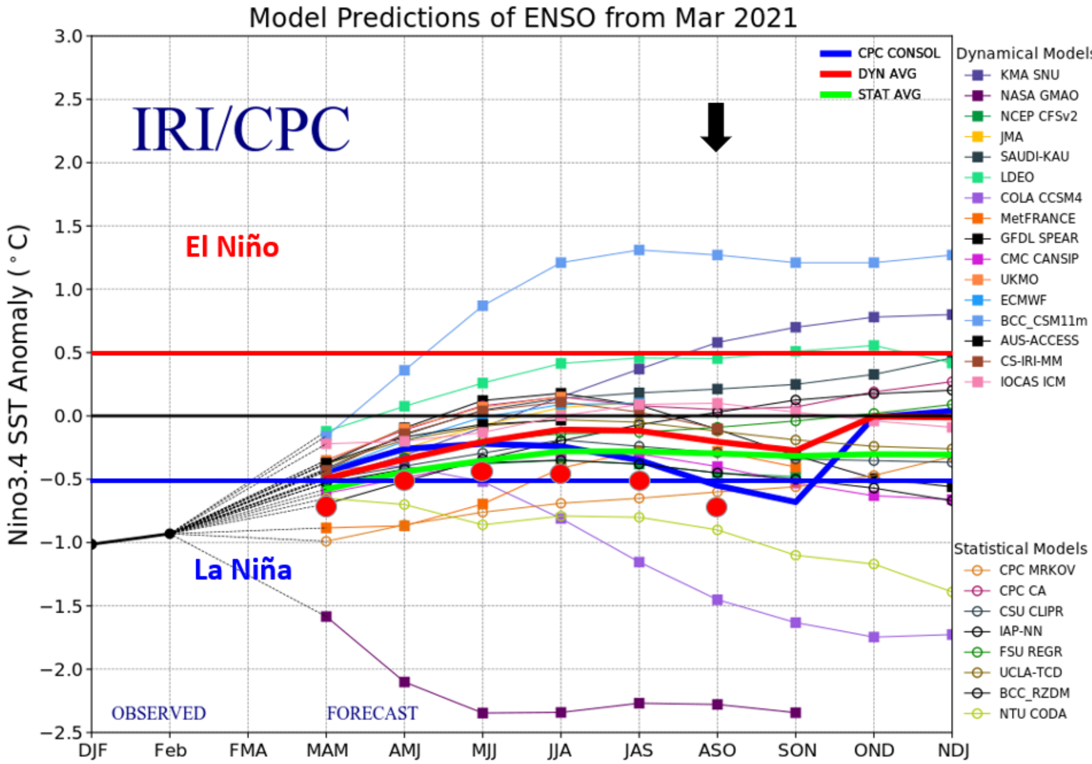

Figure 5: Ensemble prediction from 24 statistical and dynamical models for Nino 3.4 from mid-March. The black arrow highlights August-October – the peak three months of the Atlantic hurricane season. Red dots represent observed values for each three-month period.

Weak to moderate La Niña conditions were present during the winter of 2020/2021 and the early spring of 2021 before some anomalous warming caused the tropical Pacific to transition to cool neutral ENSO conditions during the early part of the summer. Anomalous cooling occurred after that time, with NOAA again declaring a La Niña event during October. Table 9 displays anomalies in the various Nino regions in January, April, July and October 2021, respectively.

Table 9: January anomalies, April anomalies, July anomalies, and October anomalies for the Nino 1+2, Nino 3, Nino 3.4 and Nino 4 regions. SST anomaly differences from January 2021 are in parentheses.

Region	January 2021 Anomaly (ºC)	April 2021 Anomaly (ºC)	July 2021 Anomaly (ºC)	October 2021 Anomaly (ºC)
Nino 1+2	-0.6	-0.9 (-0.3)	+0.5 (+1.1)	-0.2 (+0.4)
Nino 3	-0.6	-0.7 (-0.1)	-0.1 (+0.5)	-0.5 (+0.1)
Nino 3.4	-1.0	-0.5 (+0.5)	-0.3 (+0.7)	-0.8 (+0.2)
Nino 4	-1.3	-0.2 (+1.1)	-0.2 (+1.1)	-0.7 (+0.6)

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 last winter, anomalously warmed through May to slightly above-average levels and have since generally declined (although rebounding somewhat over the last month). Current upper ocean heat content anomalies in the eastern and central tropical Pacific are typically associated with weak to moderate La Niña events.

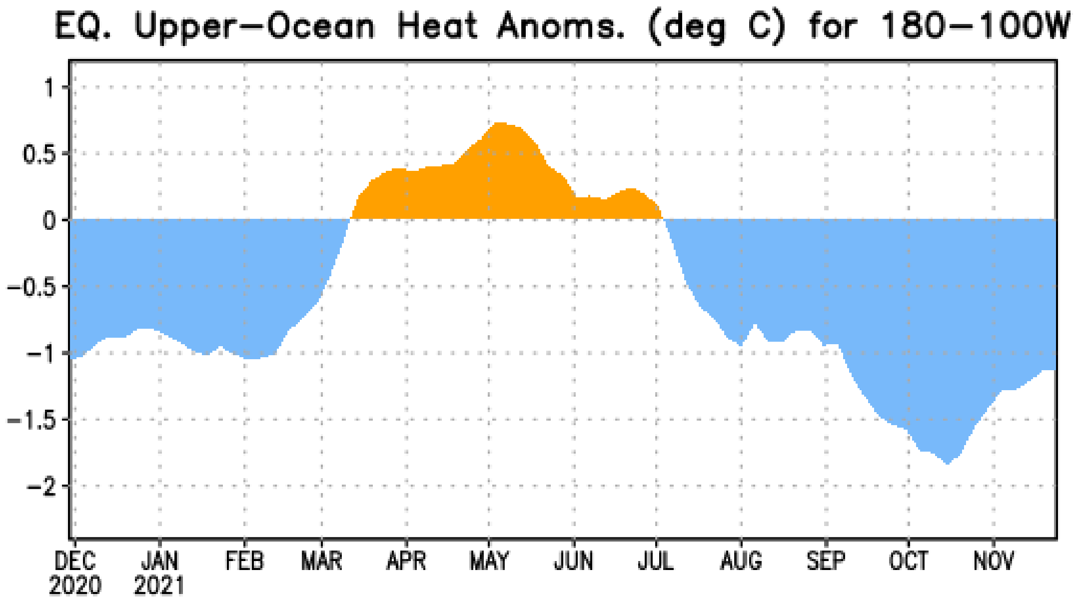

Figure 6: Upper ocean (0-300 meter) heat content anomalies in the eastern and central tropical Pacific from December 2020 – November 2021.

6.2 Intra-Seasonal Variability

The MJO was relatively weak during the latter part of August and most of September (Figure 7), although enhanced convection was generally favored over the Indian Ocean during this time. This large-scale vertical motion forcing tends to reduce Atlantic vertical wind shear and enhance Atlantic hurricane activity. Table 9 displays the historical relationship between MJO and Atlantic TC activity.

The MJO did begin to amplify in late September into early October and transited the Maritime Continent and into the tropical Pacific, likely suppressing Atlantic hurricane activity following a very active late August through late September. The MJO was shifted towards the right-hand side of the phase-space diagram over the 90-day period, which is typical with a transition to La Niña (which favors enhanced convection over the Maritime Continent). The peak of the 2021 Atlantic hurricane season when measured by ACE was characterized by an above-average August and September and a near-average October.

Almost all of October's ACE came from Hurricane Sam which became post-tropical on 5 October (Figure 8).

Table 10 displays the number of storms that were first named in each phase of the MJO over the course of the 2021 Atlantic hurricane season. Seventeen named storms formed during phases 1-3 of the MJO, while no named storms formed during phases 5-7 of the MJO. As noted earlier, however, the MJO spent very little time in phases 5-7 during the peak of the 2021 Atlantic season, given the transition towards La Niña that was underway. Climatologically, phases 1-3 of the MJO are the most active for Atlantic TC formation and intensification, while phases 5-7 of the MJO are the most inactive. In general, the relationships that have previously been documented between MJO phase and Atlantic hurricane activity matched up well with what was observed in 2021.

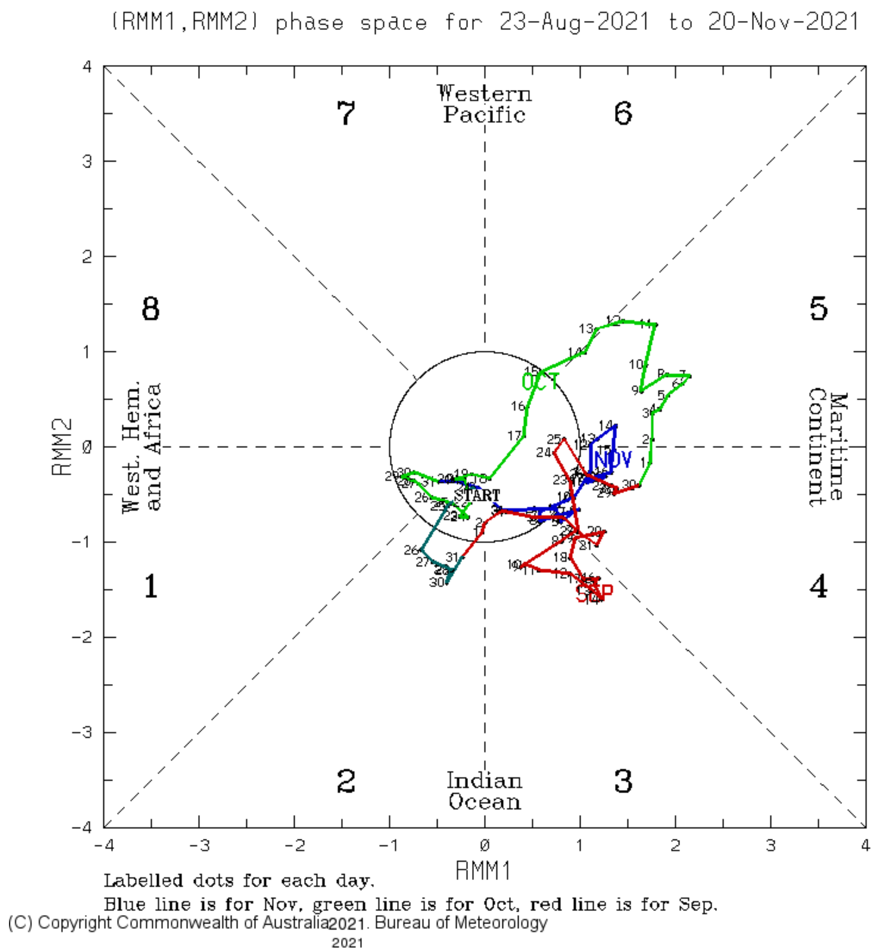

Figure 7: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 23 to November 20. Figure courtesy of Bureau of Meteorology.

Table 9: 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

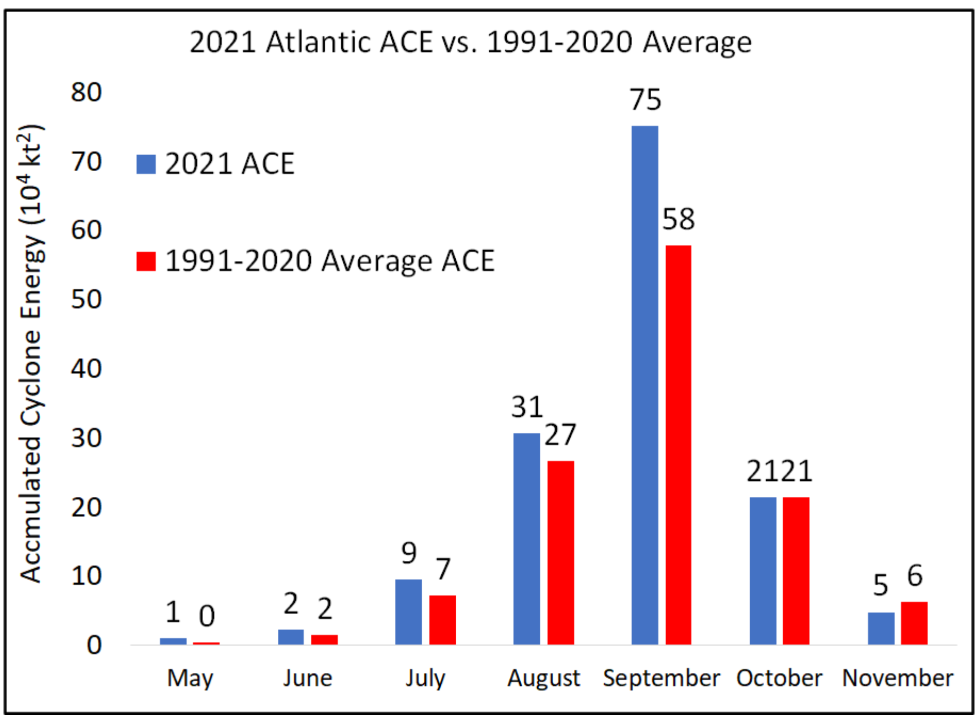

Figure 8: Atlantic Accumulated Cyclone Energy generated by month during 2021 (blue columns) compared with the 1991-2020 average (red columns)

Table 10: TC formations by MJO phase during the 2021 Atlantic hurricane season.

MJO Phase	TC Formations
1	2
2	10
3	5
4	4
5	0
6	0
7	0
8	0

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 has a stronger correlation with Atlantic TC activity during the early spring.

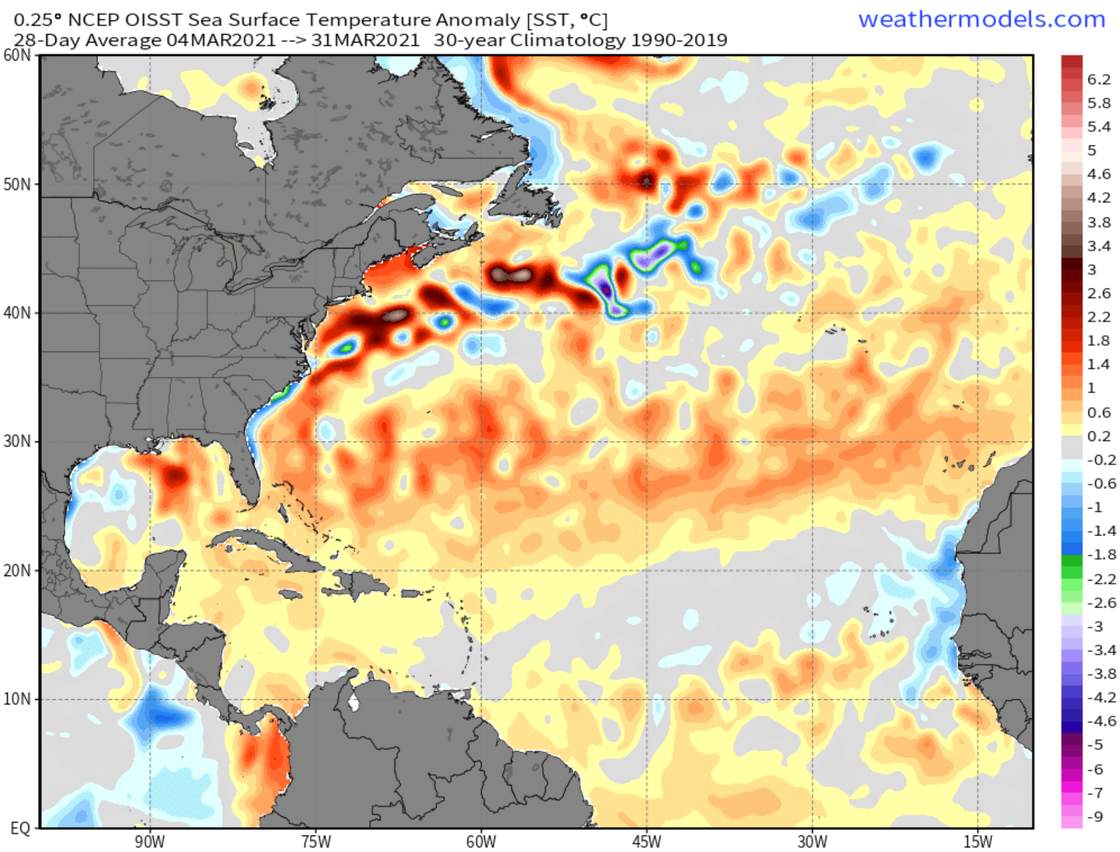

Figure 9: 28-day-averaged SST anomalies ending on March 31, 2021.

While the tropical Atlantic underwent some anomalous cooling from March to May, the subtropical Atlantic anomalously warmed (Figure 10). Both regions have strong positive correlations between SST and seasonal Atlantic TC activity in May. The mixed signals in the May North Atlantic SST pattern is one of several reasons why we maintained our slightly above-average seasonal TC forecast with our early June outlook.

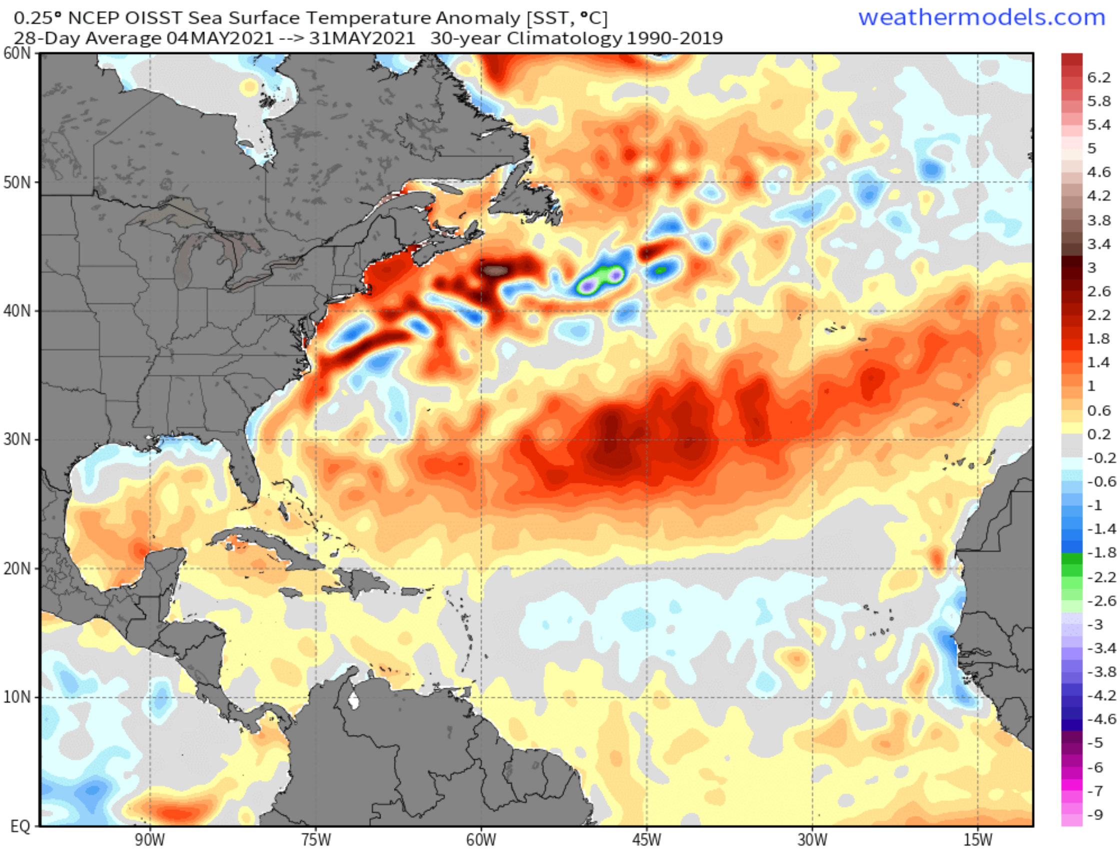

Figure 10: 28-day-averaged SST anomalies ending on May 31, 2021.

Tropical Atlantic SSTs anomalously warmed back to near normal levels by July (Figure 11). The tropical Atlantic, which we define to be 10-20°N, 60-20°W, was 0.1°C above the 1991-2020 average for July.

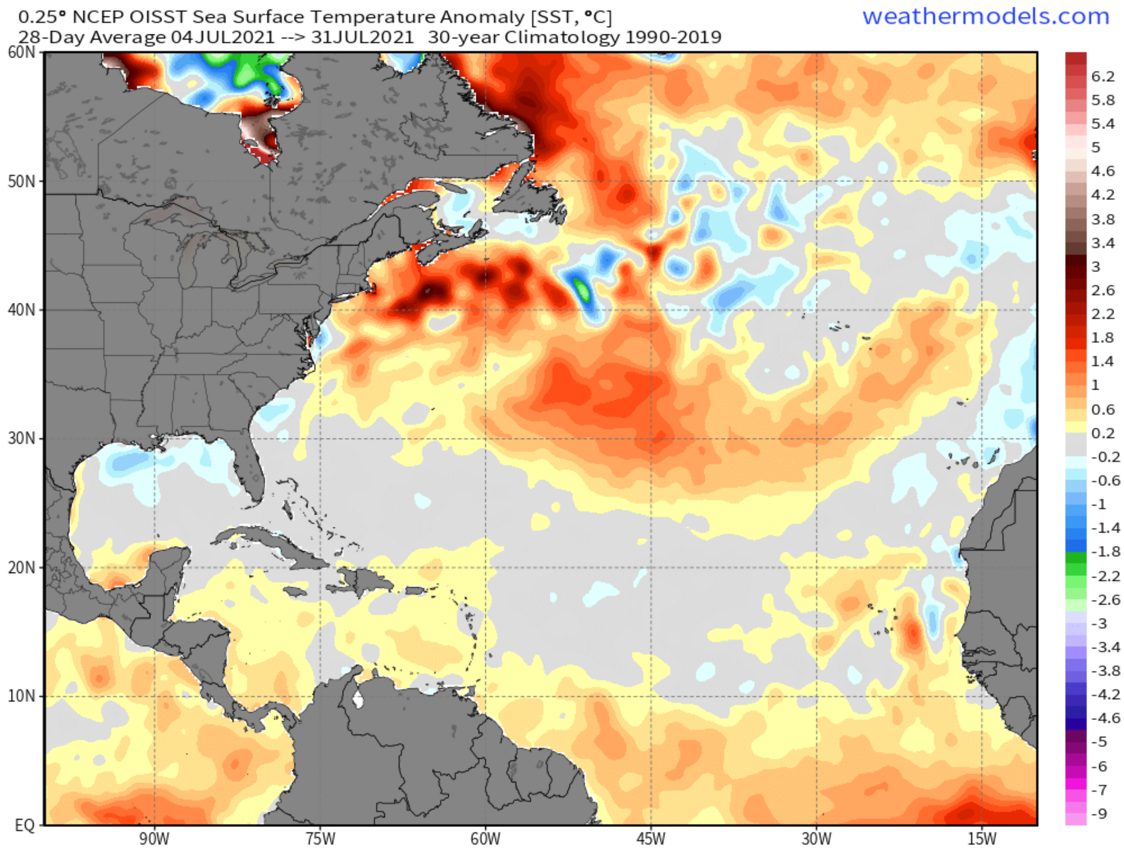

Figure 11: 28-day-averaged SST anomalies ending on July 31, 2021.

Anomalous tropical Atlantic warming continued for the next couple of months, with SST anomalies by September reaching well above-average levels (Figure 12). September 2021 SST anomalies in the tropical Atlantic were 0.3°C above the 1991-2020 average. Despite warm SST anomalies in the Caribbean in September (as well as October-November), the Caribbean was surprisingly quiet for TC activity during the latter part of the season.

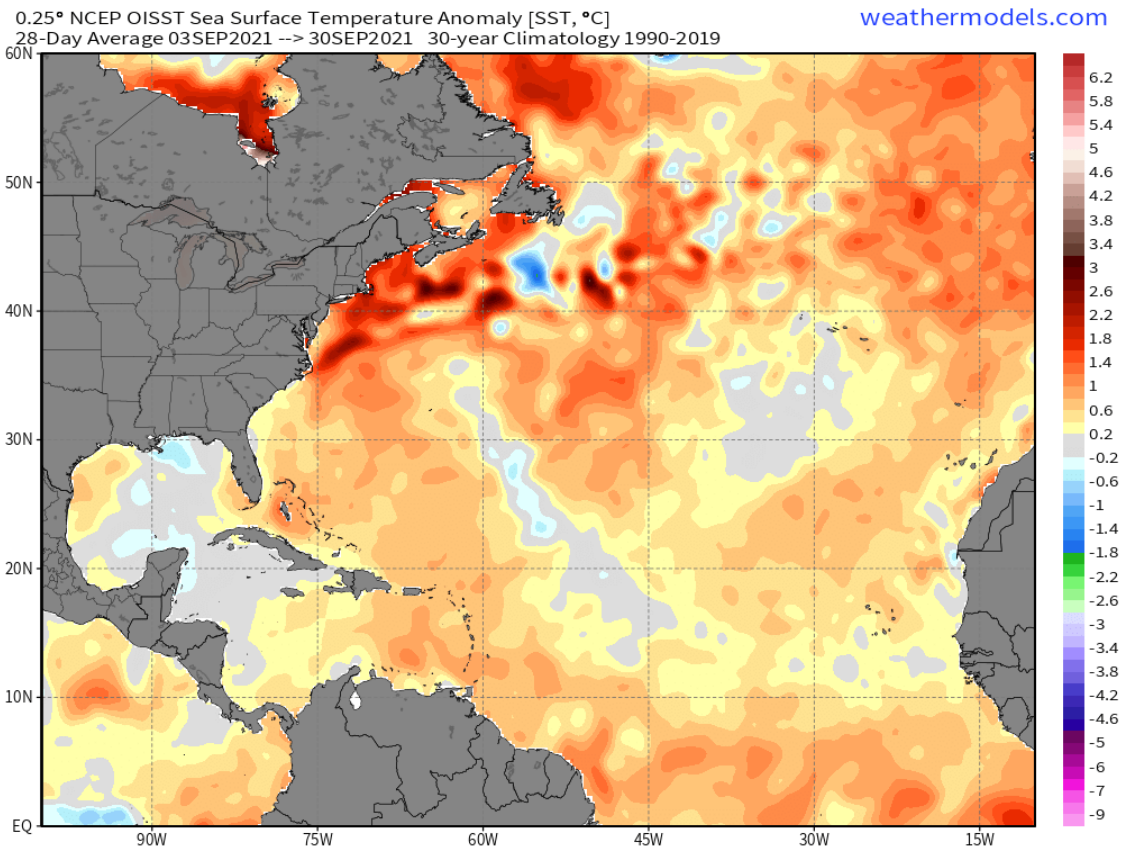

Figure 12: 28-day-averaged SST anomalies ending on September 30, 2021.

6.4 Tropical Atlantic SLP

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 2021 Atlantic hurricane season was characterized by slightly below-normal sea level pressures across most of the tropical Atlantic (Figure 13), in line with the slightly above-average hurricane season that occurred.

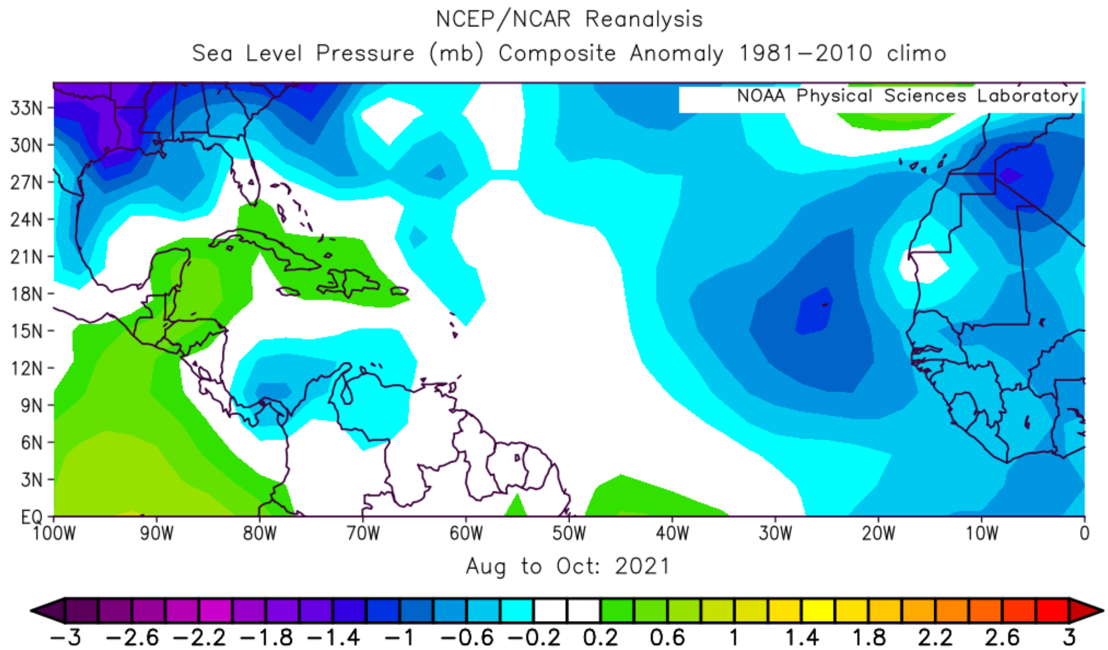

Figure 13: August-October 2021 tropical and sub-tropical North Atlantic sea level pressure anomalies.

6.5 Tropical Atlantic Vertical Wind Shear

During August and September, wind shear anomalies were below-normal across most of the tropical Atlantic and elevated across the Caribbean (Figure 14). Also highlighted in Figure 14 is the Main Development Region for TCs, which we define to extend from 10-20°N, 85-20°W. In general, the eastern and central tropical Atlantic were very active for Atlantic TC formation during these two months, which tracks well with where vertical wind shear was reduced. We will address late season vertical wind shear in the next section where we discuss the surprisingly quiet end to the 2021 season.

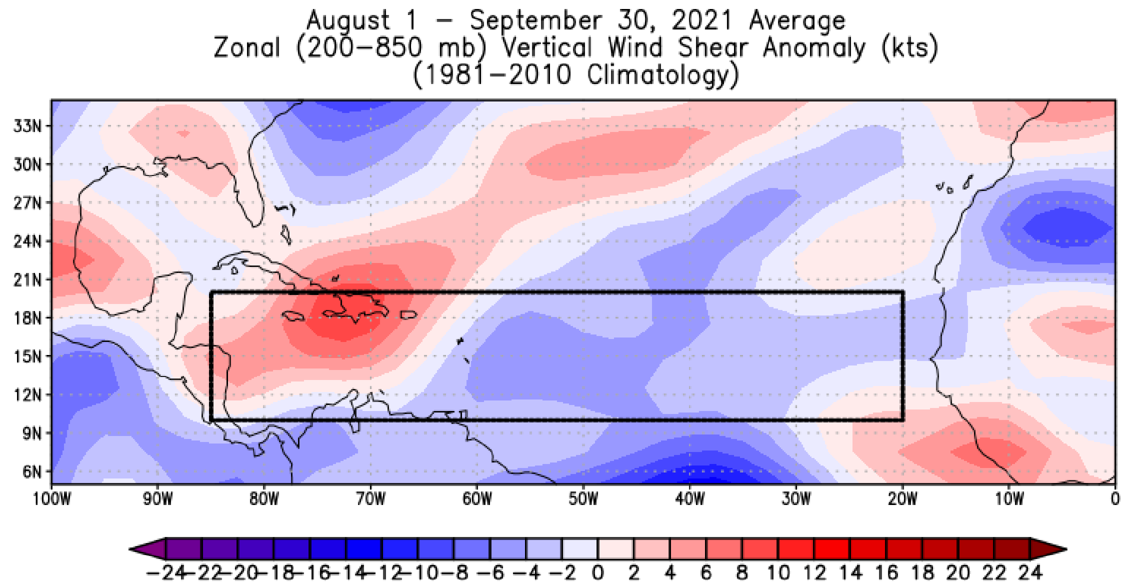

Figure 14: Anomalous vertical wind shear observed across the Atlantic from August to September 2021. The black box highlights the Main Development Region for Atlantic TCs.

6.5 Why Was the Latter Part of the 2021 Atlantic Hurricane Season So Quiet?

Through early October, the Atlantic hurricane season was well above average, and the large-scale SST setup of La Niña in the tropical Pacific and anomalous warmth in the Caribbean typically leads to an active late season, especially in the Caribbean (see Klotzbach et al. 2021 for more details). However, after Sam became post-tropical on 5 October, the only Atlantic TC to form was Wanda, which formed as a sub-tropical cyclone at high latitudes.

Figure 15 displays vertical wind shear anomalies from 1 October – 20 November across the tropical and sub-tropical Atlantic, with the black box denoting the Caribbean – where most strong late-season hurricanes form. Elevated vertical wind shear persisted across the Caribbean during this time, suppressing Atlantic TC formation.

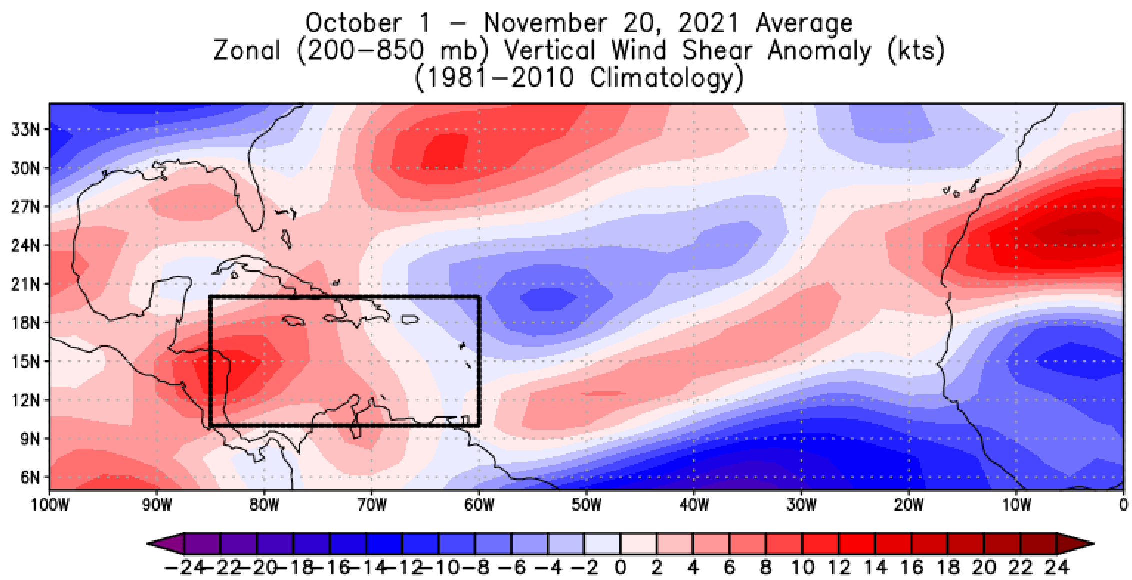

Figure 15: Anomalous vertical wind shear observed across the Atlantic from 1 October to 20 November 2021. The black box highlights the Caribbean – the region where most strong late season Atlantic TCs form.

The primary driver of the increased vertical wind shear in the latter part of 2021 was an anomalous upper-level low across the western Atlantic. Figure 16 displays the upper-level height difference between October 2021 and October 2020, which clearly shows the strong upper-level low (e.g., lower heights) in October 2021 relative to October 2020. This upper-level low and associated enhanced wavebreaking drove increased vertical wind shear across the western Atlantic that suppressed the latter part of the season. The exact physical drivers of the anomalous upper-level low and enhanced wavebreaking are currently under investigation.

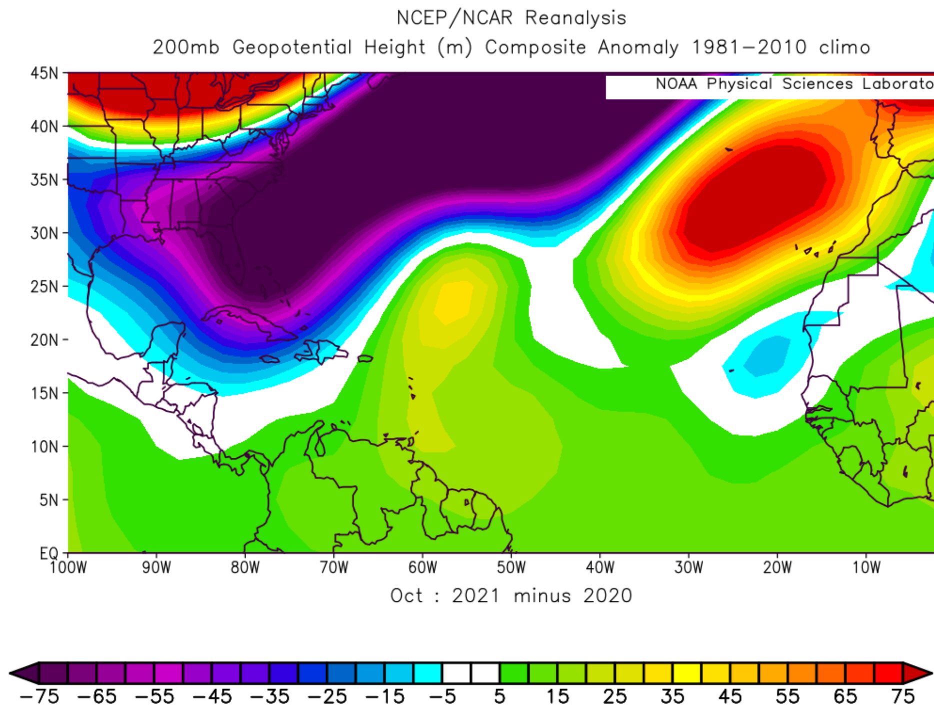

Figure 16: 200 hPa geopotential height difference between October 2021 and October 2020.

6.6 Steering Currents

The steering currents in August-October 2021 were characterized by an anomalous mid-level high pressure zone located from the southeastern United States extending northeastward towards the Atlantic Provinces of Canada (compared to the 2006-2016 period of the US major hurricane landfall drought) (Figure 17). This type of steering pattern aided in TCs tracking generally westward across the Atlantic. As was the case last year, several storms that formed in the eastern Atlantic were sheared apart before they could reach the central to western Atlantic.

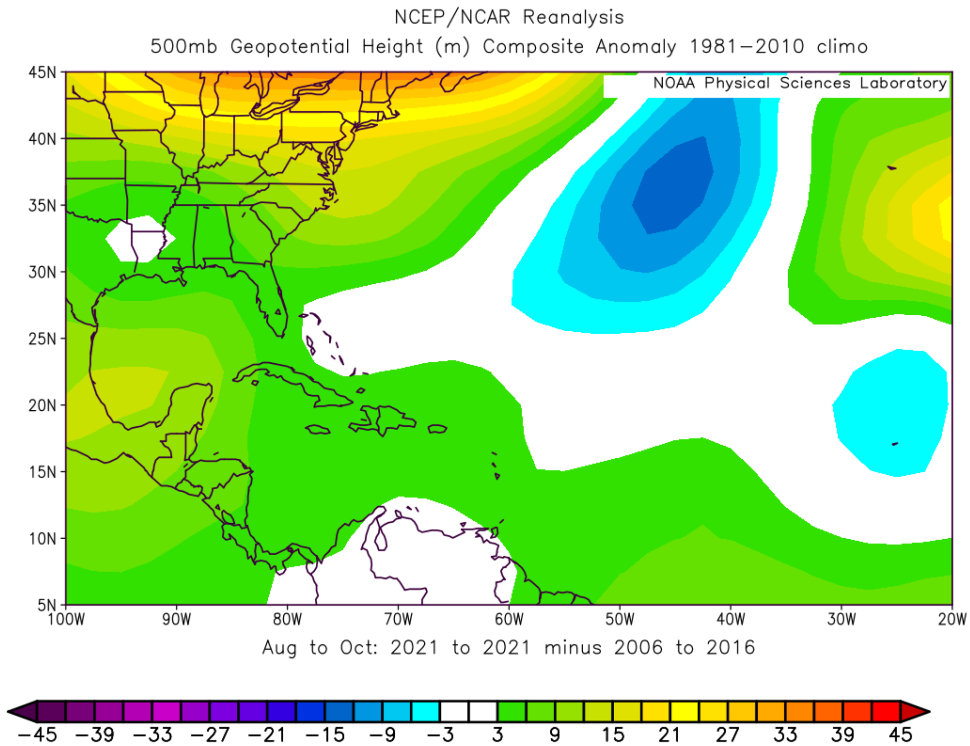

Figure 17: 500-mb height in the central and western part of the Atlantic from August to October in 2021 differenced from the August-October 2006 to 2016 period.

7 Forecasts of 2022 Hurricane Activity

We will be issuing our first outlook for the 2022 hurricane season on Thursday, 9 December 2021. This forecast will provide a qualitative outlook for factors likely to impact the 2022 hurricane season. This December forecast will include the dates of all of our updated 2022 forecasts. All of these forecasts will be made available online.

8 Verification of Previous Forecasts

Figure 18 displays the observed versus predicted real-time CSU August seasonal named storm forecasts from 1984-2021. The forecast correlates with observations at 0.80, indicating that CSU's August seasonal named storm forecast can explain ~60% of the variance in observed Atlantic named storm activity.

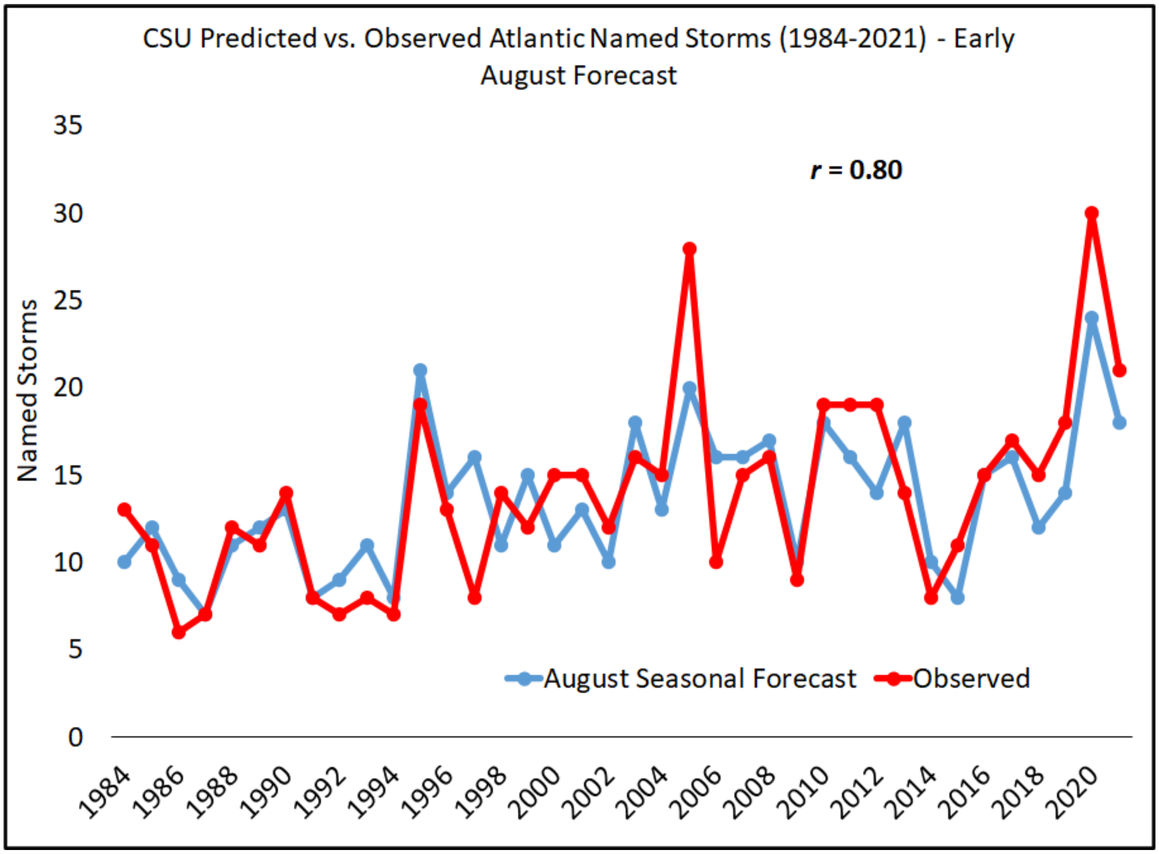

Figure 18: Observed versus predicted Atlantic named storms from 1984-2021.

CSU's seasonal hurricane forecasts have also 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 19 displays correlations between observed and predicted Atlantic hurricanes from 1984-2013, from 2014-2021 and from 1984-2021, respectively. Correlation skill has improved at all lead times in recent years, with the most noticeable improvements at longer lead times. While eight 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.

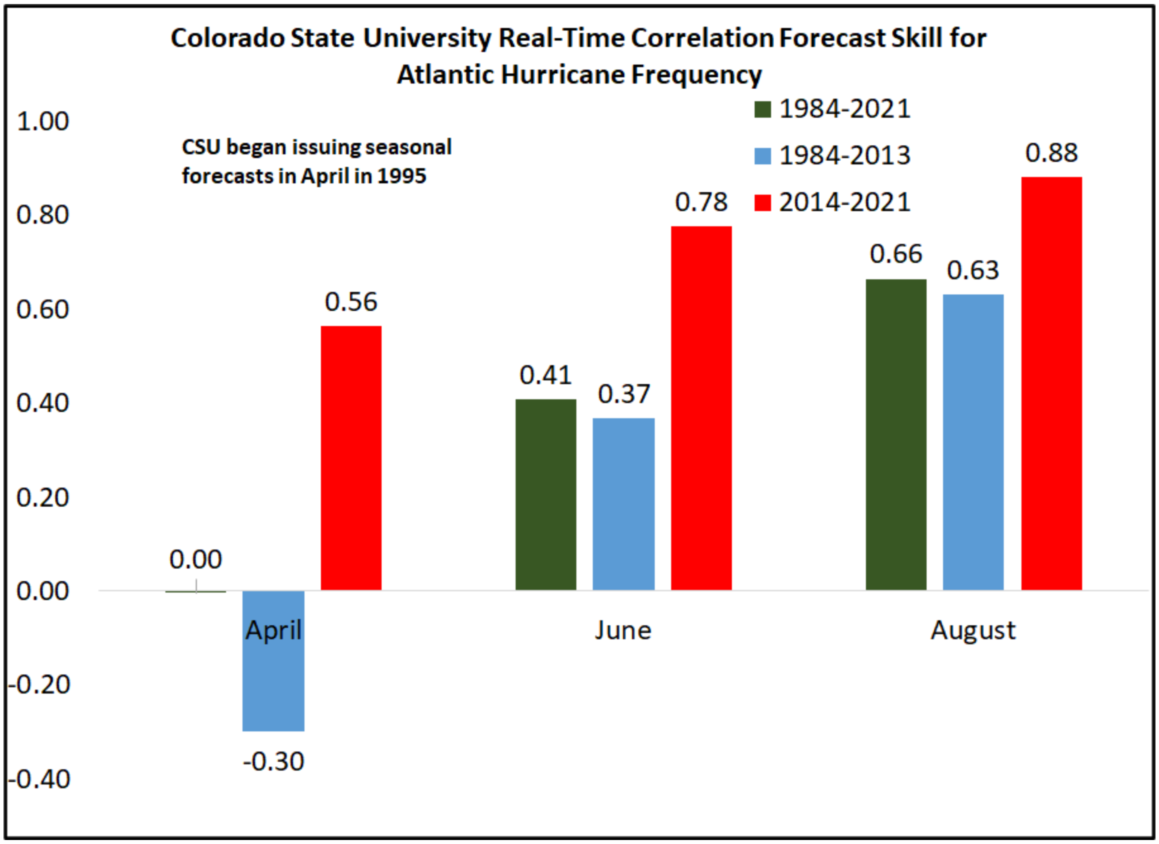

Figure 19: CSU's real-time forecast skill for Atlantic hurricanes using correlation as the skill metric. Correlation skills are displayed for three separate time periods: 1984-2013, 2014-2021 and 1984-2021, respectively.