AGU ADVANCING EARTH AND SPACE SCIENCES

Geophysical Research Letters

RESEARCH LETTER
10.1029/2025GL116580

Extreme Ocean Conditions of the 2024 Hurricane Season Formed by Rare Combination of Drivers

E. A. Harris[1,2], R. Marsh[1], J. P. Grist[3], and A. T. Blaker[3]

[1]Department of Ocean and Earth Science, University of Southampton, Southampton, UK, [2]Cedar Trace Limited, Hamilton, Bermuda, [3]National Oceanography Centre, Southampton, UK

Key Points:

- High hurricane activity was possible in 2024 due to an unprecedented volume of warm water across the tropical North Atlantic
- Anomalous surface heat flux, mainly latent heat flux, contributed to the development of this volume of warm water through 2023 and 2024
- Additionally, ocean circulation moved water of record-breaking warmth in 2023 westward by 2024 into regions where it was available for rapid intensification of storms

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

E. A. Harris,
kingfisherbda@gmail.com

Citation:

Harris, E. A., Marsh, R., Grist, J. P., & Blaker, A. T. (2025). Extreme ocean conditions of the 2024 hurricane season formed by rare combination of drivers. *Geophysical Research Letters*, *52*, e2025GL116580. https://doi.org/10.1029/2025GL116580

Received 24 APR 2025
Accepted 20 OCT 2025

Abstract Record heat was observed in the tropical North Atlantic in 2023 and 2024. However, in 2024, in contrast to the previous year, most of the record-breaking surface and sub-surface temperatures were focused in the western two thirds of the basin. This allowed for intensification of hurricanes into major storms prior to landfall. Water mass transformation analysis reveals much of the anomalous warm water volume arose from atmospheric heat flux into the ocean. Lagrangian analysis then shows how, atypically, warm water was advected to the west by a rarely observed zonal pathway. Thus, combined heat exchanges via air-sea heat transfer and ocean currents coordinated to result in record breaking temperatures in the western tropical Atlantic in 2024, allowing development of landfalling major hurricanes when atmospheric and oceanic conditions were aligned and conducive to tropical cyclone development.

Plain Language Summary In 2023 and 2024, the tropical North Atlantic experienced unusually warm ocean temperatures, more than 0.5°C above normal. These warm waters helped 2024 hurricanes become stronger before hitting land. The extra heat in the ocean mainly came from heat exchange with the atmosphere. We used a method called Water Mass Transformation to understand this process and show that it was driven by less evaporation from the ocean surface. We also found that unusually, in 2024, the very warmest water moved from the eastern to western tropical regions by ocean currents. The combination of heat exchange from the air into the sea, along with ocean currents, led to the record-breaking temperatures of consequence for hurricanes.

1. Introduction

The 2024 hurricane season was extremely active, driven by a combination of cool-neutral El Niño Southern Oscillation (ENSO) conditions and extreme warm Sea Surface Temperature (SST) in the tropical North Atlantic (Klotzbach, 2024). Total Accumulated Cyclone Energy (ACE) was in the 68% percentile of the 1991–2020 mean, with 5 major hurricanes in the Atlantic. Of the 5 hurricane landfalls along the US coastline, 2 were major hurricanes: Milton and Helene. These storms caused 124 billion United States (US) dollars of damage (NCEI, 2025).

Global upper ocean heat content (OHC) has been steadily increasing since the 1950s, with the Atlantic warming faster than the Pacific (Cheng et al., 2022). Record high global mean monthly SSTs were observed from March 2023 (Huang et al., 2024). These persisted into mid-2024, despite a shift from El Niño conditions to cool-neutral SST in the tropical Pacific (Cheng et al., 2025), resulting in record high OHC in 6 of the world's 8 oceans, including the Atlantic. Cheng et al. (2019) observed peak tropical North Atlantic SSTs developing 5 months after El Niño, due to atmospheric heat flux exchange in the west Atlantic and Ekman dynamics in the east Atlantic. These changes will have created a shift in hurricane climate dynamics, which are heavily influenced by both Atlantic and Pacific tropical SST (Bell & Chelliah, 2006; Kossin et al., 2010).

Increased hurricane activity is well-established to be attributed to a warming tropical Atlantic (Emanuel, 2021a, 2021b; Goldenberg et al., 2001; Saunders & Lea, 2008; Vecchi & Soden, 2007); highlighted by cases of recent extreme Atlantic warmth (Moharana & Swain, 2023; Murakami et al., 2018; Pfleiderer et al., 2022). Choi et al. (2024) find that Atlantic hurricanes 1982–2019 which interacted with a marine heatwave had a lifetime maximum intensity 28 knots higher than otherwise. Radfar et al. (2024) note that marine heatwaves affected 70% of Gulf of Mexico (GoM) hurricanes between 1950 and 2022. Hurricanes have been able to rapidly intensify over extreme warm SSTs due to a highly unstable vertical atmospheric temperature profile (Balaguru et al., 2018; Bhatia et al., 2022; Majumdar et al., 2023). This mechanism for increased intensification of storms has produced an increasing proportion of the strongest category hurricanes Holland & Bruyère, 2014; Wang & Toumi, 2022).

Climate models forced with additional greenhouse gases predict continued Atlantic warming as the meridional overturning declines (Harris et al., 2024). While high resolution climate models detect lower hurricane frequency in a warmer climate (Roberts et al., 2020), the strongest storms are not resolved, and SST biases remain large. Downscaling techniques, meanwhile, suggest increasing frequency and severity (Emmanuel, 2021b). Intra-seasonal variability is proposed to increase due to a larger difference in tropical Atlantic SST relative to tropical Pacific SST, thus driving additional wind shear and lower atmospheric stability (Lopez et al., 2024). While frequency is still not well understood (Sobel et al., 2021), these analyses suggest that the probability of major landfalling hurricanes will continue to increase as the Atlantic warms.

Here we apply novel analysis methods to observational and hindcast model data which diagnose processes leading to the recent increase in the volume of warm water in 2023 and 2024. The Water Mass Transformation (WMT) framework is used to calculate the amount of water warmer than 26.5°C generated from heat exchange with the atmosphere. Any residual volume of warm water, unexplained by surface heating, must then have developed due to ocean heat transport divergence. To explore the role of ocean circulation, and specifically to examine the regional build-up of heat in the western tropics, we back track warm waters over seasonal timescales using complementary Lagrangian analyses.

2. Materials and Methods

2.1. WMT

The volume of water warmer than 26.5°C which is generated due to heat flux between the atmosphere and ocean is calculated using the WMT framework in temperature space (Groeskamp et al., 2018; Harris et al., 2022; Walin, 1982). The volume flux across isotherms each month is found by transforming the net heat flux (Q_{net}) into the ocean to a volume, dividing by a reference density (ρ) and the specific heat capacity of seawater (c_p) and multiplying by seconds in a month.

2.2. Lagrangian Analysis

Lagrangian tracking analysis is performed with data from the National Oceanography Centre's Near-Present Day (NPD, https://noc-msm.github.io/NOC_Near_Present_Day/) eORCA025 (¼°) hindcast. The NPD configuration is based on GOSI9 (Guiavarc'h et al., 2025), with the NEMO version updated to v4.2.2. The model is forced with ERA5 (Hersbach et al., 2020), with a climatological correction toward JRA55-do (Tsujino et al., 2018) applied to the surface air temperature where sea-ice is present. The mass-conserving Ariane package (Blanke & Raynaud, 1997) is used offline with NPD data, to evaluate advective pathways and along-pathway warming, following Harris et al. (2023). North of 10°N, particles are allocated to every grid cell where temperature exceeds 29°C in September. These particles are tracked backwards for 9 months from September.

3. Data

3.1. Hurricane Data

International Best Tracks for Climate Stewardship data (IBTraCS) version 4 contains 6-hourly time-stamped point data for global tropical cyclones, with more regular data closer to landfall, including latitude, longitude, minimum central pressure and 1-min mean maximum wind speed, rounded to 5 knots (Knapp et al., 2010, 2018).

3.2. Atmospheric and Oceanic Observational Data Sets

Q_{net} is calculated using National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis from 1980 through 2024 (Kalnay et al., 1996). Data gridded at 2.5° is available from 1950 to present. Q_{net} is obtained by combining net shortwave radiation with net longwave radiation, sensible heat, and latent heat flux (Q_{lh}).

The UK Met Office HadISST data set is a global gridded data set of monthly mean SST at 1° resolution. Daily SST time-series 1980–2024 are obtained from the ERA5 global reanalysis (Hersbach et al., 2020). The depth of the 29°C isotherm is plotted using UK Met Office Hadley Centre EN.4.2.2 (EN4) (Good et al., 2013).

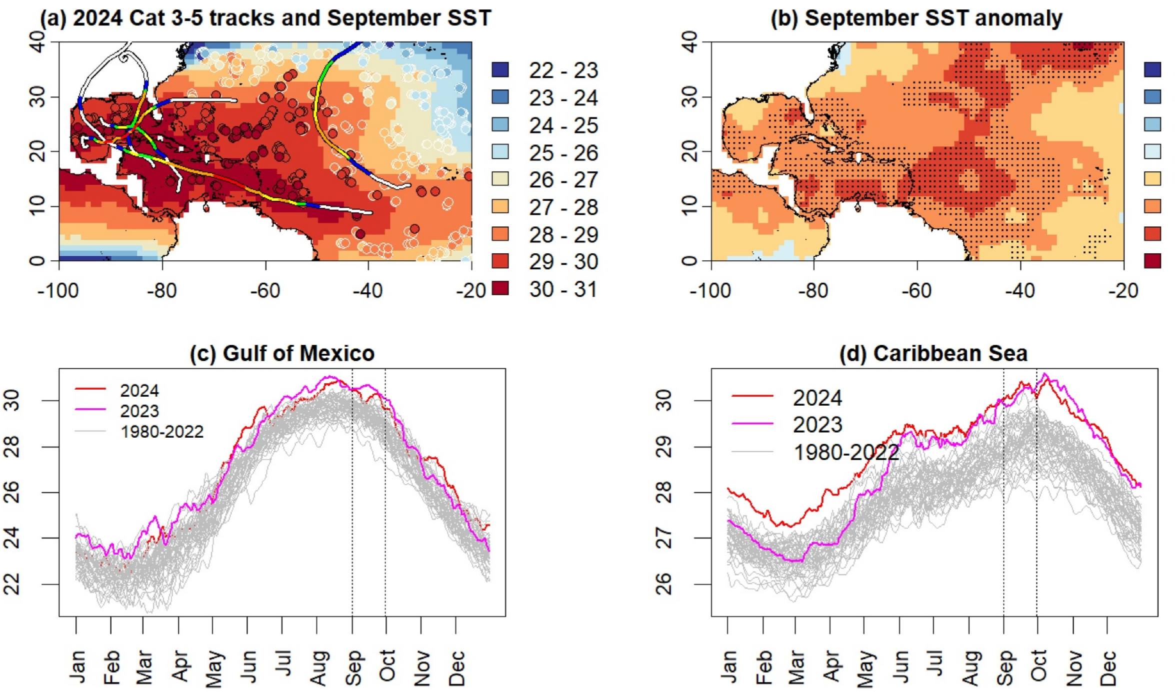

Figure 1. (a) 2024 September HadISST, Argo float SST (circles—black outline where 29°C or warmer), and major hurricane tracks colored by category (0—white, 1—blue, 2—green, 3—yellow, 4—orange, 5—red), (b) September HadISST anomaly versus 1990–2020 mean (stippling indicates record SST 1856–2023), (c) daily ERA5 SST by year for the GoM and (d) Caribbean Sea (1980–2022—gray, 2023—magenta, 2024—red).

Potential temperature from the NCEP Global Ocean Data Assimilation System (GODAS) reanalysis is used to diagnose subsurface temperatures in the WMT calculation and the comparable observed volume of water warmer than 26.5°C north of 10°N in the Atlantic (Behringer & Xue, 2004). GODAS is forced with NCEP/NCAR fluxes.

Surface temperature data from the Argo program (Wong et al., 2020) is examined alongside the monthly HadISST observations (Rayner et al., 2003) and daily values from ERA5. We further examine multi-year upper-ocean temperature profiles, as sampled by Argo floats in areas relevant to 2024 hurricane development. We select three Argo floats, deployed on 16 May 2021 in the GoM (float 4903354, data accessed on 14 October 2024 from the AOML Data Assembly Centre), and deployed on 22 October 2022 in the Caribbean Sea (floats 2903766 and 3902457, data accessed on 28 March 2025 from the Coriolis Data Assembly Centre (https://data-argo.ifremer.fr/dac/coriolis/).

4. Results

We show the extent of anomalous heat available in the tropical Atlantic during the 2024 hurricane season and quantify mechanisms for heat transfer via atmospheric heat flux and ocean currents into and through the region. We first outline the unique temperature conditions present during the 2024 hurricane season and discuss resulting storm activity. This includes analysis of region-specific Argo float vertical temperature profiles. Following this, the monthly volume of water transformed by atmospheric heat flux across thresholds relevant to hurricane development is calculated using the WMT framework. Lagrangian pathways for warm water transport into the western tropical Atlantic are then examined, to emphasize the combined effect of widespread anomalous surface heating and westward redistribution of the warming waters.

4.1. September 2024 SST Anomalies

The 2024 US landfalling major hurricanes Milton and Helene tracked over areas of extreme ocean heat, enabling rapid intensification on their approach toward the west coast of Florida (Figure 1a). While the September-mean SST shows the heat potential for the storm development, it should be noted that storm development through most of September was limited due to intraseasonal variability in atmospheric conditions, including a more northerly position of the African easterly jet, weaker Potential Intensity, and timing of the Madden-Julian Oscillation.

10.1029/2025GL116580

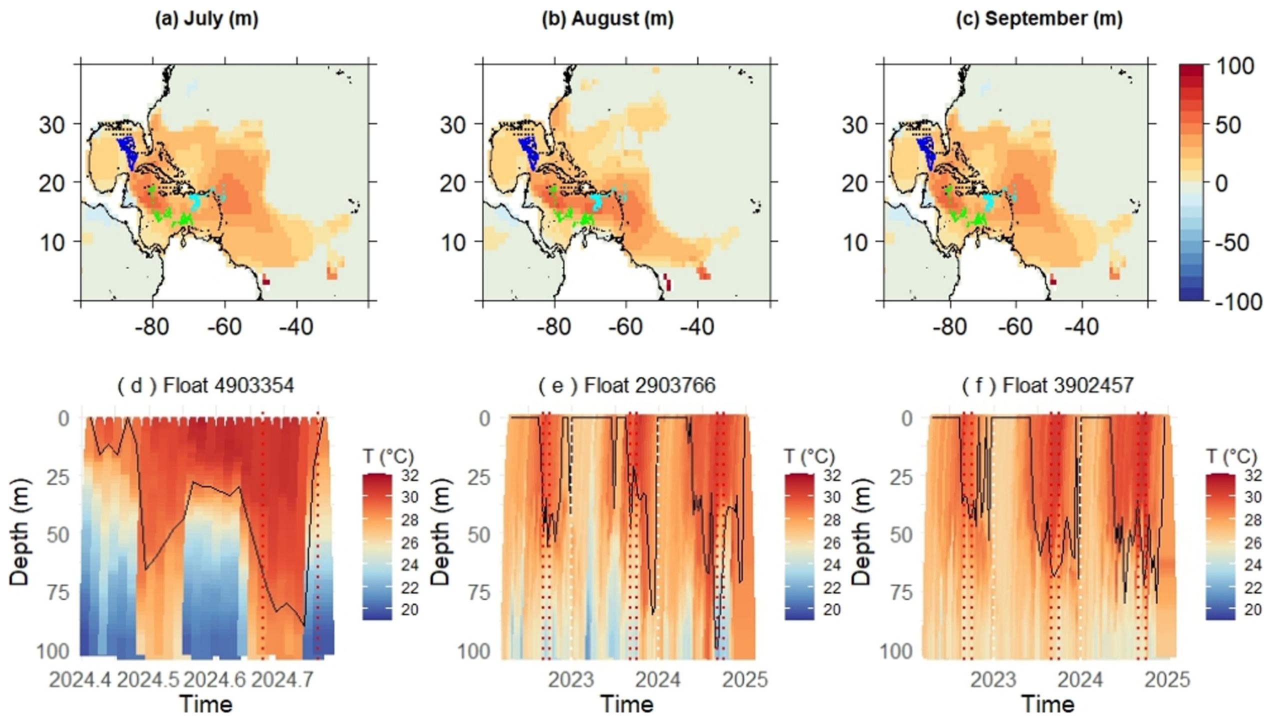

Figure 2. (a–c) EN4 isotherm (29°C) depth anomaly for July, August, and September 2024, with records (black stippling) and selected Argo float tracks (float 4903354 in the GoM–blue; float 2903766 in the central Caribbean–green; float 3902457 in the eastern Caribbean—cyan), (d–f) Argo floats sampling the upper 100 m over selected periods, highlighting the 29°C isotherm: (d) float 4903354 over June-October 2024; (e) float 2903766 and (f) float 3902457 over 2022–2025. In (d–f), September is bound by red dotted lines, while the beginning of each year is indicated with the white dotted lines.

However, between September 24th and the end of the season, storm development was exceptionally high with there being 11 named storms including 4 major hurricanes (Klotzbach et al., 2025).

In 2024, the September-mean SST exceeded 29°C throughout the GoM, Caribbean Sea, and extending to 30°N as far as 50°W (Figure 1a). Most of the Main Development Region (MDR) was at least 0.5°C warmer than the 1990–2020 mean, confirmed by daily September Argo float observations. September-mean SST anomalies reached record highs over most of the Caribbean Sea, the southwest corner of the GoM, and the MDR to 40°W (Figure 1b). Averaged over the Caribbean Sea, the daily SST for September 2024 was 0.6°C warmer than any previous maxima except 2023, compared to which it was still ~0.1°C warmer. October 2024 was not as warm as 2023 but was still on average 1.0°C warmer than any 1980–2022 maxima (Figure 1d). Overall, 2024 exhibited a continuation of the anomalous SST of 2023 in regions impacting 2024 US landfalls. These conditions, combined with anomalously low wind shear due to cool-neutral ENSO, facilitated the development of strong hurricanes during periods when intraseasonal atmospheric influences allowed.

4.2. Vertical Structure of Temperature Anomalies

Hurricane intensity is better correlated with OHC than SST, as deep reserves of warm water can better support strong storms (Hallam et al., 2021; Mainelli et al., 2008). Hence, the depth of the warm isotherms in the 2024 hurricane season was important in the rapid intensification of Helene and Milton. While the 26.5°C isotherm has been used in previous studies (McTaggert-Cowan et al., 2015) as the minimum SST which can sustain hurricane strength storms, higher temperatures have been shown to impact rapid intensification (Bhatia et al., 2022). Based on an evaluation of temperature thresholds, the 29°C isotherm is selected here to highlight the unique vertical ocean temperature structure which impacted the 2024 hurricane season.

The EN4 29°C isotherm depth anomalies in September 2024 exceeded 20 m for several grid cells in the GoM, along the west coast of Florida (Figures 2a–2c). Record 29°C isotherm depths are experienced in the eastern GoM, under the tracks of Milton and Helene. These unusual conditions were well-developed by July, which allowed Beryl to intensify into a Category 5 hurricane as it approached the Yucatan peninsula.

Focusing on the 2024 hurricane season, Argo temperature profiles suggest a much deeper penetration of this isotherm on short (synoptic) timescales, as deep as 90 m in late September (Figure 2d).

Turning to the evolution of upper ocean heat over a longer timescale, across the Caribbean Sea, progressive warming and associated deepening of isotherms are evident in Argo float data (Figures 2e and 2f). Compared to 2022, the 29°C isotherm deepens by ~20 m in different parts of the Caribbean during late summer and autumn of 2023. By September 2024, the 29°C isotherm deepened by a further ~10 m. The anomalous warmth that developed in 2023 thus persisted into 2024, most pronounced across the Caribbean Sea.

4.3. Warm Water Development by Q_{net}

The total warm water volume available for hurricane intensification was analyzed in Harris et al. (2022). It was found that in some hurricane seasons, much of the anomalous volume of water warmer than 26.5°C in the tropical Atlantic north of 10°N can be explained by Q_{net}, using the WMT framework in temperature space. However, in other years, warm water volume anomalies calculated using WMT fail to explain a significant volume of warm water, leaving room for development of warm water volume anomalies by ocean heat transport. In this section, we quantify the volume of warm water made available for anomalous hurricane activity in 2024 due to heat transfer from the atmosphere.

Four years since 1980 have seen 5 major hurricanes, including 2024 (Figure 3a). 2024 was also unusual in that it was one of only 7 years in the hurricane record, which begins in 1851, with at least two category 5 hurricanes recorded. This high activity of the most intense storms is related to atmospheric instability resulting from the amount of unusually warm water available to drive intensification. However, while activity in 2024 was higher than that in 2023 due to ENSO conditions (Klotzbach Jones et al., 2024), intraseasonal variability during the climatological peak affected total 2024 activity (Klotzbach et al., 2025). The September volume of warm water north of 10°N is positively correlated with major hurricane count 1980–2024 (Figure 3b), with a Pearson correlation coefficient 0.50, statistically significant at the 99% confidence level. The anomalous warm water volume in September 2024 was the highest observed to date in both the EN4 and GODAS data sets.

Month to month, the anomalous volume of water transformed across isotherms warmer than 26.5°C closely matches the observed warm water volume warmer than 26.5°C, particularly in 2023 (Figure 3c). However, the transformed volume anomalies from Q_{net} are larger toward the end of 2024 than the actual month to month anomalies, suggesting that heat transfer into the ocean could have created a larger volume of warm water for hurricane development than was experienced, due to horizontal and vertical re-distribution of heat by ocean currents.

Q_{net} into the MDR increased dramatically through 2023, and remained at record levels through 2024, largely driven by Q_{lh} (Figure 3d). This mechanism for warming the North Atlantic in 2023 is discussed by Carton et al. (2025). Subsequently, warm water in the Atlantic tropics continued to develop through 2024. While there are positive peak MDR Q_{net} anomalies for individual months of a larger magnitude than 2023, these are short-lived. Recently, MDR Q_{net} anomalies have been consistently positive since March 2023. Persistent extreme SST in the tropical Atlantic was available for hurricane intensification in late 2024, when atmospheric conditions were favorable.

Extremely weak trade winds over the MDR limited heat transfer into the atmosphere from evaporation at the ocean surface. Due to a very weak subtropical high (Klotzbach Jones et al., 2024), MDR mean March–August zonal surface winds in 2023 were the second highest (lowest easterly trade winds) after 2005 (Figure S1 in Supporting Information S1), particularly in the eastern Atlantic. MDR zonal winds in 2024 continued to be highly anomalous. Hence, less evaporation from the ocean surface contributed to reduced surface heat loss through two consecutive springs.

4.4. Development by Ocean Advection

WMT analysis in Figures 2b and 2c implicitly considers the entire warm water volume, spanning much of the tropical Atlantic. We now consider the upper ocean heat budget in the central-western tropics (North Atlantic south of 30.8°N, west of 40.25°W, Figure 4), where most of the anomalous warm water is found in late summer 2024 (Section 3.2). The relative importance of advective divergence and surface heat input in the NPD hindcast over 2020–24 are first quantified with monthly-mean volume and heat budgets for the upper 100 m of the western

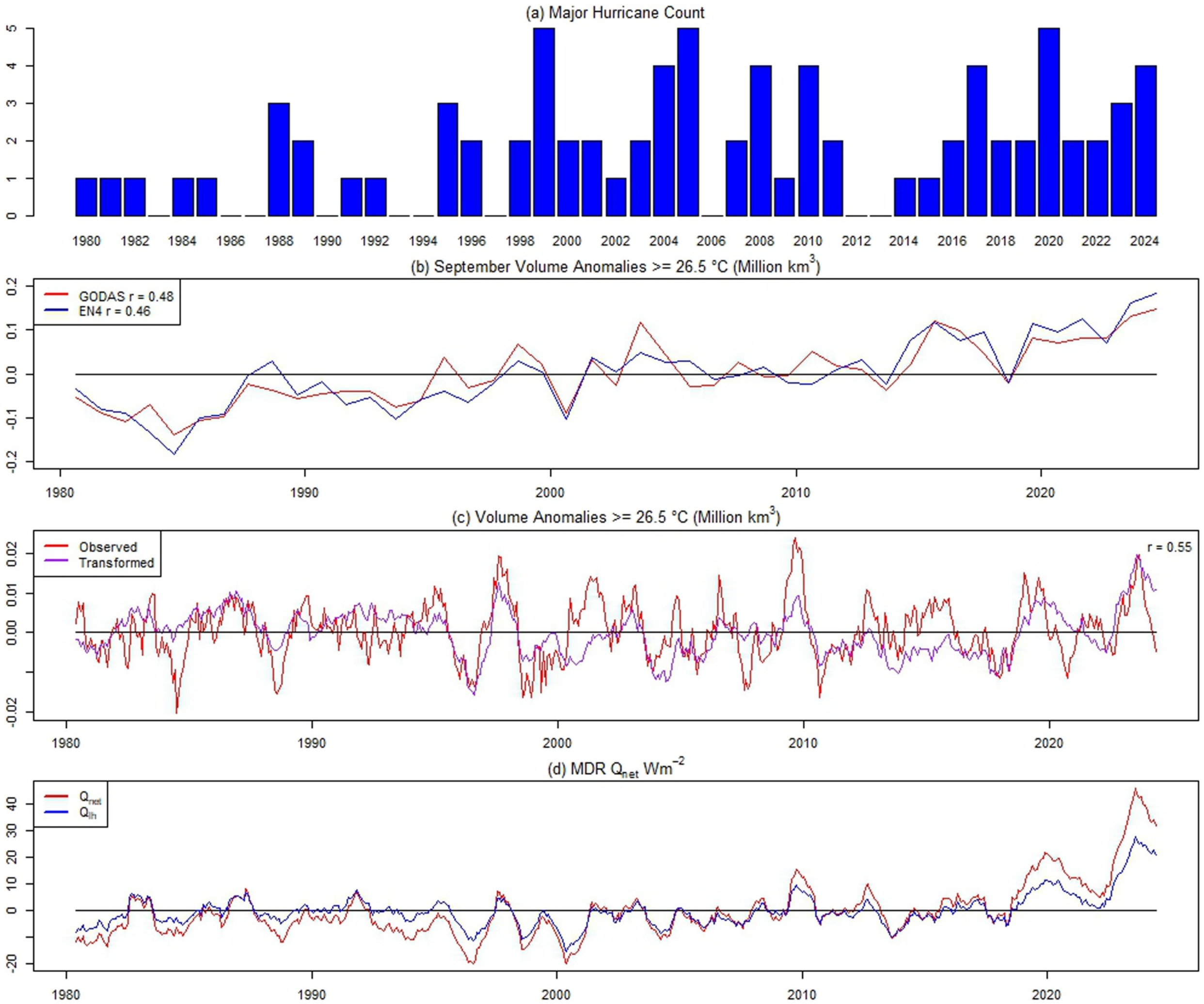

Figure 3. (a) Category 3–5 hurricanes per year 1980–2024, (b) 1980–2024 September volume anomalies (relative to September means over 1980–2024) of Atlantic north of 10°N and warmer than 26.5°C (GODAS—red, EN4—blue), (c) 12-month smoothed GODAS (red) month-to-month warm water volume anomalies (Million km^3 per month) and corresponding volume anomalies transformed by surface heat flux (purple), (d) NCEP 1980–2024 MDR 12-month smoothed Q_{net} (red) and Q_{lh} (blue) Wm^{-2}.

tropics and southern subtropics (Figure S2 in Supporting Information S1). Seasonally varying inflow at the eastern boundary is, to first order, balanced by corresponding variations of vertical flow (downwelling) through the 100 m surface. Regarding the heat budget, seasonal temperature changes in the region ("dh100c" in Figure S2 in Supporting Information S1) are largely attributed to surface heat fluxes. As for volume transport, variable heat transport through the eastern boundary is linked with downwelling heat transport through the 100 m surface. Additional volume and heat transport across the eastern boundary and downward heat flux at 100 m are evident in early 2024, motivating closer scrutiny of the role of ocean advection in shaping the excess heat of that summer.

Given the close link between upper ocean heat content, divergence of advective heat transport and surface heat fluxes in the central-western tropics, we subsequently use Lagrangian diagnostics to examine the seasonal evolution of anomalous heat in this region. North of 5°N, all water warmer than 29°C in September (Figure S3 in Supporting Information S1) is back-tracked over 9 months, for each of the last 25 years. Ensemble statistics of these back-tracking calculations are summarized in Figure 4. For 2022–2024 (Figure 4a–4c), gridded fractional presence of particles (number of particle transitions through a grid cell divided by total number of transitions) indicates predominant inflow along the North Brazil Current (NBC) in each year, but with additional inflow in 2023 and 2024 from the eastern tropical Atlantic. This pathway exists throughout 2001–2025 as part of the

10.1029/2025GL116580

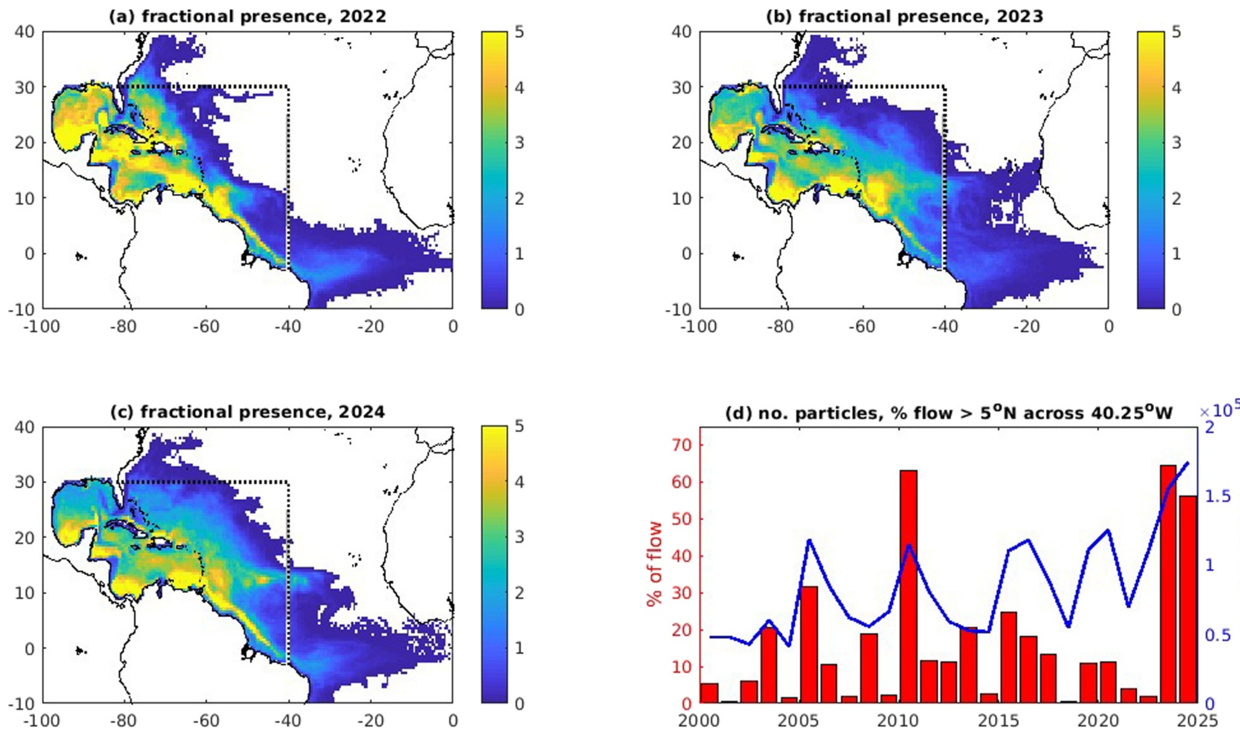

Figure 4. Ensemble statistics for 9-month back-tracking of warm waters ($T > 29°C$) initialized in September of 2022–2024 (a–c), indicating fractional presence of particles ($\times 10^{-4}$). The time series in (d) are obtained from this annual backtracking over each of the past 25 years, recording the percentage of flow north of 5°N at 40.25°W (red bars) and the total number of tracked particles per year (blue line). In (a–c), black dotted lines indicate the eastern and northern bounding sections for a western basin upper ocean heat budget. The white and gray lines indicate the sections at 40.25°W where we sample flows north and south of 5°N.

southern flank of the subtropical gyre which continues to the western tropics, but only in 2010, 2023, and 2024 does this pathway provide waters warmer than 29°C to the western tropics by September.

In most years (2001–2025), a large number of the back-tracked particles are initialized in the GoM; particles initialized in 2022 remain in the GoM and along the western boundary, hence highest fractions appear here, compared to 2023 and 2024; consequently, particles in 2022 spend less time elsewhere, notably the northern tropics. Higher fractions in 2022 are also relative, as substantially more particles are back-tracked in 2023 and 2024 (see Figure S3 in Supporting Information S1). Higher percentage inflows from the northern tropics generally coincide with a higher number of back-tracked particles, hence a larger warm water volume. Further analysis of temperature changes along particle pathways (Figures S4b, S4d, and S4f in Supporting Information S1) reveals heat gain along most pathways, with rapid advection along the NBC and northern tropical pathways indicated by younger ages (Figures S4a, S4c, and S4e in Supporting Information S1). In summary, it appears that much of the excess heat of the western tropics in September 2024 (and 2023) accumulated along flow pathways from the eastern tropics over the preceding 9 months. Targeted backward tracking of the warmest surface waters is thus complementary to a regional upper ocean heat budget which indicated recent increases in eastward and downward heat transport.

5. Conclusions

We have shown that the active periods of the Atlantic hurricane season of 2024 coincided with exceptional ocean warmth, most evident in the western tropical Atlantic, specifically the Caribbean Sea and the GoM. During September 2024, SST anomalies in the range 0.5–1.5°C were established across most of the region, persisting since mid-2023 when large regions of the global ocean notably warmed. Unprecedented warming extended to considerable depth, with the 29°C isotherm anomalously deep by 25–100 m across the western tropical Atlantic through July–September of 2024, evident in gridded observations and as sampled with Argo floats.

At basin scale, the cumulative volume of warm water (above selected temperature thresholds) attained record levels in 2024, associated with a long-term upward trend. As with previous years, the record volume of 2024 is largely attributed to positive anomalies of Q_{net}, quantified as WMT in temperature space. Critically, large positive Q_{net} anomalies persisted over many months through 2023 and 2024, largely due to anomalous Q_{lh} into the ocean without climatological spring trade winds allowing evaporative cooling at the surface.

While attributed to surface heat gain across the basin, excess warm water volume is crucially redistributed by surface ocean currents. Backtracking the warmest (excess) of the warm water volume that is largely established in the western tropics by September, over seasonal timescales for 2024 and recent years, we obtain a Lagrangian perspective on the evolution of excess heat in a region vulnerable to hurricane intensification. Much of the anomalous upper ocean warmth in the Caribbean and GoM was clearly acquired in preceding months over the eastern and central Atlantic, during westward transit. Compared to preceding cooler years, an additional zonal pathway also appears at around 15°N in 2023 and 2024. Since 2000, the only previous year when this pathway appeared dominant was 2010, notable for then-record warmth and extreme hurricane activity (Hallam et al., 2019).

The 2023 El Niño, the second largest this century, was connected to a slowdown in Walker circulation across global tropics and a peak in global surface temperature (Jiang et al., 2025). As the Walker circulation increased, and tropical Pacific SSTs transitioned to neutral ENSO, extreme warm waters were advected into the western Atlantic MDR in 2024, eventually into the Caribbean Sea and the GoM. This mechanism appears to be a feature of strong El Niño events, leading to active hurricane seasons the following year. However, the extreme Eastern Tropical Atlantic temperatures of 2023 allowed the mechanism to be more effective in 2024.

Anomalous surface net heat gain by already warm surface waters across much of the tropics as a primary driver of the excess warmth in September is consistent with the basin-scale heat budget analysis of Carton et al. (2025). In addition to this perspective, we emphasize again the key role of tropical ocean circulation in shaping the distribution of this excess heat on seasonal timescales. In summary, unprecedented upper ocean warmth evident across the western tropical Atlantic in 2024 can be attributed to a combination of anomalous surface net heat gain and the basin-scale surface ocean circulation acting on seasonal to longer timescales. The upper ocean remains unusually warm across the region, of likely consequence for upcoming and future hurricane seasons.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The IBTrACS data is available at Gahtan et al. (2024). The HadISST data is available at https://www.metoffice.gov.uk/hadobs/hadisst/. ERA5 daily SST is available at Copernicus Climate Change Service, Climate Data Store. (2024). The EN4 data is available at https://www.metoffice.gov.uk/hadobs/en4/. The GODAS data is available at https://www.psl.noaa.gov/data/gridded/data.godas.html. The Argo float data is available at https://data-argo.ifremer.fr/dac/. The NCEP/NCAR data is available at https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html.

Acknowledgments

A.T.B. and the NPD simulation was supported by NERC ATLANTIS(NE/Y005589/1). EN.4.2.2 data were obtained from https://www.metoffice.gov.uk/hadobs/en4/ and are © Crown Copyright, Met Office, provided under a Non-Commercial Government License http://www.nationalarchives.gov.uk/doc/non-commercial-government-licence/version/2/.

References

Balaguru, K., Foltz, G. R., & Leung, L. R. (2018). Increasing magnitude of hurricane rapid intensification in the central and eastern tropical Atlantic. *Geophysical Research Letters*, *45*(9), 4238–4247. https://doi.org/10.1029/2018gl077597

Behringer, D., & Xue, Y. (2004). Evaluation of the global ocean data assimilation system at NCEP: The Pacific Ocean. In *Eighth Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface*.

Bell, G. D., & Chelliah, M. (2006). Leading tropical modes associated with interannual and multidecadal fluctuations in North Atlantic hurricane activity. *Journal of Climate*, *19*(4), 590–612. https://doi.org/10.1175/jcli3659.1

Bhatia, K., Baker, A., Yang, W., Vecchi, G., Knutson, T., Murakami, H., et al. (2022). A potential explanation for the global increase in tropical cyclone rapid intensification. *Nature Communications*, *13*(1), 6626. https://doi.org/10.1038/s41467-022-34321-6

Blanke, B., & Raynaud, S. (1997). Kinematics of the Pacific equatorial undercurrent: An Eulerian and Lagrangian approach from GCM results. *Journal of Physical Oceanography*, *27*(6), 1038–1053. https://doi.org/10.1175/1520-0485(1997)027<1038:KOTPEU>2.0.CO;2

Carton, J. A., Chepurin, G. A., Hackert, E. C., & Huang, B. (2025). Remarkable 2023 North Atlantic Ocean Warming. *Geophysical Research Letters*, *52*(3), e2024GL112551. https://doi.org/10.1029/2024gl112551

Cheng, L., Abraham, J., Trenberth, K. E., Reagan, J., Zhang, H. M., Storto, A., et al. (2025). Record high temperatures in the ocean in 2024. *Advances in Atmospheric Sciences*, *42*(6), 1–18. https://doi.org/10.1007/s00376-025-4541-3

Cheng, L., Trenberth, K. E., Fasullo, J. T., Mayer, M., Balmaseda, M., & Zhu, J. (2019). Evolution of ocean heat content related to ENSO. *Journal of Climate*, *32*(12), 3529–3556. https://doi.org/10.1175/jcli-d-18-0607.1

Cheng, L., von Schuckmann, K., Abraham, J. P., Trenberth, K. E., Mann, M. E., Zanna, L., et al. (2022). Past and future ocean warming. *Nature Reviews Earth & Environment*, *3*(11), 776–794. https://doi.org/10.1038/s43017-022-00345-1

Choi, H. Y., Park, M. S., Kim, H. S., & Lee, S. (2024). Marine heatwave events strengthen the intensity of tropical cyclones. *Communications Earth & Environment*, *5*(1), 69. https://doi.org/10.1038/s43247-024-01239-4

Copernicus Climate Change Service, Climate Data Store. (2024). ERA5 post-processed daily-statistics on single levels from 1940 to present [Dataset]. *Copernicus Climate Change Service (C3S) Climate Data Store (CDS)*. https://doi.org/10.24381/cds.4991cf48

Emanuel, K. (2021a). Atlantic tropical cyclones downscaled from climate reanalyses show increasing activity over past 150 years. *Nature Communications*, *12*(1), 7027. https://doi.org/10.1038/s41467-021-27364-8

Emanuel, K. (2021b). Response of global tropical cyclone activity to increasing CO 2: Results from downscaling CMIP6 models. *Journal of Climate*, *34*(1), 57–70. https://doi.org/10.1175/jcli-d-20-0367.1

Gahtan, J., Knapp, K. R., Schreck, C. J., III., Diamond, H. J., Kossin, J. P., & Kruk, M. C. (2024). International best track archive for climate stewardship (IBTrACS) project, version 4.01. [WP, NP, NA, SI, NI, SP] [Dataset]. *NOAA National Centers for Environmental Information*. https://doi.org/10.25921/82ty-9e16

Goldenberg, S. B., Landsea, C. W., Mestas-Nuñez, A. M., & Gray, W. M. (2001). The recent increase in Atlantic hurricane activity: Causes and implications. *Science*, *293*(5529), 474–479. https://doi.org/10.1126/science.1060040

Good, S. A., Martin, M. J., & Rayner, N. A. (2013). EN4: Quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates. *Journal of Geophysical Research: Oceans*, *118*(12), 6704–6716. https://doi.org/10.1002/2013jc009067

Groeskamp, S., & Iudicone, D. (2018). The effect of air-sea flux products, shortwave radiation depth penetration, and albedo on the upper ocean overturning circulation. *Geophysical Research Letters*, *45*(17), 9087–9097. https://doi.org/10.1029/2018gl078442

Guiavarc'h, C., Storkey, D., Blaker, A. T., Blockley, E., Megann, A., Hewitt, H., et al. (2025). GOSI9: UK Global Ocean and Sea Ice configurations. *Geoscientific Model Development*, *18*(2), 377–403. https://doi.org/10.5194/gmd-18-377-2025

Hallam, S., Guishard, M., Josey, S. A., Hyder, P., & Hirschi, J. (2021). Increasing tropical cyclone intensity and potential intensity in the subtropical Atlantic around Bermuda from an ocean heat content perspective 1955–2019. *Environmental Research Letters*, *16*(3), 034052. https://doi.org/10.1088/1748-9326/abe493

Hallam, S., Marsh, R., Josey, S. A., Hyder, P., Moat, B., & Hirschi, J. J. M. (2019). Ocean precursors to the extreme Atlantic 2017 hurricane season. *Nature Communications*, *10*(1), 1–10. https://doi.org/10.1038/s41467-019-08496-4

Harris, E., Dey, D., Marsh, R., & Grist, J. (2024). Meridional heat convergence will increase tropical North Atlantic heat content available for hurricane intensification. In *Advances in Hurricane Risk in a Changing Climate* (pp. 77–95). Springer Nature Switzerland.

Harris, E. A., Marsh, R., & Grist, J. P. (2023). Tracing Oceanic sources of heat content available for Atlantic hurricanes. *Journal of Geophysical Research: Oceans*, *128*(5), e2022JC019407. https://doi.org/10.1029/2022JC019407

Harris, E. A., Marsh, R., Grist, J. P., & McCarthy, G. D. (2022). The water mass transformation framework and variability in hurricane activity. *Climate Dynamics*, *59*(3–4), 961–972. https://doi.org/10.1007/s00382-022-06169-5

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *246*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Holland, G., & Bruyère, C. L. (2014). Recent intense hurricane response to global climate change. *Climate Dynamics*, *42*(3–4), 617–627. https://doi.org/10.1007/s00382-013-1713-0

Huang, B., Yin, X., Carton, J. A., Chen, L., Graham, G., Hogan, P., & Zhang, H. M. (2024). Record high sea surface temperatures in 2023. *Geophysical Research Letters*, *51*(14), e2024GL108369. https://doi.org/10.1029/2024gl108369

Jiang, N., Zhu, C., Hu, Z. Z., McPhaden, M. J., Lian, T., Zhou, C., et al. (2025). El Niño and sea surface temperature pattern effects lead to historically high global mean surface temperatures in 2023. *Geophysical Research Letters*, *52*(2), e2024GL113733. https://doi.org/10.1029/2024gl113733

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al. (1996). The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, *77*(3), 437–472. https://doi.org/10.1175/1520-0477(1996)077<0437:tnyrp>2.0.co;2

Klotzbach, P. J. (2024). *Summary of 2024 Atlantic tropical cyclone activity and verification of authors' seasonal and two-week forecasts*. Colorado State University. Retrieved from https://tropical.colostate.edu/Forecast/2024-11.pdf

Klotzbach, P. J., Bercos-Hickey, E., Wood, K. M., Schreck, C. J., III., Bell, M. M., Blake, E. S., et al. (2025). The remarkable 2024 North Atlantic mid-season hurricane lull. *Geophysical Research Letters*, *52*(19), e2025GL116714. https://doi.org/10.1029/2025gl116714

Klotzbach, P. J., Jones, J. J., Wood, K. M., Bell, M. M., Blake, E. S., Bowen, S. G., et al. (2024). The 2023 Atlantic hurricane season: An above-normal season despite strong El Niño conditions. *Bulletin of the American Meteorological Society*, *105*(9), E1644–E1661. https://doi.org/10.1175/bams-d-23-0305.1

Knapp, K. R., Diamond, H. J., Kossin, J. P., Kruk, M. C., & Schreck, C. J. (2018). International best track archive for climate stewardship (IBTrACS) project, version 4.[WP, NP, NA, SI, NI, SP].

Knapp, K. R., Kruk, M. C., Levinson, D. H., Diamond, H. J., & Neumann, C. J. (2010). The international best track archive for climate stewardship (IBTrACS) unifying tropical cyclone data. *Bulletin of the American Meteorological Society*, *91*(3), 363–376. https://doi.org/10.1175/2009bams2755.1

Kossin, J. P., Camargo, S. J., & Sitkowski, M. (2010). Climate modulation of North Atlantic hurricane tracks. *Journal of Climate*, *23*(11), 3057–3076. https://doi.org/10.1175/2010jcli3497.1

Lopez, H., Lee, S. K., West, R., Kim, D., Foltz, G. R., Alaka Jr, G. J., & Murakami, H. (2024). Projected increase in the frequency of extremely active Atlantic hurricane seasons. *Science Advances*, *10*(46), eadq7856. https://doi.org/10.1126/sciadv.adq7856

Mainelli, M., DeMaria, M., Shay, L. K., & Goni, G. (2008). Application of Oceanic heat content estimation to operational forecasting of recent Atlantic category 5 hurricanes. *Weather and Forecasting*, *23*(1), 3–16. https://doi.org/10.1175/2007waf2006111.1

Majumdar, S. J., Nebylitsa, S., Klotzbach, P. J., Masiello, C., & Michael, Z. R. (2023). North Atlantic tropical cyclone intensification: Regional drivers and trends. *Geophysical Research Letters*, *50*(17), e2023GL104803. https://doi.org/10.1029/2023gl104803

McTaggart-Cowan, R., Davies, E. L., Fairman, J. G., Galarneau, T. J., & Schultz, D. M. (2015). Revisiting the 26.5°C sea surface temperature threshold for tropical cyclone development. *Bulletin of the American Meteorological Society*, *96*(11), 1929–1943. https://doi.org/10.1175/bams-d-13-00254.1

Moharana, S. S., & Swain, D. (2023). On the recent increase in Atlantic Ocean hurricane activity and influencing factors. *Natural Hazards*, *118*(2), 1387–1399. https://doi.org/10.1007/s11069-023-06061-3

Murakami, H., Levin, E., Delworth, T. L., Gudgel, R., & Hsu, P.-C. (2018). Dominant effect of relative tropical Atlantic warming on major hurricane occurrence. *Science*, *362*(6416), 794–799. https://doi.org/10.1126/science.aat6711

National Centers for Environmental Information. (2025). *Billion-dollar weather and climate disasters: Time series*. NOAA. Retrieved from https://www.ncei.noaa.gov/access/billions/time-series/US/cost

Pfleiderer, P., Nath, S., & Schleussner, C. F. (2022). Extreme Atlantic hurricane seasons made twice as likely by ocean warming. *Weather and Climate Dynamics*, *3*(2), 471–482. https://doi.org/10.5194/wcd-3-471-2022

Radfar, S., Moftakhari, H., & Moradkhani, H. (2024). Rapid intensification of tropical cyclones in the Gulf of Mexico is more likely during marine heatwaves. *Communications Earth & Environment*, *5*(1), 421. https://doi.org/10.1038/s43247-024-01578-2

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., et al. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research*, *108*(D14), 4407. https://doi.org/10.1029/2002jd002670

Roberts, M. J., Camp, J., Seddon, J., Vidale, P. L., Hodges, K., Vannière, B., et al. (2020). Projected future changes in tropical cyclones using the CMIP6 HighResMIP multimodel ensemble. *Geophysical Research Letters*, *47*(14), e2020GL088662. https://doi.org/10.1029/2020GL088662

Saunders, M. A., & Lea, A. (2008). Large contribution of sea surface warming to recent increase in Atlantic hurricane activity. *Nature*, *451*(7178), 557–560. https://doi.org/10.1038/nature06422

Sobel, A. H., Wing, A. A., Camargo, S. J., Patricola, C. M., Vecchi, G. A., Lee, C. Y., & Tippett, M. K. (2021). Tropical cyclone frequency. *Earth's Future*, *9*(12), e2021EF002275. https://doi.org/10.1029/2021ef002275

Tsujino, H., Urakawa, S., Nakano, H., Small, R. J., Kim, W. M., Yeager, S. G., et al. (2018). JRA-55 based surface dataset for driving ocean–sea-ice models (JRA55-do). *Ocean Modelling*, *130*, 79–139. https://doi.org/10.1016/j.ocemod.2018.07.002

Vecchi, G. A., & Soden, B. J. (2007). Increased tropical Atlantic wind shear in model projections of global warming. *Geophysical Research Letters*, *34*(8), L08702. https://doi.org/10.1029/2006gl028905

Walin, G. (1982). On the relation between sea-surface heat flow and thermal circulation in the ocean. *Tellus*, *34*(2), 187–195. https://doi.org/10.1111/j.2153-3490.1982.tb01806.x

Wang, S., & Toumi, R. (2022). More tropical cyclones are striking coasts with major intensities at landfall. *Scientific Reports*, *12*(1), 5236. https://doi.org/10.1038/s41598-022-09287-6

Wong, A. P. S., Wijffels, S. E., Riser, S. C., Pouliquen, S., Hosoda, S., Roemmich, D., et al. (2020). Argo data 1999–2019: Two million temperature-salinity profiles and subsurface velocity observations from a global array of profiling floats. *Frontiers in Marine Science*, *7*(700), 700. https://doi.org/10.3389/fmars.2020.00700