The 2023 Atlantic Hurricane Season: An Above-Normal Season Despite Strong El Niño Conditions

Philip J. Klotzbach,[a] Jhordanne J. Jones,[b] Kimberly M. Wood,[c] Michael M. Bell,[a] Eric S. Blake,[d] Steven G. Bowen,[e] Louis-Philippe Caron,[f] Daniel R. Chavas,[g] Jennifer M. Collins,[h] Ethan J. Gibney,[i] Carl J. Schreck III,[j] Ryan E. Truchelut[k]

[a] *Department of Atmospheric Science, Colorado State University, Fort Collins, CO*

[b] *Cooperative Programs for the Advancement of Earth System Science, University Corporation for Atmospheric Research, Boulder, CO*

[c] *Department of Hydrology and Atmospheric Sciences, The University of Arizona, Tucson, AZ*

[d] *National Hurricane Center, National Oceanic and Atmospheric Administration, Miami, FL*

[e] *Gallagher Re, Chicago IL*

[f] *Ouranos, Montreal, QC, Canada*

[g] *Department of Earth, Atmospheric and Planetary Sciences, Purdue University, West Lafayette, IN*

[h] *School of Geosciences, University of South Florida, Tampa, FL*

[i] *University Corporation for Atmospheric Research/Cooperative Programs for the Advancement of Earth System Science, San Diego, CA*

[j] *North Carolina Institute for Climate Studies, Cooperative Institute for Satellite Earth Systems Studies, North Carolina State University, Asheville, NC*

[k] *WeatherTiger LLC, Tallahassee, FL*

Submitted to the Bulletin of the American Meteorological Society

Date: 12 March 2024

Revised: 14 June 2024

Corresponding author: Philip J. Klotzbach, philk@atmos.colostate.edu

Early Online Release: This preliminary version has been accepted for publication in *Bulletin of the American Meteorological Society*, may be fully cited, and has been assigned DOI 10.1175/BAMS-D-23-0305.1. The final typeset copyedited article will replace the EOR at the above DOI when it is published.

ABSTRACT

The 2023 Atlantic hurricane season was above normal, producing 20 named storms, 7 hurricanes, 3 major hurricanes and seasonal Accumulated Cyclone Energy that exceeded the 1991–2020 average. Hurricane Idalia was the most damaging hurricane of the year, making landfall as a Category 3 hurricane in Florida, resulting in eight direct fatalities and $3.6 billion USD in damage.

The above-normal 2023 hurricane season occurred during a strong El Niño event. El Niño events tend to be associated with increased vertical wind shear across the Caribbean and tropical Atlantic, yet vertical wind shear during the peak hurricane season months of August–October was well below normal. The primary driver of the above-normal season was likely record warm tropical Atlantic sea surface temperatures (SSTs), which effectively counteracted some of the canonical impacts of El Niño. The extremely warm tropical Atlantic and Caribbean were associated with weaker-than-normal trade winds driven by an anomalously weak subtropical ridge, resulting in a positive wind-evaporation-SST feedback.

We tested atmospheric circulation sensitivity to SSTs in both the tropical and subtropical Pacific and the Atlantic using the atmospheric component of the Community Earth System Model version 2.3. We found that the extremely warm Atlantic was the primary driver of the reduced vertical wind shear relative to other moderate/strong El Niño events. The concentrated warmth in the eastern tropical Pacific in August–October may have contributed to increased levels of vertical wind shear than if the warming had been more evenly spread across the eastern and central tropical Pacific.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

SIGNIFICANCE STATEMENT

The 2023 Atlantic hurricane season produced above-normal activity despite strong El Niño conditions. The season had 20 named storms, along with 7 hurricanes and 3 major hurricanes. Normally, El Niño decreases Atlantic hurricane activity due to increases in vertical wind shear. In 2023, vertical wind shear was below average, likely driven by the record warm tropical Atlantic and Caribbean sea surface temperatures which led to tropical circulation patterns that were considerably different from the atmospheric flow typically observed during El Niño events. This manuscript also uses a state-of-the-art climate model to investigate the impacts of Atlantic and Pacific SST configurations on Atlantic vertical wind shear patterns.

CAPSULE

Despite strong El Niño conditions, 2023 North Atlantic hurricane activity was above normal, likely fueled by record warm tropical and subtropical Atlantic sea surface temperatures.

KEY WORDS

Hurricane, tropical cyclone, El Niño, climate model, Pacific decadal oscillation

Introduction

The 2023 North Atlantic (hereafter Atlantic) hurricane season was classified as above normal based on NOAA's definition[1], with 20 named storms (e.g., a tropical cyclone (TC) or subtropical cyclone with ≥ 34 kt 1-minute maximum sustained winds), 7 hurricanes, 3 major hurricanes (maximum sustained winds ≥96 kt; Category 3–4–5 on the Saffir-Simpson Hurricane Wind Scale) and 148×10^4 kt^2 Accumulated Cyclone Energy (ACE; Bell et al. 2000). This activity compares with the 1991–2020 average of 14 named storms, 7 hurricanes,

[1] NOAA defines Atlantic hurricane seasons based on ACE. An above-normal season has $>126.1 \times 10^4$ kt^2 ACE (https://www.cpc.ncep.noaa.gov/products/outlooks/Background.html).

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

3 major hurricanes and 123 × 10^4 kt^2 ACE (Table 1). The 2023 season ranked joint with 1933 for 4th most named storms, 8th for named storm days and 26th for most ACE in the observed Atlantic historical record dating back to 1851 (e.g., HURDAT2; Landsea and Franklin 2013). Most other parameters were close to their 1991–2020 averages. We note that Atlantic hurricane activity is likely underestimated prior to the satellite era (e.g., 1966–onwards; Vecchi and Knutson 2011), while short-lived named storm activity is likely underestimated prior to the real-time usage of scatterometry in 2000 by the National Hurricane Center (Brennan et al. 2009; Villarini et al. 2011; Klotzbach et al. 2022).

TC Metric	2023 Activity	1991–2020 Average	2023 Activity as % of 1991–2020 Average
Named storms	20	14.4	139%
Named storm days	100.50	69.4	145%
Hurricanes	7	7.2	97%
Hurricane days	31.5	27.0	117%
Major hurricanes	3	3.2	94%
Major hurricane days	7.25	7.4	98%
ACE	148	123	120%

Table 1. 2023 Atlantic TC activity compared with the 1991–2020 average.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

Notably, the 2023 Atlantic hurricane season occurred during a strong El Niño[2], with an August–October-averaged (hereafter ASO) Oceanic Nino Index[3] (ONI) value of 1.6°C. El Niño typically reduces Atlantic hurricane activity due to increases in Caribbean and tropical Atlantic vertical wind shear, with stronger El Niño events typically having larger impacts on vertical wind shear and Atlantic hurricane activity (e.g., Gray 1984; Patricola et al. 2014; Klotzbach et al. 2022). This strong El Niño occurred at the same time as record warm sea surface temperatures (SSTs) across the tropical Atlantic and Caribbean (Fig. 1). Anomalously warm SSTs in the tropical Atlantic and Caribbean are typically associated with more active Atlantic hurricane seasons due to a more favorable thermodynamic and dynamic environment including reduced levels of vertical wind shear (e.g., Wang et al. 2006; Patricola et al. 2014; Saunders et al. 2020; Klotzbach et al. 2022). In addition, the latitudinal extent of the warm anomalies in the 2023 El Niño event was atypically limited, meaning the subtropical North Pacific was much cooler than normal for a strong El Niño.

[2] NOAA defines El Niño intensity operationally based on values of the ONI. ONI values ≥1.5°C are classified as strong El Niño events (L'Heureux et al. 2019).

[3] The ONI is defined to be three-month running averages of Nino 3.4 (5°S–5°N, 170–120°W) anomalies based on 30-year centered based periods updated every five years.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

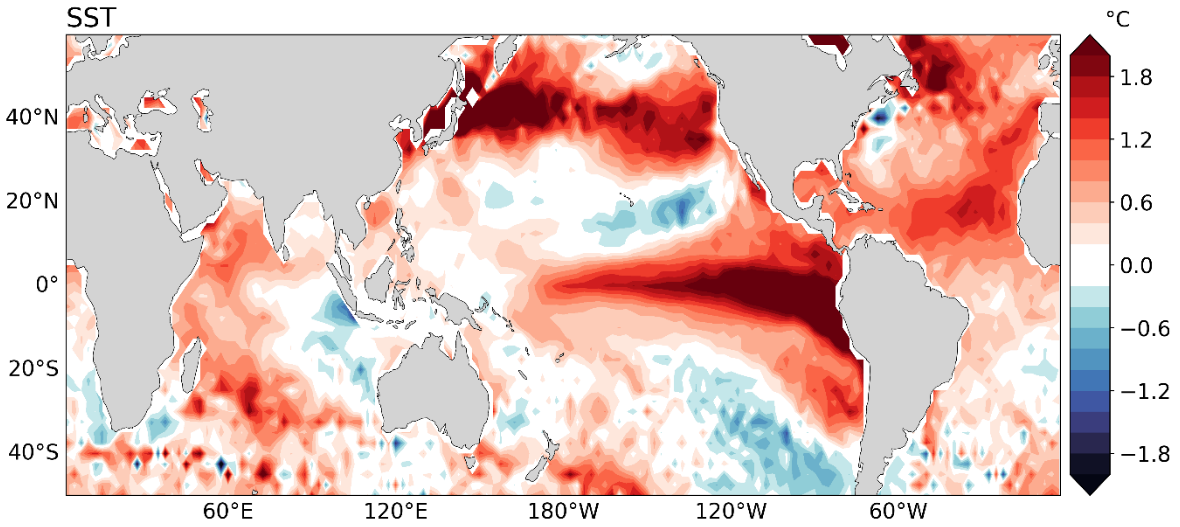


Figure 1: 2023 August–October-averaged SST anomalies relative to 1991–2020.

A lack of robust historical analog years with contemporaneous El Niño, record tropical Atlantic warmth, and an anomalously cool subtropical North Pacific led to publicly-available Atlantic seasonal hurricane forecasts highlighting the larger-than-normal uncertainty in the outlooks for 2023 (e.g., Klotzbach et al. 2023; NOAA 2023a). For example, NOAA's 25 May outlook called for a 40% chance of a near-normal season, a 30% chance of an above-normal season, and a 30% chance of a below-normal season (NOAA 2023a). These outlooks from CSU and NOAA also noted that the anomalous Atlantic warmth might counteract some of the enhanced shear typically associated with El Niño.

There was also greater than normal spread in the seasonal forecasts submitted to the Seasonal Hurricane Predictions forum (https://seasonalhurricanepredictions.bsc.es/; Caron et al. 2020). From the 30 groups who submitted 2023 season outlooks, the mean number of expected hurricanes was 7.7, but the standard deviation was 2.3, a value nearly double the average from the 2016–2022 period (1.2). The forum became operational in 2016.

This study investigates the 2023 Atlantic hurricane season by first identifying pre-season climatic conditions that led to the record warm tropical Atlantic and Caribbean. We also examine how large-scale atmospheric conditions evolved during the season, leading to periods of heightened or decreased Atlantic hurricane activity. Finally, we explore impacts of varied SST anomaly configurations on the observed ASO atmospheric circulation patterns using a state-of-the-art atmosphere-only climate model.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0305.1.

Data and modeling approach

Data and climate indices

We used the hourly, 0.25° European Centre for Medium-Range Weather Forecasts Fifth Generation Reanalysis (ERA5; Hersbach et al. 2020) for all large-scale analyses. The reanalysis is currently available from 1940–present, but analyses in this paper focused on the period from 1979–present when global coverage of both geostationary and polar-orbiting satellites is available (Smith et al. 1979). Sea surface temperatures from ERA5 were obtained from the Hadley Centre Sea Ice and Sea Surface Temperature dataset version 2.1.0.0 from 1979–August 2007 and from the Operational Sea Surface Temperature and Ice Analysis for September 2007–onwards (Hersbach et al. 2020). Potential intensity (PI) was calculated using the Bister and Emanuel algorithm (2002) and the tcpyPI package (Gilford 2020; Gilford 2021). Anomalies were calculated with respect to a 1991–2020 average.

HURDAT2[4] was used to compute all TC metrics for the Atlantic. The dataset consists of 6-hourly estimates from 1851–2023 of TC maximum intensity and location, with additional storm characteristics (e.g., wind radii, radius of maximum wind) added in more recent years. In addition, TC intensity and location are provided outside of 6-hourly intervals for specific events such as landfalls. We used GIS data based on HURDAT2 and archived in the International Best Track Archive for Climate Stewardship (Knapp et al. 2010; Knapp et al. 2018) to construct our track map (Fig. 3). We primarily compared 2023 Atlantic TC activity with the 1991–2020 average, as this is NOAA's current climatological base period. We also briefly evaluated eastern North Pacific hurricane activity using HURDAT2. HURDAT2 for the eastern North Pacific is available from 1949–2023.

We explored multiple indices to quantify the El Niño Southern Oscillation (ENSO) state in 2023. The Oceanic Niño Index (ONI), used by NOAA to classify ENSO events, represents a 3-month running average of SST anomalies over 5°S–5°N, 170–120°W – referred to as the

[4] HURDAT was downloaded on 20 May 2024.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

Niño 3.4 region. We also evaluated the Niño 1+2 index (10°S–0°, 90–80°W) as a 3-month running average. Both this index and ONI were provided by NOAA's Climate Prediction Center. The ENSO Longitude Index (ELI; Williams and Patricola 2018) offers an additional perspective on ENSO phase by approximating where the center of deep convection is located across the tropical Pacific.

In addition to ENSO indices, we assessed the Indian Ocean Dipole (IOD) using the Dipole Mode Index (DMI) as defined by Saji et al. (1999) and calculated directly from ERA5 SST. The DMI is defined as the SST gradient between the western equatorial Indian Ocean (10°S–10°N, 50–70°E) and the southeastern equatorial Indian Ocean (10°S–0°, 90°–110°E). We used the Pacific decadal oscillation (PDO; Mantua et al. 1997) index from the National Centers for Environmental Information for insight into the SST configuration across the North Pacific. The SST component of the Atlantic Meridional Mode (AMM; Kossin and Vimont 2007), as provided by the Physical Sciences Laboratory, was used to assess the state of the SST configuration over the tropical Atlantic. Finally, we used the Real-Time Multivariate (RMM) Madden-Julian oscillation (MJO) index of Wheeler and Hendon (2004) to diagnose subseasonal variability likely associated with the MJO.

A two-tailed Student's *t*-test was used to test statistical significance throughout this study. Each year was treated as an individual degree of freedom. Statistical significance was tested at the 5% level.

Climate modeling approach

We ran the Community Earth System Model version 2.3 (CESM2; Danabasoglu et al. 2020) on a 1.9° latitude by 2.5° longitude grid to analyze the impacts of various SST configurations on atmospheric circulation patterns, with a focus on the Atlantic. This resolution was too coarse to resolve TCs, which is why we focused on large-scale pattern responses. The Community Atmosphere Model version 6 was forced with a prescribed 1991–2020 12-month SST climatology from ERA5 (seasonally varying SSTs). We examined the simulated atmospheric response to four different sets of SST configurations (Fig. 2):

1) FULL2023: 2023 January–November SST forcing

2) 2023ATLONLY: 2023 Atlantic SSTs only and climatology elsewhere

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

3) ELNINOPAC: 2023 SSTs with Pacific SSTs swapped for a 1982, 1987, 1997, 2002, and 2015 El Niño years composite, and

4) ATLCLIM: Atlantic SSTs set to climatology with 2023 SSTs elsewhere

These SST configurations were chosen to study the impacts of the atmospheric response driven by various SST configurations. 2023ATLONLY examined how the atmospheric circulation would have changed with climatological SSTs in all basins other than the Atlantic. ELNINOPAC was the average of all other moderate/strong El Niño events[5] during ASO since 1979. These other moderate/strong El Niño events were characterized by a much warmer northern subtropical Pacific than was observed in 2023, so this allowed us to examine the impacts of those warm subtropical Pacific SSTs on the atmospheric circulation pattern, represented here by the deep-layer vertical wind shear. ATLCLIM examined how the atmospheric circulation pattern would have responded if Atlantic SSTs were set to their long-term averages.

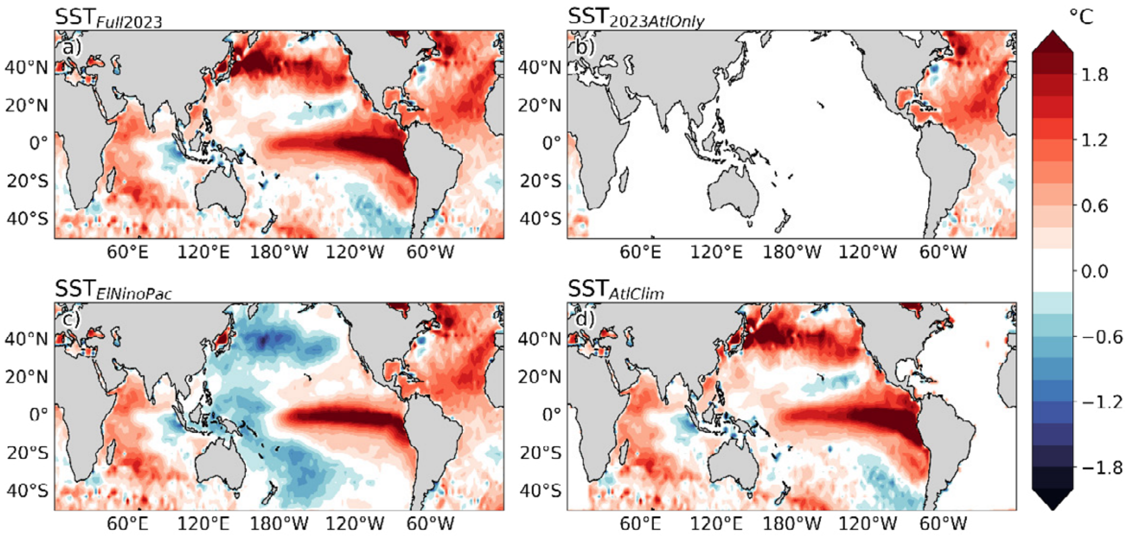


Fig. 2. SST anomaly forcings for the four atmosphere-only simulations: (a) FULL2023, (b) 2023ATLONLY, (c) ELNINOPAC, and (d) ATLCLIM.

---

[5] NOAA defines moderate El Niño events to have an Oceanic Nino Index value between 1.0°–1.4°C (L'Heureux et al. 2019).

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

Vertical wind shear was defined as the total wind difference between 200 and 850 hPa. The SST forcing patterns were global and extended from ~80°S–80°N. In the case of basin SST forcings (for example, 2023ATLONLY), the SST forcing extended from ~50°S–70°N.

The 2023 Atlantic hurricane season

2023 Atlantic hurricane season TCs

Here, we focused on systems forming during the official Atlantic hurricane season (1 June–30 November), noting that an unnamed subtropical storm occurred in January (Fig. 3). ACE activity was above-normal in June, August, and September, and near-normal in July and October. No named storms formed in November (Fig. 4a).

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

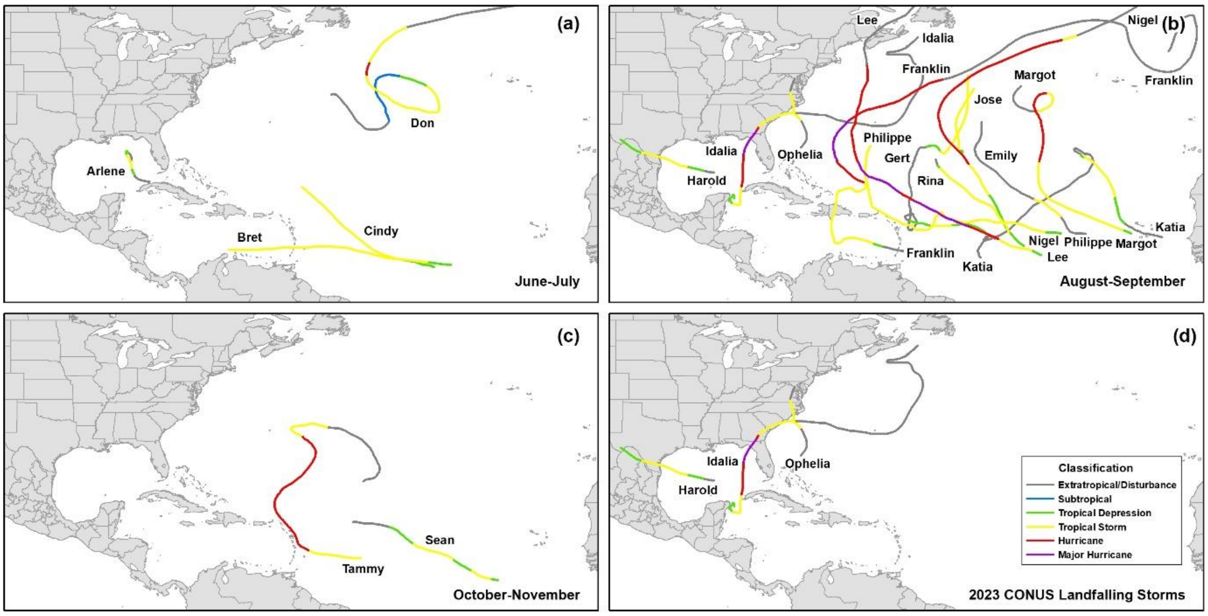
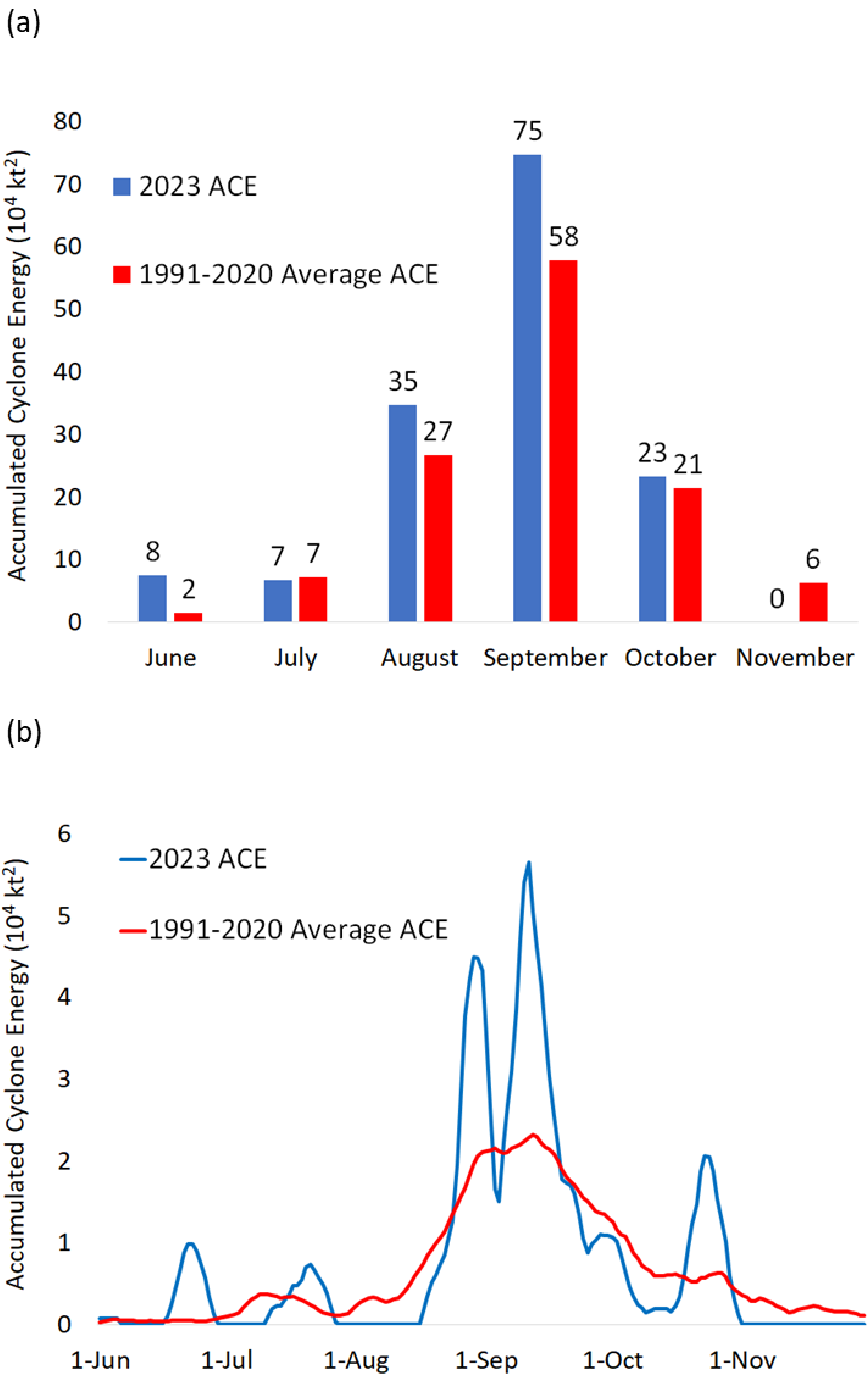


Fig. 3. Tracks of 2023 Atlantic named storms during (a) June–July, (b) August–September, and (c) October–November. (d) Tracks of CONUS landfalling named storms.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.



Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

Fig. 4. (a) Monthly and (b) daily ACE during the 2023 Atlantic hurricane season compared with the 1991–2020 average. Daily ACE was smoothed with a 7-day average, with the date denoted on the x-axis corresponding to the mid-point of the 7-day average.

The season began quickly, with three named storms forming in June, including the first time on record that two June TCs (Bret and Cindy) formed in the tropical Atlantic (defined here to be south of 20°N, east of 60°W). Following that early burst of activity, only one named storm formed between 23 June – 19 August.

In contrast, the climatological peak of the Atlantic hurricane season was extremely busy, with 13 named storms forming between 20 August – 28 September (Fig. 3b), breaking the previous record of 12 named storm formations between those two dates set in 2020. Five of the seven hurricane formations, all three major hurricane formations, and all three of 2023's continental US (CONUS) named storm landfalls occurred during this time (Fig. 3d). Tropical Storm Harold caused minimal damage in Texas (Pasch et al. 2024), while Tropical Storm Ophelia caused moderate damage across North Carolina and the mid-Atlantic ($450 million USD; Brown et al. 2024). Idalia was the most damaging storm to make CONUS landfall in 2023, causing $3.6 billion USD in damage when it made landfall in the Big Bend of Florida (Cangialosi and Alaka 2024).

Each of 2023's three major hurricanes set or came close to setting records. Hurricane Franklin's central pressure dropped to 926 hPa at 29°N, the lowest pressure on record for a hurricane that far north in the open Atlantic (e.g., not in the Gulf of Mexico). Franklin brought heavy rain and tropical storm-force winds when it made landfall in the Dominican Republic. Franklin also brought tropical storm-force winds to Bermuda while tracking northwest of the island. Reported damage from the system was relatively minimal.

Hurricane Idalia made landfall in the Big Bend region of Florida as a Category 3 hurricane with maximum winds of 100 kt (Cangialosi and Alaka 2024). Idalia was the strongest hurricane to make landfall in that region since Hurricane Easy in 1950 (105 kt). The storm had a maximum storm surge inundation of 8–12 ft between Keaton Beach and Steinhatchee (Cangialosi and Alaka 2024).

Hurricane Lee was the strongest hurricane of the 2023 season, achieving a peak intensity of 145 kt on 8 September after intensifying by 75 kt between 6 UTC on 7 September and 8 September. Only three other Atlantic named storms on record have intensified by 75 kt or

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

more in 24 h: Wilma (2005), Felix (2007), and Matthew (2016). Lee subsequently underwent rapid weakening by 45 kt in the 24 h following its lifetime maximum intensity. Lee brought tropical storm-force winds to Bermuda and threatened eastern New England before becoming a post-tropical cyclone and making multiple landfalls in Atlantic Canada, causing minor wind and storm surge damage.

Two named storms formed in the Atlantic during October. Sean became a named storm on 11 October – the farthest east named storm formation in the tropical Atlantic that late in the calendar year. Tammy also developed in the tropical Atlantic and became a hurricane as it approached the Lesser Antilles on 20 October – the latest calendar year hurricane in the tropical Atlantic since 1896. Tammy brought hurricane force-winds but minimal damage to portions of the northeastern Leeward Islands.

Large-scale changes between March and July

Marked changes occurred in SST anomalies between March and July, with the most notable being anomalous warming in both the eastern and central tropical Pacific as well as the tropical and subtropical Atlantic (Fig. 5a). While the trend towards El Niño was well-anticipated by dynamical and statistical models, as well as the official forecast from NOAA, the extremely rapid warming in the tropical and subtropical Atlantic was less well anticipated. As an example, Figs. S1a and S1b display forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF) from a 1 March initialization for Niño 3.4 and for the tropical Atlantic. While the ECMWF ensemble average was somewhat too cool for the Nino 3.4 region for the boreal summer, it did correctly anticipate a robust El Niño event (Fig. S1a). However, observed tropical Atlantic SSTs, which ECMWF defines to span from 5°–25°N, 60–15°W, were above the 95th percentile of ECMWF's forecast for each month from April to September – when the 1 March ECMWF forecast terminated (Fig. S1b). Most other climate models also considerably under-forecasted the anomalous warming that occurred across the tropical Atlantic during boreal spring and summer (figures not shown). This anomalous warming in the tropical Atlantic also led to concomitant increases in PI (Fig. 5b), implying a more conducive thermodynamic environment for TC intensification (Klotzbach et al. 2022).

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

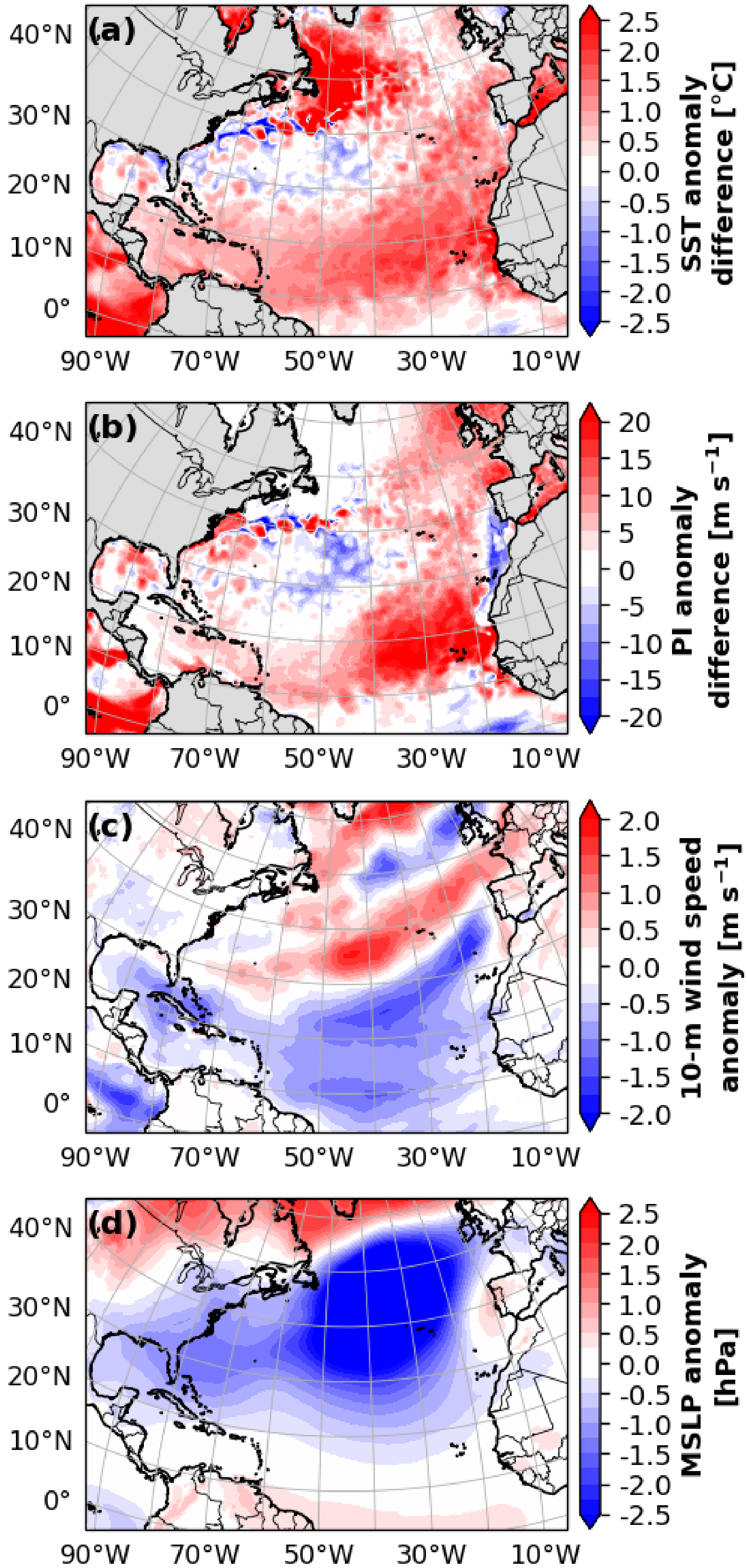


Fig. 5. (a) 2023 July minus 2023 March SST anomalies. (b) 2023 July minus 2023 March PI anomalies. (c) 2023 March–July-averaged 10-meter wind speed anomalies. (d) 2023 March–July-averaged MSLP anomalies.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

The primary driver of the observed Atlantic warming during boreal spring and summer appeared to be weaker trade winds (Fig. 5c) linked with a marked weakening of the subtropical high (Fig. 5d), with March–July sea level pressure anomalies well below normal across the subtropical Atlantic. These anomalously low pressures led to a concomitant weakening of the subtropical-tropical pressure gradient across the Atlantic, resulting in the aforementioned weaker trade winds (Fig. 5c). These weaker trades reduced evaporation, upwelling and turbulent mixing, causing anomalous warming of the tropical and subtropical Atlantic (Fig. 5a) via a positive wind–evaporation–SST feedback (e.g., Kossin and Vimont 2007).

The anomalous warming across the Main Development Region (MDR; Goldenberg and Shapiro 1996), defined as 10–20°N, 85–20°W in this manuscript, occurred quickly during the boreal spring and summer. February MDR SSTs were near their 1991–2020 averages. By June, MDR SSTs were at record warm levels , >1°C above the long-term average, and remained at record warmth through October (Fig. 1). This anomalous warming led to consistent upward adjustments in seasonal Atlantic TC forecasts by most groups, including Tropical Storm Risk (TSR; Lea and Wood 2023), Colorado State University (CSU; Klotzbach et al. 2023) and NOAA (NOAA 2023b) – the three groups that have consistently issued publicly-available Atlantic seasonal hurricane forecasts for the longest time (Fig. S2; Klotzbach et al. 2017). All three groups generally underestimated activity in their early outlooks with improved skill as the peak of the Atlantic hurricane season approached. The forecast entities submitting seasonal forecasts to the Seasonal Hurricane Predictions forum (Caron et al. 2020) also generally raised their forecast numbers from pre-season outlooks to final outlooks. The average forecast[6] increased from 14.3 to 17.1 for named storms, from 6.6 to 8.0 for hurricanes, from 2.6 to 3.3 for major hurricanes and from 113 to 150 for ACE between the periods of March–April and July–August. The two dynamical models (ECMWF and UK Met) that contributed to the forum forecasted higher levels of activity with their final

[6] This analysis only considered groups which submitted a forecast for both periods.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

forecast than the average of the other model contributions (e.g., 205 ACE vs. 150 ACE), which were predominately hybrid (e.g., statistical/dynamical). Figure S3 displays the final seasonal hurricane forecasts issued in 2023 by each entity on the Seasonal Hurricane Predictions forum. Some of the groups submitting forecasts to the forum did not predict hurricanes (e.g., they only forecasted named storms or ACE).

Large-scale conditions during the peak of the Atlantic hurricane season (August–October)

OCEANIC CONDITIONS AND ASSOCIATED CLIMATE MODES

The ASO period was characterized by a strong El Niño event (Fig. 1) with an ONI value of 1.6°C. The anomalous tropical Pacific warmth was strongest near the west coast of South America, where the Nino 1+2 value was 2.9°C. The ASO value of the ELI was strongly shifted eastward (175.4°E). Since 1979, the ONI ranked as the 5^{th} highest (trailing in descending order from highest: 2015, 1997, 1987 and 1982). The four highest ONI ranked seasons all were below-average Atlantic hurricane seasons based on NOAA's definition (ACE $< 73 * 10^4$ kt^2). The Nino 1+2 region ranked as the 2nd highest, trailing only 1997. The ELI ranked as the fourth most eastward ELI, trailing from farthest east: 1997, 2015 and 1982. The eastward shift in the ELI indicated an eastward-shifted Walker Circulation, which implied a strong El Niño (Williams and Patricola 2018).

One unique feature of the 2023 Atlantic hurricane season was the combination of a strong El Niño and a strongly negative PDO (Fig. 1). A negative phase of the PDO typically has colder-than-normal waters in the eastern and central subtropical Pacific, as was the case in ASO 2023. This combination has not happened in the longer-term historical record (e.g., since 1950 when the ONI dataset began). The ASO PDO index was the most negative ASO value in our primary study period since 1979 and the lowest since 1955. Historically, El Niño and positive phases of the PDO tended to occur together, likely due to the atmospheric bridge mechanism linking the tropical and North Pacific (Alexander et al. 2002). There is a significant correlation of 0.60 between ASO ONI and ASO PDO from 1979–2022 (Fig. 6a).

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

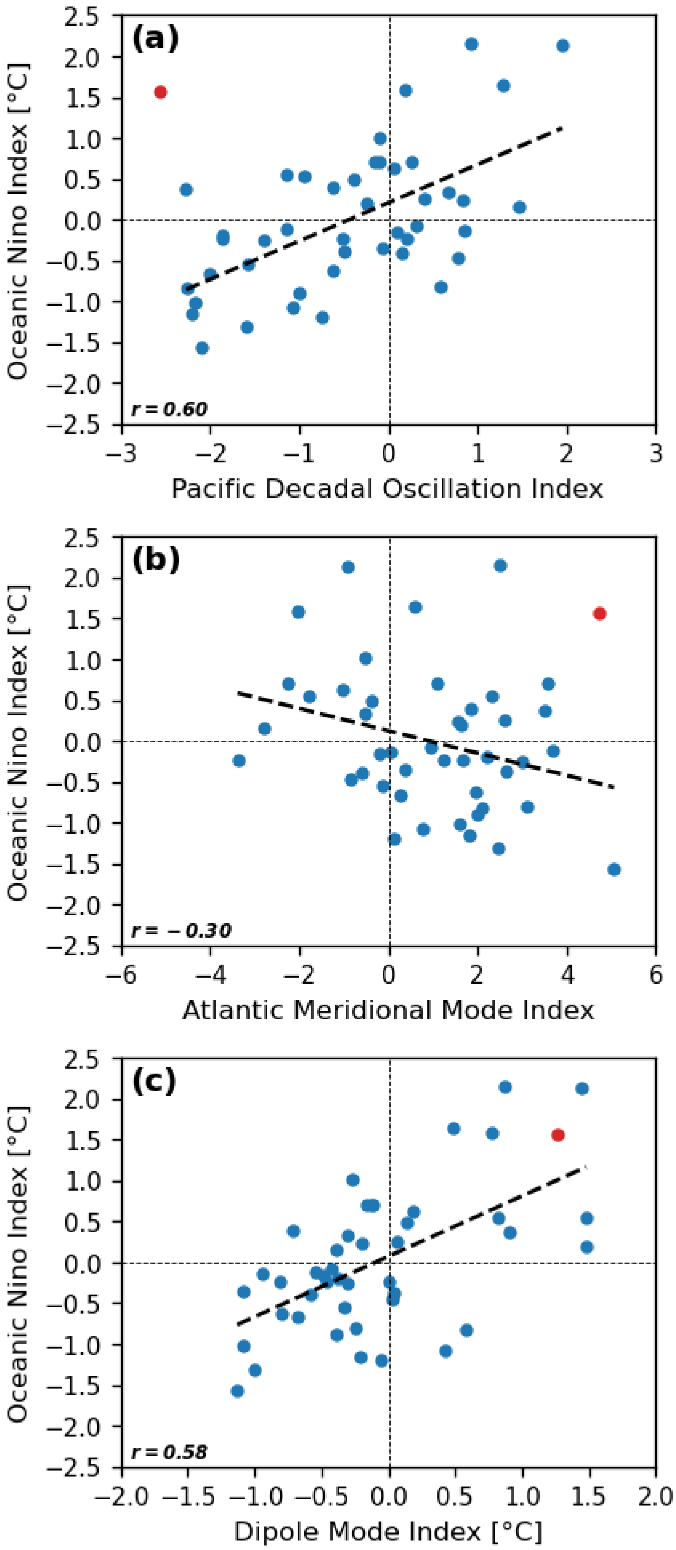


Fig. 6. Comparisons of ASO values during 1979-2023 for (a) ONI and PDO; (b) ONI and AMM; and (c) ONI and DMI. Dashed line denotes the 1979–2022 best fit with associated correlation values depicted on each panel. The red dot indicates 2023.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0305.1.

The Atlantic MDR in 2023 was the warmest on record for ASO (Fig. 1). SSTs were ~0.5°C warmer than 2010—the previous warmest ASO Atlantic MDR. Associated with these increased SSTs was increased PI (Fig. 7a). Given the record warmth in the Atlantic MDR, the ASO-averaged AMM was the 2nd most positive AMM since 1979, trailing only 2010. A positive AMM is typically associated with anomalously warm northern tropical Atlantic SSTs, increased low-level convergence, anomalously positive low-level vorticity, and reduced vertical wind shear in the MDR (Kossin and Vimont 2007). Historically, there is a relatively weak but significant negative relationship between ASO ONI and ASO AMM (r = -0.30; Fig. 6b), likely due to the stronger low-level trade winds (and associated increased evaporation and anomalous cooling) that typically occur in the Caribbean and MDR during boreal summer and fall of El Niño years.

The tropical Indian Ocean was characterized by a strongly positive IOD, with an ASO-averaged DMI value of +1.67°C—the 4th highest value since 1979. A positive IOD tends to occur when El Niño events are present (r = 0.58 between ASO IOD and ASO ONI from 1979–2022; Fig. 6c), as prior studies have shown that the tropical Pacific and tropical Indian Oceans are linked together via both the atmospheric bridge mechanism (e.g., Alexander et al. 2002) and the oceanic tunnel mechanism (e.g., Yuan et al. 2013).

ATMOSPHERIC CONDITIONS

As is typically seen in El Niño years, anomalous upward motion occurred across the eastern and central tropical Pacific (Fig. 7e). However, as will be discussed in the next section in more detail, the anomalous subsidence that typically occurs near the Maritime Continent in El Niño years was weaker than in other recent moderate/strong El Niño events.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

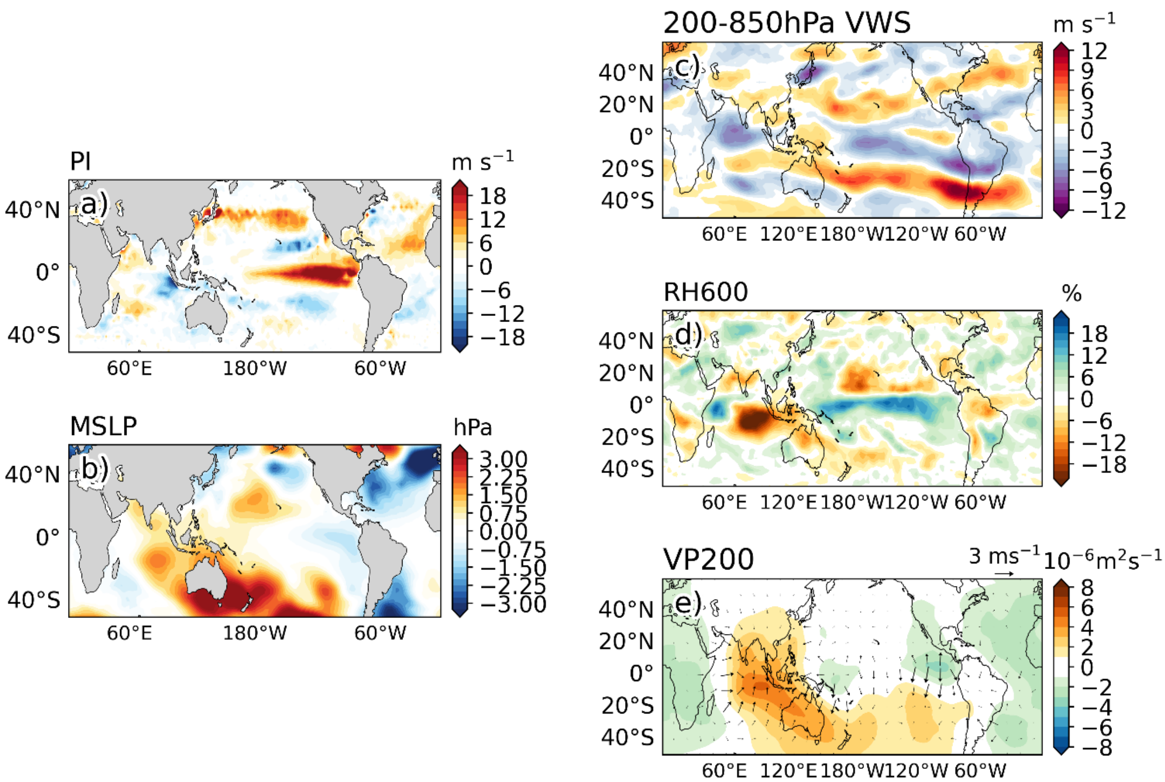


Fig. 7. Atlantic ASO 2023 anomalies relative to 1991–2020 for (a) PI; (b) mean sea level pressure; (c) 200–850-hPa vertical wind shear; (d) 600-hPa relative humidity and (e) 200-hPa velocity potential anomalies with 200-hPa divergent winds shown in quivers.

The more tepid-than-normal atmospheric response to El Niño conditions, combined with the extreme warmth in the tropical Atlantic, led to anomalous rising motion over Africa. This circulation pattern supported anomalously weak vertical wind shear in the MDR during ASO (Fig. 7c). Vertical wind shear anomalies were the most negative over the eastern and central tropical Atlantic, which was an area that saw frequent TC traffic during ASO (Fig. 3). MDR-averaged vertical wind shear anomalies during ASO were the weakest on record (Fig. 7c), which was especially remarkable given the historical positive relationship between ENSO and MDR vertical wind shear (Fig. 8a; e.g., Gray 1984; L'Heureux et al. 2024).

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

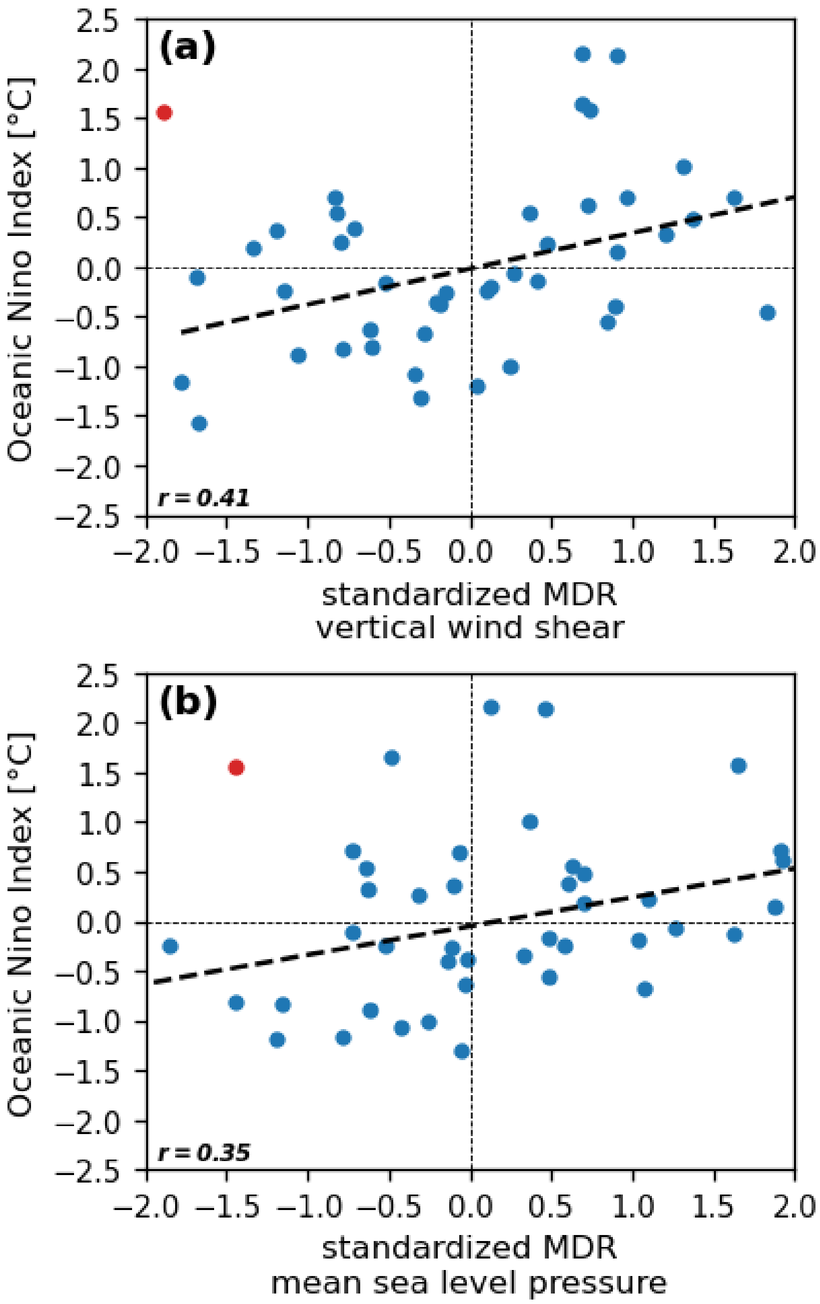


Fig. 8. Comparisons of ASO values during 1979–2023 for (a) ONI and MDR vertical wind shear and (b) ONI and MDR MSLP. The dashed line denotes the 1979–2022 best fit with associated correlation values depicted on each panel. The red dot indicates 2023.

ASO MDR-averaged mean sea level pressure (MSLP) anomalies were the 4th lowest on record (Fig. 7b), trailing (in order from lowest): 2010, 2008 and 1995. These negative MSLP anomalies were consistent with record warm tropical Atlantic conditions but inconsistent with a strong El Niño. In strong El Niño events, the MDR is characterized by sinking motion associated with the eastward-shifted Walker Circulation. Consequently, the observed MSLP

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0305.1.

anomalies in 2023 were much lower than would be expected given the historical relationship between ENSO and MDR MSLP (Fig. 8b). Both the vertical wind shear and MSLP patterns during ASO in the MDR tended to suggest that the anomalously warm MDR dominated over the strong El Niño, in terms of its influence on the 2023 hurricane season.

While 600-hPa relative humidity was above normal across most of the tropical Atlantic, it was below normal across the Caribbean (Fig. 7d). This may have been associated with enhanced sinking motion driven by the El Niño basic state. Consequently, while the Atlantic had an above-normal season, only two TC formations occurred in the Caribbean (Franklin and Idalia; Fig. 3b), which is slightly below the 1991–2020 average of 2.4 named storm formations in the Caribbean.

Subseasonal variability

As noted with the ASO-averaged analysis (Fig. 7e), stationary velocity potential signals were much weaker than would be expected for a strong El Niño (Fig. 9a). During the peak of the 2023 Atlantic hurricane season, eastward moving fluctuations between anomalous subsidence and rising motion over the central/eastern tropical Pacific appeared to be the primary driver of busy/quiet periods for Atlantic hurricane activity. At the beginning of August, convection was enhanced (e.g., negative velocity potential anomalies) over the Central Pacific (Fig. 9a), which was associated with unfavorable westerly shear anomalies over the Atlantic (Fig. 9b). No named storms formed over the Atlantic during this time. The RMM was generally in phases 8 and 1, which are typically neutral to favorable for the Atlantic (Klotzbach 2014), but it may have been reflecting the rapid transition towards El Niño. The RMM index subtracts the 120-day running mean from its calculations (Wheeler and Hendon 2004), so the index can sometimes be preferentially located in specific phases when rapid ENSO transitions are occurring.

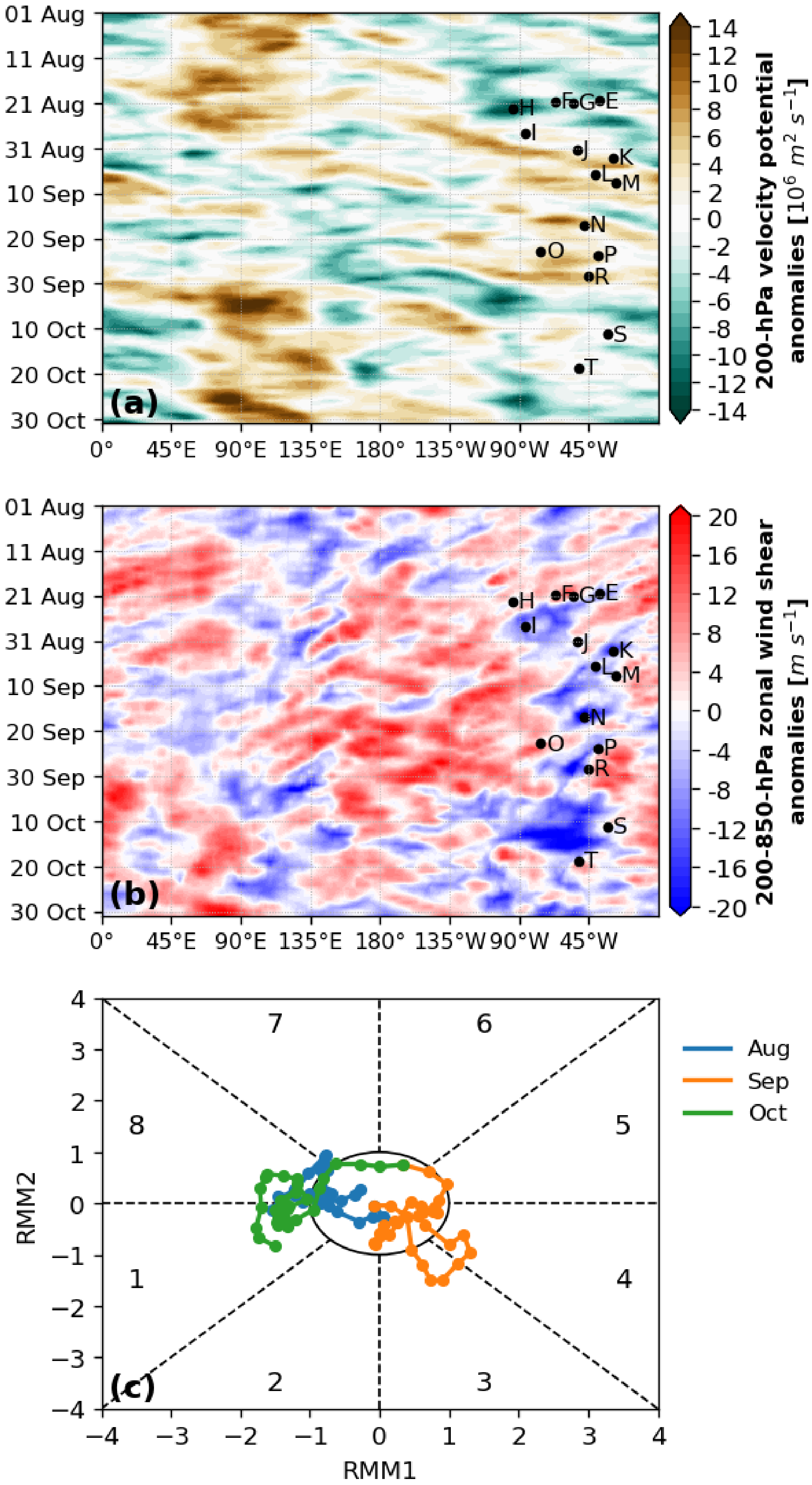
The enhanced convection moved eastward during August (Fig. 9a). The leading edge of this convection was moving over >10 m s^{-1}, which is consistent with a Kelvin wave. However, the broader envelope of enhanced convection behind it was consistent with a broader MJO. The leading Kelvin wave reached Africa around 20 August as the suppressed MJO phase developed over the Central Pacific. This combination shifted the Walker Circulation and as such produced favorable easterly shear anomalies over the Atlantic (Fig. 9b). Given the record warm Atlantic SSTs, the combination of an extremely favorable thermodynamic and dynamic environment led to a hyperactive period for Atlantic TC

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

activity, with 13 named storms forming between 20 August and 28 September—the most on record during that time. As is typical for the Atlantic, these storms generally formed to the west of the MJO's enhanced convection rather than within it (e.g., Klotzbach 2014). This shift is because of the reduced vertical shear to the west of the convection (Fig. 9b). This also confirms that the velocity potential signals reflected the broader circulation rather than the TCs themselves, as they would have produced enhanced convection. The relative lack of movement of the pattern over the Western Hemisphere during this time may have been due to westward-propagating equatorial Rossby waves inhibiting continued eastward movement of the MJO.

During October, velocity potential anomalies over the Western Hemisphere were relatively weak. The circulation was dominated by subsidence over the Indian Ocean and western tropical Pacific—likely related to the strongly positive IOD. This positive IOD may have been one reason why the Atlantic TC season ended rather abruptly in late October, as late season Atlantic TC activity is reduced in positive IOD events (Wood et al. 2020). Anomalous rising motion also redeveloped over the eastern North Pacific during October, favoring subsidence in the western Caribbean, where strong Atlantic TCs typically occur during October (Klotzbach et al. 2022).

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.



Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

Fig. 9. (a) Hovmöller plot of 200-hPa velocity potential anomalies averaged from 5°S–5°N during ASO. (b) As in (a) but for 200–850-hPa zonal wind shear anomalies averaged from 10°N–20°N. Black dots denote the date and longitude of Atlantic TC formations, with the letter denoting the storm that formed (e.g., ‘E’ for Emily). (c) Propagation of the MJO during ASO as measured by the Wheeler–Hendon index.

Climate model analyses

We began examining our simulations by analyzing the atmospheric circulation associated with observed SSTs (e.g., the control simulation) (Fig. 2a). Changes in PI closely resembled those in SST (Fig. S4), so they are not discussed further in this analysis. Simulated ASO-averaged vertical wind shear across the Atlantic were similar to observations, although the magnitude of the vertical wind shear response in the tropical Atlantic was somewhat weaker than observed (Figs. 7c, 10a). We also found a 600-hPa (e.g., mid-level) relative humidity response that matched closely with observations (e.g., increased relative humidity in the central and eastern tropical Atlantic and decreased relative humidity in the Caribbean) (Figs. 7d, 11a). The good qualitative agreement between observed and simulated shear and relative humidity using observed 2023 SSTs motivated us to examine the atmospheric response, with a focus on vertical wind shear and 600 hPa relative humidity, to various SST configurations.

We note that this shear response is somewhat more Atlantic hurricane-favorable to what was modeled in Patricola et al. (2014) when forced with Pacific SSTs from a strong El Niño case (1987) and Atlantic SSTs from a positive AMM case (2005). That study found that Atlantic wind shear was close to its climatological average in the strong El Niño/positive AMM (i.e., these two forcings tended to cancel out each other).

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

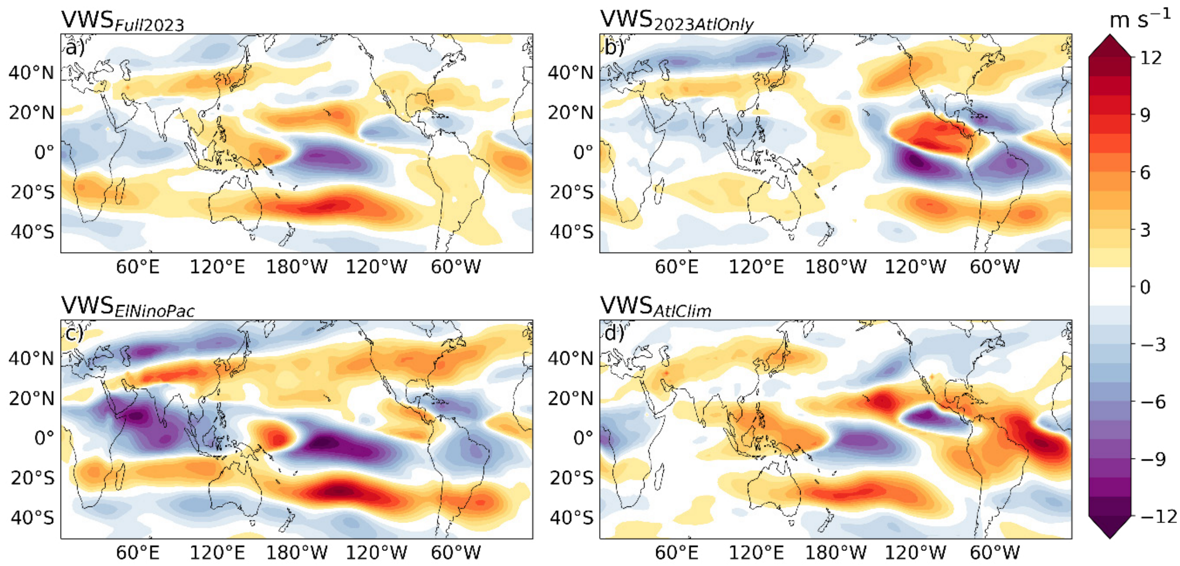


Fig. 10. ASO 200–850-hPa vertical wind shear anomalies relative to the ASO 1991–2020 climatological mean for the (a) FULL2023, (b) 2023ATLONLY, (c) ELNINOPAC, and (d) ATLCLIM atmosphere-only simulations.

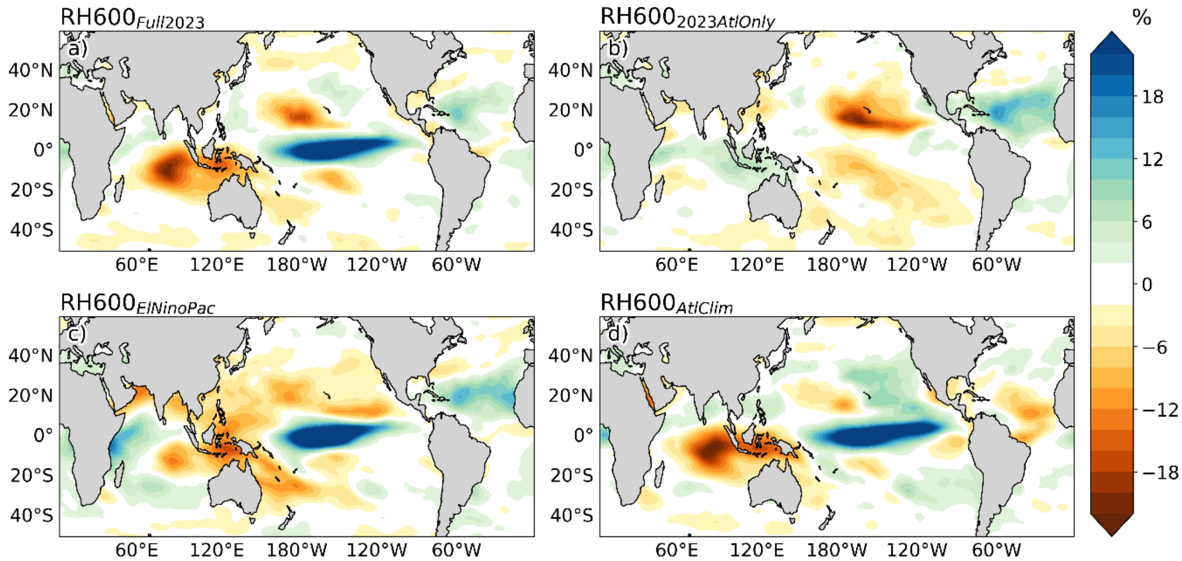


Fig. 11. As in Fig. 10 but for 600-hPa relative humidity

Our 2023ATLONLY experiment examined how vertical wind shear and mid-level relative humidity would change if 2023 Atlantic SSTs were maintained but with 1991–2020-averaged SSTs used elsewhere (Fig. 2b). As would be expected, removing the El Niño signal significantly reduced the tropical Atlantic vertical wind shear (Fig. 10b) and increased the mid-level relative humidity (Fig. 11b), given the strongly positive AMM present in 2023 (e.g., Patricola et al. 2014). Anomalous warmth in the MDR favored anomalous upward

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0305.1.

motion over the Atlantic as well as Africa, increasing mid-level relative humidity (Figs. 11b, 12b). The lack of anomalous warmth in the tropical eastern and central Pacific resulted in anomalous sinking motion and drying there. This combination of anomalous rising/sinking motion drove anomalous upper-level easterlies that counteracted the prevailing westerlies typically found at upper levels in the MDR, resulting in reduced vertical wind shear.

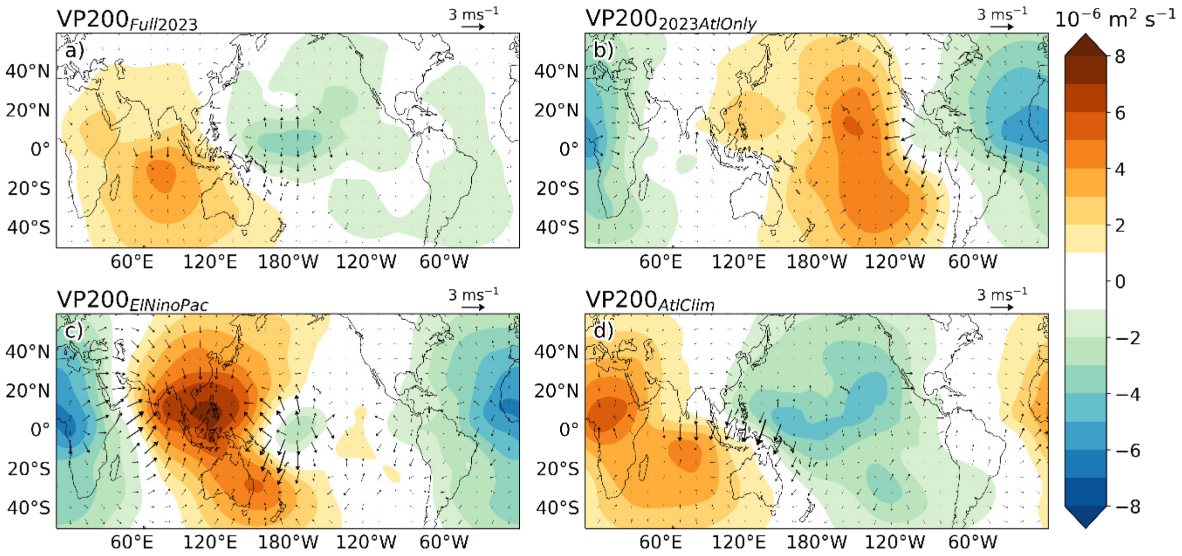


Fig. 12. As in Fig. 10 but for 200-hPa velocity potential anomalies relative to the ASO 1991–2020 climatological mean for the (a) FULL2023, (b) 2023ATLONLY, (c) ELNINOPAC, and (d) ATLCLIM atmosphere-only simulations.

When maintaining Atlantic SSTs at their 2023 levels and setting Pacific SST conditions to the average of all other moderate/strong El Niños since 1979 (Fig. 2c) (e.g., ELNINOPAC), the Atlantic vertical wind shear response and mid-level relative humidity lay between that found for observed 2023 SSTs and that for tropical Pacific SSTs set to their long-term averages (Figs. 10c, 11c). The reduction in tropical Atlantic wind shear and increase in mid-level moisture from the observed 2023 SST pattern may be due to the strongest warming being concentrated in the eastern tropical Pacific in 2023 when compared with the other five moderate/strong El Niño years (e.g., average Nino 1+2 anomalies of 1.6°C in five other moderate/strong El Niño years and 2.9°C in 2023). Other potential influences on the atmospheric response could be the lack of anomalous cooling in the western tropical Pacific in 2023 compared with other moderate/strong El Niño years. In addition, the negative

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0305.1.

PDO in 2023 may have played a role in modifying the vertical wind shear response. Disentangling the roles of each of these SST anomaly patterns is beyond the scope of this manuscript but will be the focus of future research. We also found slightly stronger upward motion over Africa in this simulation (Fig. 12c), which would also favor reduced vertical wind shear when compared with the FULL2023 simulation.

Finally, we examined the atmospheric response to observed 2023 SSTs in all basins other than the Atlantic, where SSTs were set to their long-term averages (e.g., ATLCLIM; Fig. 2d). Vertical wind shear strongly increased while mid-level relative humidity across the Atlantic MDR decreased (Figs. 10d, 11d), as would be expected given the strong El Niño forcing and lack of warm Atlantic SST forcing (e.g., Gray 1984). Pronounced anomalous rising motion over the tropical Pacific and sinking motion over Africa and the Indian Ocean (Fig. 12d), which is typical of an El Niño and an eastward-shifted Walker Circulation, resulted in increased upper-level westerlies (and hence increased vertical wind shear) across the Atlantic MDR. Our simulation results highlight the importance of considering both Pacific and Atlantic SST forcings when making seasonal Atlantic hurricane forecasts. These simulations also indicate that the cold anomaly in the subtropical North Pacific, associated with the negative PDO, may have played only a small role in the observed Atlantic wind shear forcing, given that shear was reduced in the ELNINOPAC simulation relative to the control run.

Discussion and conclusions

Despite strong El Niño conditions, the 2023 Atlantic hurricane season produced above-average activity likely due to the record warm MDR that resulted in vertical wind shear, mid-level relative humidity and vertical motion patterns that were much more favorable for TC development than normally occurs during a strong El Niño. Though most seasonal outlooks in 2023 emphasized higher-than-normal uncertainty given the combination of the strong El Niño and record warm Atlantic MDR, the consensus of seasonal outlooks issued in early August correctly anticipated an above-normal season. The observed active 2023 season along with the modeling results presented here should reduce that uncertainty the next time that a strong El Niño and an extremely warm MDR occur together.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

The atmospheric response to this El Niño was more diffuse over the tropical Pacific than normally occurs in moderate/strong El Niño events, potentially due to the lack of anomalous cooling in the western tropical Pacific. While the anomalously cold subtropical North Pacific was also unusual for moderate to strong El Niño events, our model simulations hinted that these cold anomalies may have played a limited role in modulating MDR vertical wind shear.

Our results demonstrate how simulation experiments can be used to disentangle the effects of SSTs in various basins on TC activity via modulations of the large-scale circulation. While the modeling portion of this study focused on SST impacts in the Pacific and Atlantic sectors, in future work, we intend to also examine the impact of the IOD on Atlantic vertical wind shear patterns, as well as show how Atlantic vertical wind shear patterns may be modulated by strong El Niño/warm tropical Atlantic events in a future warmer climate state. We also note that the 2023 Atlantic hurricane season is one response of the climate system to a specific SST configuration. Similar Atlantic SST-El Niño configurations during the hurricane season in the future could yield somewhat different Atlantic TC responses.

The 2023 hurricane season was also unusual in that it featured above-normal hurricane activity in both the Atlantic and eastern North Pacific (to 140°W) basins[7], while the two basins typically have an inverse relationship (Collins 2010) (r = -0.37 from 1988[8]–2022). The four other years since 1988 having above-normal seasons in both basins were: 1998, 2011, 2016 and 2018. Although both hurricane seasons ended up above normal, while the Atlantic

---

[7] NOAA defines eastern North Pacific hurricane seasons based on ACE. An above-normal season has >115 × 10^4 kt^2 ACE (https://www.cpc.ncep.noaa.gov/products/Epac_hurr/Background.html). The 2023 eastern North Pacific hurricane season generated ~133 × 10^4 kt^2 ACE.

[8] We started our eastern North Pacific analysis in 1988, as eastern North Pacific TC statistics are generally considered more reliable once the National Hurricane Center became the operational center for that basin (Klotzbach and Landsea 2015).

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

was undergoing its record-breaking spate of named storm activity from August 20–September 28, the eastern North Pacific generated only three named storms between those two dates (the 1991–2020 average is five named storms).

This study re-emphasized the importance of considering atmospheric and oceanic conditions across the globe when making predictions for seasonal TC activity. Dr. William Gray, the founder of the Atlantic seasonal hurricane forecast at Colorado State University, used to say: "The global atmosphere/ocean circulation functions as a single unit" (William Gray 2015, personal communication). The atmospheric response during the 2023 Atlantic hurricane season to the strong SST forcings in the Atlantic, Pacific and Indian Oceans highlights the accuracy of this statement.

Acknowledgments

We thank Christina Patricola, Brian McNoldy, an anonymous reviewer and the editor, Chris Landsea, for helpful comments that have improved the quality of the manuscript. We thank Christina Patricola for providing the ENSO Longitude Index. P. Klotzbach thanks the G. Unger Vetlesen Foundation for financial support that helped fund this research. J. Jones was supported by the NOAA Climate and Global Change Postdoctoral Fellowship Program, administered by UCAR's CPAESS under award #NA21OAR4310383. K. Wood acknowledges support from the Department of Hydrology & Atmospheric Sciences and the College of Science at the University of Arizona. M. Bell was supported by Office of Naval Research award N000142012069. D. Chavas was supported by National Science Foundation Award AGS-1945113. E. Gibney's research was supported by NOAA's Science Collaboration Program and administered by UCAR's Cooperative Programs for the Advancement of Earth System Science (CPAESS) under award NA21OAR4310383. C. Schreck was supported by NOAA through the Cooperative Institute for Satellite Earth System Studies under Cooperative Agreement NA19NES4320002.

Data Availability Statement

Data used in this study are publicly available at the following URLs:

Atlantic meridional mode index:

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

https://psl.noaa.gov/data/timeseries/monthly/AMM/ammsst.data

Continental US hurricane landfalls:

https://www.aoml.noaa.gov/hrd/hurdat/UShurrs_detailed.html

ENSO Longitude Index:

https://portal.nersc.gov/archive/home/projects/cascade/www/ELI/ELI_ERSSTv5_1854.01-2020.05.xlsx

ERA5:

https://doi.org/10.24381/cds.143582cf

HURDAT2:

https://www.aoml.noaa.gov/hrd/hurdat/hurdat2.html

International Best Track Archive for Climate Stewardship:
https://www.ncei.noaa.gov/products/international-best-track-archive?name=ib-v4-access

Niño 1+2 index:

https://www.cpc.ncep.noaa.gov/data/indices/ersst5.nino.mth.91-20.ascii

Pacific decadal oscillation index:

https://www.ncei.noaa.gov/pub/data/cmb/ersst/v5/index/ersst.v5.pdo.dat

Oceanic Niño index:

https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

Wheeler-Hendon MJO index:

http://www.bom.gov.au/climate/mjo/graphics/rmm.74toRealtime.txt

CAM6 SST forcing simulations will be made available upon request.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

REFERENCES

Alexander, M. A., I. Bladé, M. Newman, J. R. Lanzante, N. Lau, and J. D. Scott, 2002: The Atmospheric Bridge: The influence of ENSO teleconnections on air–sea interaction over the global oceans. *J. Climate*, **15**, 2205–2231, https://doi.org/10.1175/1520-0442(2002)015<2205:TABTIO>2.0.CO;2.

Bell, G. D., and Coauthors, 2000: Climate assessment for 1999. *Bull. Amer. Meteor. Soc.,* **81,** 1328, https://doi.org/10.1175/1520-0477(2000)81[s1:CAF]2.0.CO;2.

Bister, M., and K. A. Emanuel, 2002: Low frequency variability of tropical cyclone potential intensity, 1. Interannual to interdecadal variability, *J. Geophys. Res.*, **107**, 4801, https://doi.org/10.1029/2001JD000776.

Brennan, M. J., C. C. Hennon, and R. D. Knabb, 2009: The Operational Use of QuikSCAT Ocean Surface Vector Winds at the National Hurricane Center. *Wea. Forecasting*, **24**, 621–645, https://doi.org/10.1175/2008WAF2222188.1.

Brown, D. P., A. Hagen, and L. Alaka, 2024: National Hurricane Center Tropical Cyclone Report: Tropical Storm Ophelia, 38 pp, https://www.nhc.noaa.gov/data/tcr/AL162023_Ophelia.pdf

Cangialosi, J. P., and L. Alaka, 2024: National Hurricane Center Tropical Cyclone Report: Hurricane Idalia, 47 pp, https://www.nhc.noaa.gov/data/tcr/AL102023_Idalia.pdf.

Caron, L.-P., F. Massonet, P. J. Klotzbach, T. Philp, and J. Stroeve, 2020: Making seasonal outlooks of Arctic sea ice and Atlantic hurricanes valuable - not just skillful. *Bull. Amer. Meteor. Soc.,* **101,** E36-E42, https://doi.org/10.1175/BAMS-D-18-0314.1.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

Collins, J.M., 2010: Contrasting high northeast Pacific tropical cyclone activity with low North Atlantic activity. *Southeastern Geographer*, *50,* 83–98. https://doi.org/10.1353/sgo.0.0069.

Danabasoglu, G., and Coauthors, 2020: The Community Earth System Model Version 2 (CESM2). *J. Adv. Model. Earth Syst.,* **12,** e2019MS001916. https://doi.org/10.1029/2019MS001916

Gilford, D. M., 2020: pyPI: Potential Intensity Calculations in Python, pyPI v1.3. Zenodo. http://doi.org/10.5281/zenodo.3985975.

Gilford, D. M., 2021: pyPI (v1.3): Tropical Cyclone Potential Intensity Calculations in Python, *Geosci. Model Dev.,* **14,** 2351–2369, https://doi.org/10.5194/gmd-14-2351-2021.

Goldenberg, S. B., and L. J. Shapiro, 1996: Physical mechanisms for the association of El Niño and west African rainfall with Atlantic major hurricane activity. *J. Climate*, **9**, 1169–1187, https://doi.org/10.1175/1520-0442(1996)009<1169:PMFTAO>2.0.CO;2.

Gray, W. M., 1984: Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Mon. Wea. Rev.,* **112,** 1649–1668, https://doi.org/10.1175/1520-0493(1984)112%3C1649:ASHFPI%3E2.0.CO;2.

Hersbach, H., and Coauthors, 2020: The ERA5 global reanalysis. *Quart. J. Roy. Meteor. Soc.,* **146,** 1999–2049, https://doi.org/10.1002/qj.3803.

Klotzbach, P. J., 2014: The Madden–Julian Oscillation's Impacts on Worldwide Tropical Cyclone Activity. *J. Climate*, **27**, 2317–2330, https://doi.org/10.1175/JCLI-D-13-00483.1.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

Klotzbach, P. J., and Coauthors, 2022: A hyperactive end to the Atlantic hurricane season: October-November 2020. *Bull. Amer. Meteor. Soc.,* **103,** E110-E128, https://doi.org/10.1175/BAMS-D-20-0312.1.

Klotzbach, P. J., M. M. Bell, and A. J. DesRosiers, 2023: Forecast of Atlantic seasonal hurricane activity and landfall strike probability for 2023, 45 pp. https://tropical.colostate.edu/Forecast/2023-08.pdf

Klotzbach, P. J., and C. W. Landsea, 2015: Extremely intense hurricanes: Revisiting Webster et al. (2005) after 10 years, *Journal of Climate,* **28,** 7621-7629. https://doi.org/10.1175/JCLI-D-15-0188.1

Klotzbach, P. J., M. A. Saunders, G. D. Bell, and E. S. Blake, 2017: North Atlantic seasonal hurricane prediction: Underlying science and an evaluation of statistical models. Chapter 19 in “Climate Extremes: Patterns and Mechanisms”, S. Wang et al., Eds., 14 pp, AGU monograph. https://doi.org/10.1002/9781119068020.ch19

Knapp, K. R., H. J. Diamond, J. P. Kossin, M. C. Kruk, C. J. Schreck, 2018: International Best Track Archive for Climate Stewardship (IBTrACS) Project, Version 4. [indicate subset used]. NOAA National Centers for Environmental Information. https://doi.org/10.25921/82ty-9e16 [Accessed 15 December 2023].

Knapp, K. R., M. C. Kruk, D. H. Levinson, H. J. Diamond, and C. J. Neumann, 2010: The International Best Track Archive for Climate Stewardship (IBTrACS). *Bull. Amer. Meteor. Soc.*, **91**, 363–376, https://doi.org/10.1175/2009BAMS2755.1.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

Kossin, J. P., and D. J. Vimont, 2007: A more general framework for understanding Atlantic hurricane variability and trends. *Bull. Amer. Meteor. Soc.*, **88**, 1767–1782, https://doi.org/10.1175/BAMS-88-11-1767.

Landsea, C. W., and J. L. Franklin, 2013: Atlantic hurricane database uncertainty and presentation of a new database format. *Mon. Wea. Rev.,* **141,** 3576–3592, https://doi.org/10.1175/MWR-D-12-00254.1.

Lea, A., and N. Wood, 2023: August forecast update for North Atlantic hurricane activity in 2023, 10 pp. http://tropicalstormrisk.com/docs/TSRATLForecastAugust2023.pdf

L'Heureux, M. L., and Coauthors, 2019: Strength outlooks for the El Niño–Southern Oscillation. *Wea. Forecasting*, **34**, 165–175, https://doi.org/10.1175/WAF-D-18-0126.1.

L'Heureux, M. L., D. S. Harnos, E. Becker, B. Brettschneider, M. Chen, N. Johnson, A. Kumar, M. K. Tippett, 2024: How well do seasonal climate anomalies match expected El Niño-Southern Oscillation (ENSO) impacts? *Bulletin of the American Meteorological Society*, in press.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteor. Soc.*, **78**, 1069–1080, https://doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2.

NOAA, 2023a: NOAA 2023 Atlantic hurricane season outlook. https://www.cpc.ncep.noaa.gov/products/outlooks/hurricane2023/May/hurricane.shtml

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

NOAA, 2023b: NOAA 2023 Atlantic hurricane season outlook. https://www.cpc.ncep.noaa.gov/products/outlooks/hurricane2023/August/hurricane.shtml

Pasch, R. J., A. D. Mahoney, and H. Nepaul, 2024: National Hurricane Center Tropical Cyclone Report: Tropical Storm Harold, 24 pp, https://www.nhc.noaa.gov/data/tcr/AL092023_Harold.pdf

Patricola, C. M., R. Saravanan, and P. Chang, 2014: The impact of the El Niño–Southern Oscillation and Atlantic meridional mode on seasonal Atlantic tropical cyclone activity. *J. Climate,* **27,** 5311–5328, https://doi.org/10.1175/JCLI-D-13-00687.1.

Saji, N., B. Goswami, P. Vinayachandran, and T. Yamagata, 1999: A dipole mode in the tropical Indian Ocean. *Nature,* **401**, 360–363, https://doi.org/10.1038/43854.

Saunders, M. A., P. J. Klotzbach, A. S. R. Lea, C. J. Schreck, and M. M. Bell, 2020: Quantifying the probability and causes of the surprisingly active 2018 North Atlantic hurricane season. *Earth and Space Science,* **7,** e2019EA000852, https://doi.org/10.1029/2019EA000852.

Smith, W. L., H. M. Woolf, C. M. Hayden, D. Q. Wark, and L. M. McMillin, 1979: The TIROS-N operational vertical sounder. *Bull. Amer. Meteor. Soc.*, **60,** 1177–1187, https://doi.org/10.1175/1520-0477-60.10.1177 .

Vecchi, G. A., and T. R. Knutson, 2011: Estimating Annual Numbers of Atlantic Hurricanes Missing from the HURDAT Database (1878–1965) Using Ship Track Density. *J. Climate*, **24**, 1736–1746, https://doi.org/10.1175/2010JCLI3810.1.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.

Villarini, G. G. A. Vecchi, T. R. Knutson, and J. A. Smith, 2011: Is the recorded increase in short-duration North Atlantic tropical storms spurious? *J. Geophys. Res.-Atmos,* **116,** D10114, https://doi.org/10.1029/2010JD015493.

Wang, C., D. B. Enfield, S. Lee, and C. W. Landsea, 2006: Influences of the Atlantic Warm Pool on Western Hemisphere summer rainfall and Atlantic hurricanes. *J. Climate*, **19**, 3011–3028, https://doi.org/10.1175/JCLI3770.1.

Wheeler, M. C., and H. H. Hendon, 2004: An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. *Mon. Wea. Rev.,* **132,** 1917–1932, https://doi.org/10.1175/1520-0493(2004)132%3C1917:AARMMI%3E2.0.CO;2.

Williams, I. N., and C. M. Patricola, 2018: Diversity of ENSO events unified by convective threshold sea surface temperature: A nonlinear ENSO index. *Geophys. Res. Lett.*, **45,** 9236–9244, https://doi.org/10.1029/2018GL079203

Wood, K. M., P. J. Klotzbach, J. M. Collins, L.-P. Caron, R. E. Truchelut and C. J. Schreck III, 2020: Factors affecting the 2019 Atlantic hurricane season and the role of the Indian Ocean dipole. *Geophys. Res. Lett.,* **47,** e2020GL078781, https://doi.org/10.1029/2020GL087781

Yuan, D., H. Zhou, and X. Zhao, 2013: Interannual climate variability over the tropical Pacific Ocean induced by the Indian Ocean Dipole through the Indonesian Throughflow. *J. Climate*, **26**, 2845–2861, https://doi.org/10.1175/JCLI-D-12-00117.1.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0305.1.