The Water Mass Transformation Framework and Variability in Hurricane Activity

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Abstract

Hurricane activity has been higher since 1995 than in the 1970s and 1980s. This rise in activity has been linked to a warming Atlantic. In this study, we consider variability of the volume of water warmer than 26.5 ºC, taken as the temperature threshold crucial to hurricane development, through the Water Mass Transformation framework. The volume of water transformed by surface heat fluxes to temperatures of 26.5 ºC is calculated, and compared with the year to year changes in the volume of water of this temperature. Variability of transformed volume is largely due to latent heat flux processes, associated in turn with anomalies in cloud fraction and surface winds. In some years, there is correspondence between transformed and observed volume anomalies, but in other years, alternative processes must drive observed volume anomalies. Coordinated physical mechanisms are thus responsible for anomalous ocean heat, providing fuel for larger numbers of intense hurricanes.

The Water Mass Transformation Framework and Variability in Hurricane Activity

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Key Points:

- Water Mass Transformation calculates the volume flux of water transformed across isotherms by air-sea heat fluxes.
- Anomalous transformed volume shows correspondence with observed volume anomalies in some years, dominated by latent heat flux processes.
- Anomalies in heat transport by ocean currents have played a key role in years when air-sea fluxes are less influential.

Abstract

Hurricane activity has been higher since 1995 than in the 1970s and 1980s. This rise in activity has been linked to a warming Atlantic. In this study, we consider variability of the volume of water warmer than 26.5 ºC, taken as the temperature threshold crucial to hurricane development, through the Water Mass Transformation framework. The volume of water transformed by surface heat fluxes to temperatures of 26.5 ºC is calculated, and compared with the year to year changes in the volume of water of this temperature. Variability of transformed volume is largely due to latent heat flux processes, associated in turn with anomalies in cloud fraction and surface winds. In some years, there is correspondence between transformed and observed volume anomalies, but in other years, alternative processes must drive observed volume anomalies. Coordinated physical mechanisms are thus responsible for anomalous ocean heat, providing fuel for larger numbers of intense hurricanes.

Plain Language Summary

The number of hurricanes in the North Atlantic has been higher in the last 25 years than it was in the prior 25 years. This is due a larger region of warm water providing more fuel for weaker storms to become stronger and more dangerous. The theoretical additional volume of water of a certain temperature in some years can be calculated from the amount of energy transferred into the ocean from the atmosphere. This method can identify how much of this volume can be attributed to transfer of heat from the atmosphere. The calculated volume was a good match with the actual amount of extra water of this temperature in some years. In other years, changes in ocean currents help explain the rest of the warm water changes in the area where hurricanes are found. Understanding the reasons why the amount of warm water varies between hurricane seasons will help predict years which have more deadly hurricanes.

Key Words

Hurricane, Water Mass Transformation, Surface heat flux, Atlantic, Warm water anomalies

1 Introduction

Recent North Atlantic hurricane seasons have produced several high impact hurricanes, including Harvey, Irma, and Maria in 2017, Florence and Michael in 2018, and Dorian in 2019, which resulted in 335 billion USD damage and over 3,000 deaths (NCEI, 2020). Questions remain open on drivers of high activity seasons. Variability in hurricane activity on a range of timescales has been linked to large scale climate oscillations, including the Atlantic Multidecadal Oscillation (AMO) (Goldenberg et al. 2001), or Atlantic Multidecadal Variability (AMV) (Zhang and Delworth, 2006), the El Nino Southern Oscillation (ENSO) (Bove et. al, 1998), the North Atlantic Oscillation (NAO) (Elsner and Jagger, 2004), the Quasi-Bienniel Oscillaition (QBO) (Gray,1992), as well as variations in atmospheric aerosols (Wang, 2012).

On interannual timescales, the Atlantic hurricane season is subject to variable atmospheric processes. For example, Atlantic hurricane variability is negatively correlated with El Niño indices, as anomalously warm tropical Pacific Sea Surface Temperatures (SSTs) result in higher than average vertical wind shear (VWS) in the tropical Atlantic, which inhibits vertical motion necessary for Atlantic hurricane formation (DeMaria, 1996). On timescales longer than interannual, slower modes of ocean variability are important. Associated with warmer ocean temperatures in the tropical North Atlantic is an increase in available energy in the upper ocean to fuel hurricane development (Shapiro and Goldenberg, 1998). Quantifying the atmospheric and oceanic processes that increase the volume of warm water could help us to understand hurricane variability on longer timescales.

Other work has focused on the link between SST in the northern tropical Atlantic, particularly in the Main Development Region (MDR) for Atlantic hurricanes (Goldenberg et al, 2001), generally defined as 10-20 °N, 20-80 °W. However, oceanic conditions which sustain hurricane winds are not constrained to a rectangular study area in the tropics. In particular, warm water availability outside this region is one factor which could result in major hurricane landfall further north. Wang (2011) investigated the areal extent of the Atlantic Warm Pool (AWP) and correlation with hurricane activity.

This study quantifies the contribution of surface heat flux (Q_{net}) processes to the variability of warm water volume available for hurricane development through the holistic Water Mass Transformation (WMT) framework (Groeskamp et al. 2019). This approach has the advantage of referencing the total volume of water above a temperature threshold intimately connected with hurricane development, 26.5 °C, geographically confined to the Atlantic, without being limited to a rectangular box, like the conventional MDR. Furthermore as the depth of the warm water can be important in hurricane intensification (e.g. Balaguru et al., 2013), it is likely that in some regions, the volume of potentially hurricane producing water may be a more physically meaningful metric than area-averaged SST.

The volume of water transformed across isotherms through Q_{net} is calculated using WMT. Accumulated transformation fluxes over a time interval are compared with observed changes in volume over the same interval. We thus determine the extent to which changes in the warm water volume are attributed to anomalous surface heat gain.

2 Methods

Returning to the original formulation of Walin (1982), the Water Mass Transformation framework (Groeskamp et al. 2019) can be applied in temperature space, quantifying volume fluxes across isotherms associated with variations of heat fluxes in that property space. The net surface heat flux, Q_{net}, combines absorbed shortwave (Q_{sw}) and net longwave (Q_{lw}) radiation, sensible heat (Q_{sh}), and latent heat (Q_{lh}) fluxes. Throughout this study, our convention is that heat flux is positive into the ocean:

$$Q_{net} = Q_{sw} + Q_{lw} + Q_{sh} + Q_{lh} \qquad (1)$$

Across temperature space, the volume of water transformed by Q_{net} is calculated over the North Atlantic, north of 10 °N, where there is sufficient Coriolis force for tropical storm spinup. Firstly, the Diathermal Temperature Flux, $Q_{in}(T)$ (°C m^3s^{-1}) (2), is found by area-integrating Q_{net}, where SST is at or above a given value of temperature, T, then dividing by reference density, ρ_0, and specific heat capacity, c_p, where that isotherm is outcropped.

$$Q_{in}(T) = \frac{1}{\rho_o c_p} \int_{x_w}^{x_e} \int_{y_s}^{y_n} Q_{net}(x,y)\Gamma(SST(x,y),T)dxdy \qquad (2)$$

where x, y are distance in west (w) to east (e) and south (s) to north (n) directions, and Γ is a sampling function; Γ = 1 where SST > T, otherwise Γ = 0. Q_{net} values at the potential temperature grid points are found using bilinear interpolation.

The thermal water mass transformation rate, $F_T(T)$ (m^3s^{-1}), can then be arrived at by taking differences between $Q_{in}(T)$ across two temperature surfaces.

$$F_T\left(T - \Delta T/2,\, T + \Delta T/2\right) = \frac{Q_{in}(T-\Delta T/2) - Q_{in}(T+\Delta T/2)}{\Delta T} \qquad (3)$$

where Q_{in} is calculated at temperature intervals of ΔT.

3 Data

The National Center for Environmental Prediction - National Center for Atmospheric Research (NCEP-/NCAR) reanalysis (Kalnay et al., 1996) is used for monthly mean values of heat transfer from the atmosphere into the ocean from 1980 through 2019. Wind speed and cloud cover values used are also from this source. Incorporating all available observational data, the reanalysis data consists of data at a 2.5° horizontal resolution from 1950 onwards. Previous similar uses of the WMT framework include studies of the subtropical and subpolar North Atlantic (Grist et al. 2014).

The NCEP Global Ocean Data Assimilation System (GODAS) ocean reanalysis product (Behringer and Xue, 2004) contains global potential temperature at 40 discrete depths, 1/3° latitude and 1° longitude from 1980 to present. It is important to note that observations assimilated into these products are more scarce at depth and further back in time, so the integrity of reanalysis data is consequently inconsistent.

The US National Hurricane Center (NHC) tropical cyclone data, HURDAT, was used to obtain annual hurricane counts and location of the onset of hurricane force maximum winds. This dataset includes storm center coordinates and maximum winds at 6 hourly intervals over the ocean. These wind speeds are rounded to the nearest 5 knots. This data has been incorporated in a global tropical cyclone dataset in a standard format, maintained by the international best track archive for climate stewardship (IBTrACS) (Knapp et al., 2010, Knapp et al., 2018).

4 Results

We first summarise the extent to which warm water volume and hurricane activity have co-varied since 1980. We then introduce the WMT framework in temperature space, applied to the warm water pool. Over our study period, we present evidence of a leading role for surface fluxes as the dominant driver of anomalous upper ocean warmth in several years of the last four decades.

4.1 Warm Water Volume and Hurricane Activity

North Atlantic hurricane activity has been above average since 1995, following below average activity in the preceding period (Figure 1). Recent years with the highest annual hurricane counts include 2005 and 2010. Anomalous volume of water warmer than 26.5 °C in the North Atlantic shows similar multidecadal variability, with warm episodes becoming more frequent after 1995. While the most active years don’t always occur when the volume of water greater than 26.5 °C is highest, due to, for example, the important role of VWS, active years have become more frequent during this recent regime of a larger volume of warm water.

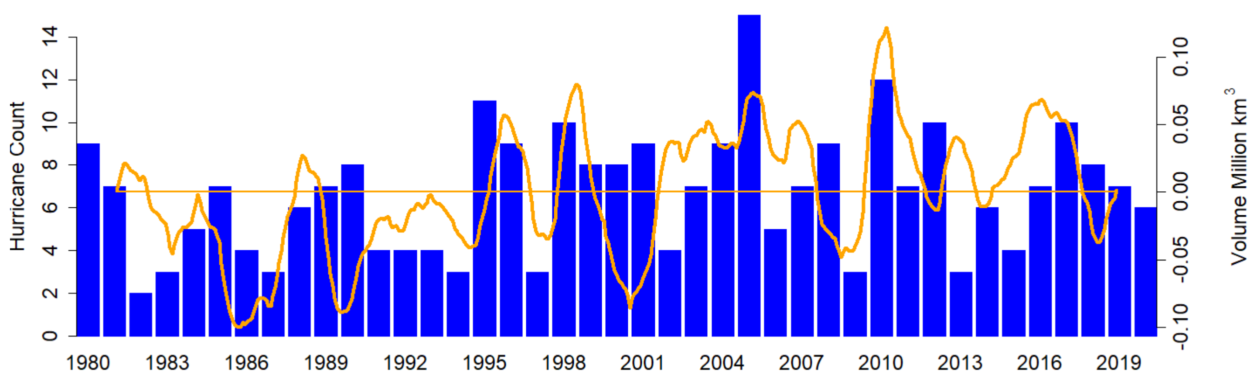

Figure 1. Annual North Atlantic Hurricane count (blue bars) and volume anomalies of water warmer than 26.5 °C in the Atlantic north of 10° N, 12 month smoothing (orange line).

4.2 Characteristics of Water Mass Transformation

WMT calculates the rate that water masses are transformed across isotherms by heat transfer between the ocean and the atmosphere. A North Atlantic WMT climatology shows the transformation rate across all isotherms likely to be found in the North Atlantic, from 0 °C to 31 °C (Figure 2). The climatology is consistent with annual net cooling and warming in different temperature ranges. Surface water is transformed by Q_{net} across isotherms: towards cooler temperatures in the range 0 to 27 °C, where $Q_{net} < 0$; towards higher temperatures between 27 °C and 30 °C, where $Q_{net} > 0$. The latter temperatures are of particular relevance to hurricane and major hurricane development. This indicates that in general, local surface fluxes act to increase the volume of water warmer warmer than 27 ºC. Other processes, including ocean mixing, and export from the region by advection, work to reduce that volume, resulting in the observed volume changes for this time period.

Considering water temperatures affecting hurricane development, annual average transformation of water to temperatures warmer than 26.5 ºC peaks in August. This leads actual warm water volume, which peaks in September (Figure 2b), over the 1980-2019 time period. This is consistent with atmosphere-ocean heat exchange being critical to creating these warm waters. We note that in a case where the surface fluxes are solely responsible for the volume variability, then actual volume anomaly would equal the time-integral of the transformation rate.

Q_{net} processes transform water from cooler SST to water warmer than 26.5 °C under the hurricane genesis and track regions (Figure 2c) through the spring and summer months. While other processes also contribute to the observed September climatological depth of the 26.5 °C isotherm in the North Atlantic (Figure 2d), there is spatial coherence between the transformed volume through the spring and early summer, and the area of 26.5 °C waters in September (Figure 2d). Relating this more closely to hurricane development metrics, the point at which 1980-2019 tropical cyclones strengthened into hurricanes with maximum sustained 1-minute mean winds of 64 knots or greater is overlaid onto the climatological depth of the 26.5 °C isotherm. These points are found south of 40 °N, west of 40 °W and south of 20 °N, east of 40 °W, and are bounded to the south around 10 °N. Few points are found north of this region of the North Atlantic, providing additional observational evidence connecting this water with hurricane development. The somewhat convoluted patterns of strong net warming and 26.5 °C isotherm depth reinforce our emphasis that ocean warming of consequence for hurricane genesis is not confined to the MDR.

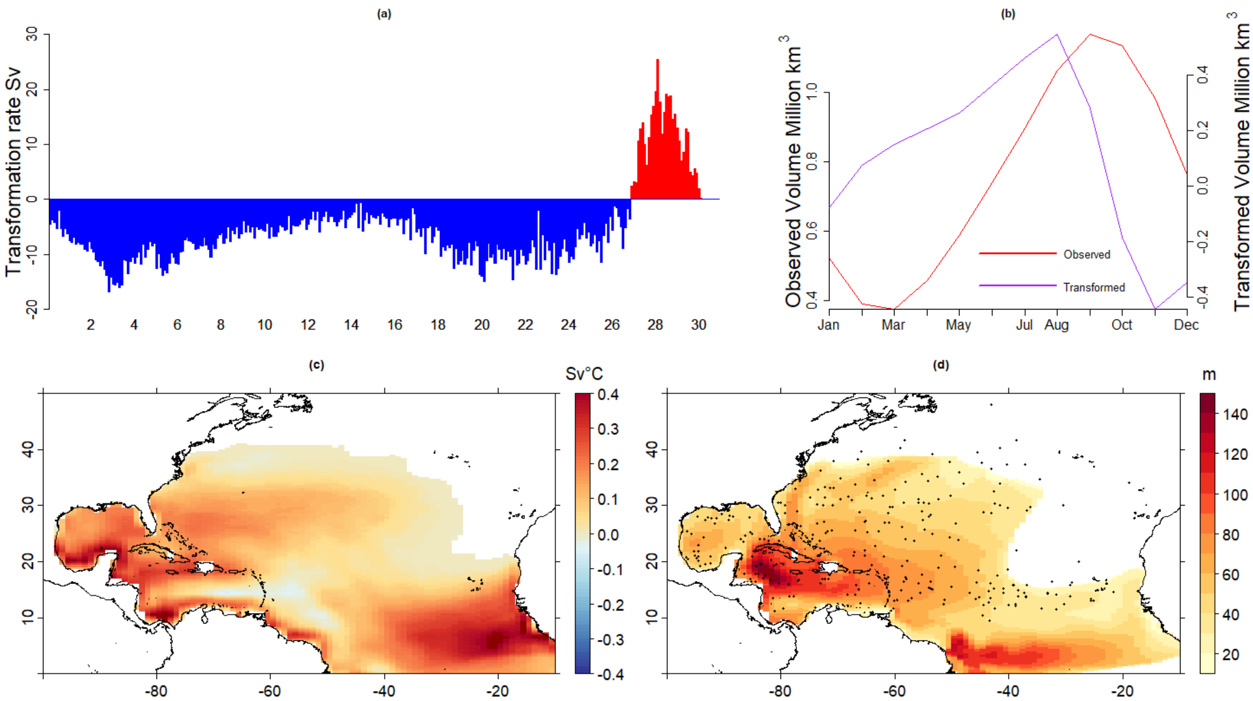

Figure 2. (a) Transformation rate (Sv) for the Atlantic north of 10°N as a function of SST 1980-2019, given diathermal temperature fluxes at 0.25 °C intervals; positive values imply transformation of water towards higher temperatures has occurred over the period, (b) 1980-2019 annual cycle of volume transformed across 26.5 °C isotherm (purple, right axis) and actual volume warmer than 26.5 °C (red, left axis) (million km^3), (c) April-September Q_{in} where SST exceeds 26.5 °C (Sv °C), (d) 1980-2019 September mean depth of 26.5°C isotherm (m) with HURDAT 1980-2019 hurricane formation points overlaid.

4.3 Inferred Warm Water Volume Changes

In Figure 3, time series of GODAS 1980-2019 observed volume anomaly difference of water warmer than 26.5 °C from one month to the next are plotted with NCEP-NCAR anomalous monthly transformation rate across 26.5 °C. The aim is to see how closely these may be linked, and how Q_{net} processes may drive development of this warm water to fuel hurricanes. Monthly anomalies of water transformed by Q_{net} are positively correlated with month-to-month actual volume change anomalies of water warmer than 26.5 °C (Figure 3a). The Pearson correlation coefficient is 0.32, which is statistically significant at the 99% confidence level.

There is particularly close correspondence between the two time series during several periods. Several months of anomalously positive transformation during 1998 occurred (Figure 3b) at the beginning of the multi-decadal (post-1998) period of above-average warm water volume available for hurricane development, with the greatest increase in transformation to the west of 50ºW. During 1998 and a notable peak in both time series, the transformation rate leads observed volume change of water warmer than 26.5 °C by a few months. In August of 1998, the anomalous transformed volume of water warmer than 26.5 °C lies to the north and east of the climatological average area of this water (Figure 3c).

1998 had above average hurricane activity (Pasch et al. 2001), with an Accumulated Cyclone Energy (ACE) of 182, 67% higher than that of the 1980-2019 average ACE, and the 5th highest since 1970, when satellite data began to cover the basin and this metric could be diagnosed appropriately (Kossin, 2007). Major Hurricanes Bonnie, Georges, and Mitch all made landfall in 1998. Anomalous net surface heating heavily contributed to this, the deadliest Atlantic Hurricane season in the last 200 years. The period 1995-1998 of enhanced transformation appears to have also been important in sustaining a shift from below average to above average warm water volume that occurred near this time (Figure 1).

On the contrary, in other years, it is clear from the difference in amplitude of these two signals that other processes must have contributed to accumulation of warm waters. The warm water volume will further vary as a consequence of anomalies in heat transport divergence associated with full-depth ocean transport and Ekman dynamics. In 2009-2010, Q_{net} fails to explain up to 15 million km^3 of anomalous volume of water warmer than 26.5 °C in a month. Bryden et al. (2014) calculate a 0.4 PW reduction in ocean heat transport across 26 °N during this period. A decrease in the Atlantic Meridional Overturning Circulation (AMOC) then allowed a greater accumulation of heat in the tropical Atlantic in this period, leading to a much greater volume of water warmer than 26.5 °C during the very active 2010 hurricane season.

The relative contributions of these heat sources will also vary on longer timescales over the study period. A downward trend has been observed in AMOC transport since 2008 in the RAPID array measurements at 26 °N (Smeed et al., 2018) which would help develop anomalously larger volume of warm North Atlantic water on a decadal timescale. Bryden et al., (2020) note a decrease of 0.17 PW across this latitude since 2009.

To be more specific about the physical processes behind Q_{net}, we examine anomalies in the four terms of the net heat flux (Equation 1). To isolate the leading component in heat flux variability for warm water, the transformation rate across the 26.5 °C isotherm was separately calculated for each component of Q_{net}. The transformation rate calculated with latent heat flux, Q_{lh} (Figure 3d) explains 35% (r = 0.59) of the transformation rate calculated using Q_{net} for this particular temperature.

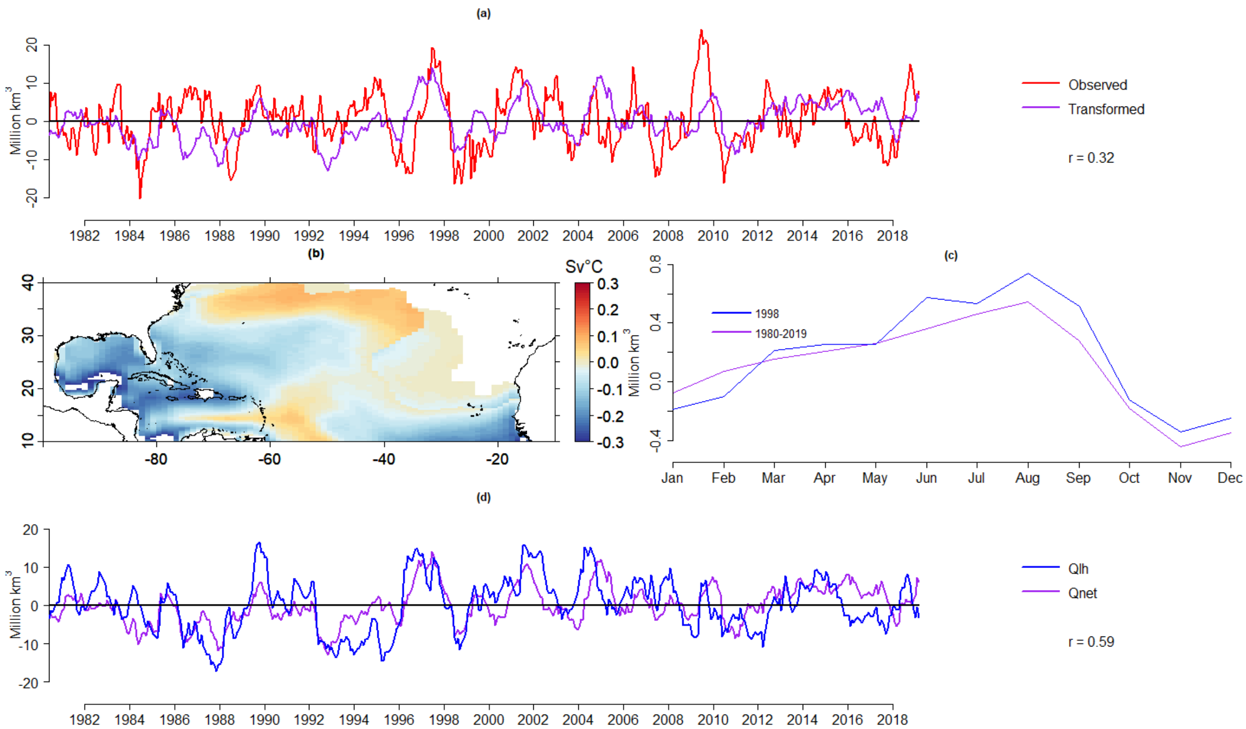

Figure 3. (a) Anomalous observed month-to-month (red) volume change of water warmer than 26.5 °C (Sv) and the anomalous transformation rate across the 26.5 °C isotherm (purple), with 12 month smoothing (Sv), (b) 1998 August Q_{in}(26.5 °C) anomalies (Sv °C), (c) 1980-2019 (blue) annual cycle of volume transformed across 26.5°C isotherm (million km^3) versus climatology (purple), (d) transformation rate across the 26.5 °C isotherm calculated from Q_{net} (purple, as in (a)) and Q_{lh} (blue), with 12 month smoothing.

4.4 Drivers of Warm Water Volume Changes

Having identified Q_{lh} as the main driver of anomalous transformation of water towards temperatures above 26.5 °C, the impact of the atmospheric conditions on latent heat exchange into the ocean can be considered. Heat is gained by the ocean when there is a lower rate of evaporation or less latent heat flux to the atmosphere. In Figure 4, we plot the local correlation coefficient between Q_{lh} and wind speed (Figure 4a) and cloud cover (Figure 4b). Conditions conducive to a low evaporation rate and reduced latent heat loss include high surface humidity and light winds. Q_{lh} is negatively correlated to a larger degree ($r < -0.5$) with wind speed in the hurricane MDR (Figure 4a), and cloud cover in the eastern MDR (Figure 4b), linking calmer winds and clearer skies with reduced latent heat loss and an increase of net heat flux into the ocean. These conditions have been found to strengthen under a positive phase of the tropical AMO (Bellomo et al., 2016).

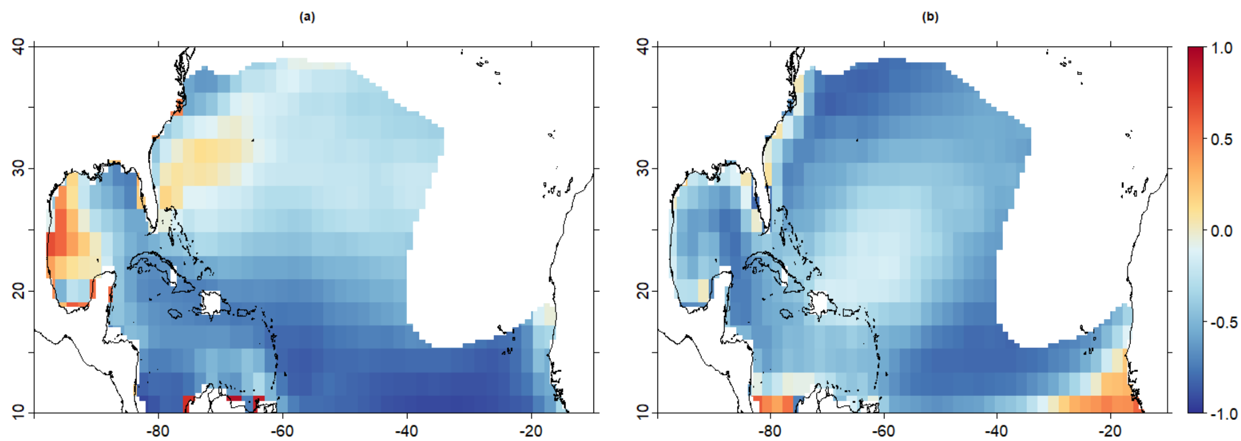

Figure 4. (a) Correlation coefficient heat map for Q_{lh} anomalies and wind speed (b) correlation coefficient heat map for Q_{lh} anomalies and cloud fraction using NCEP-NCAR data spanning 1980-2019. Values are only plotted where 1980-2019 September mean depth of 26.5°C isotherm is greater than 10 m.

5 Conclusions

It is well established that seasonal hurricane activity is largely associated with the volume of water water in the tropical Atlantic. We have applied the WMT framework (Groeskamp et al. 2019) in temperature space to quantify the volume of water transformed at the surface through air-sea interaction, attributed to the net surface heat flux, Q_{net}. It is shown that the amount of water warmer than 27 °C has increased in the last 40 years, with the transformed volume of water warmer than 26.5 °C leading observed volume anomalies through the spring and early summer. The transformed volume of water warmer than 26.5 °C is spatially coherent with the observed volume, which is closely tied to the area identified earlier, where storms are able to intensify into hurricanes.

Anomalous positive WMT increases the volume of warm water to the north and east of this hurricane development area. Wang et al. (2010) note that years where the AWP is larger than average have increased genesis further east and more re-curving tracks. While some of these tracks may remain over the open ocean, the chance of landfall in the US Northeast states is also likely to increase (Dailey et al., 2009). Similarly, Kossin et al. (2010) group Atlantic storms into clusters, finding that increasing trends in recent hurricane activity are driven by the storm clusters originiating in the deep tropics. These storms make up the largest proportion of major hurricanes and also account for the majority of storms making landfall further north along the US coastline.

Transformation rate anomalies across 26.5 °C in the North Atlantic are highly variable on timescales from intra-seasonal to multidecadal. A variable fraction of this variability is attributed to Q_{net}, using the WMT framework to calculate monthly volume anomalies that can be compared with observed anomalies. We identify the active and deadly hurricane season of 1998 (Pasch et al. 2001) as a year with particularly close correspondence between transformed and observed volume anomalies of substantial magnitude.

The variability of Q_{net} is dominated by anomalies in Q_{lh}, in turn associated with anomalies in wind speed and cloud fraction. Specifically, surface heat gain through air-sea fluxes increases in years when winds are light, humidity is low, and cloud cover is low, conditions linked to a positive phase of the AMO. Yuan et al. (2016) and Brown et al. (2016) describe modulation of the tropical AMO by low cloud and dust feedbacks.

The other major influences on intraseasonal variability of the warm water volume are likely anomalous ocean heat transport divergence, associated with changes in both the AMOC (Zhang et al. 2019, and references therein) and Ekman dynamics, both of which are related in turn to the same anomalous winds that modulate the turbulent surface fluxes. Heat transport changes associated with the 30% AMOC downturn of 2010 potentially account for the observed increase of warm water volume in that exceptional year.

This analysis using the WMT framework thus suggests that, at interannual and decadal timescales, coordinated physical mechanisms related to cloud cover and surface winds explain recent warming of the tropical North Atlantic, conducive to more intense hurricane seasons and more frequent landfall of destructive storms.

Acknowledgements

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References

Balaguru, K., Leung, L. R., & Yoon, J. H. (2013). Oceanic control of northeast Pacific hurricane activity at interannual timescales. *Environmental Research Letters*, *8*(4), 044009.

Behringer, D. W., & Xue, Y. (2004, January). Evaluation of the global ocean data assimilation system at NCEP: The Pacific Ocean. In Proc. Eighth Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface. Seattle, Wash: AMS 84th Annual Meeting, Washington State Convention and Trade Center.

Bellomo, K., Clement, A. C., Murphy, L. N., Polvani, L. M., & Cane, M. A. (2016). New observational evidence for a positive cloud feedback that amplifies the Atlantic Multidecadal Oscillation. Geophysical Research Letters, 43(18), 9852-9859.

Bove, M. C., Elsner, J. B., Landsea, C. W., Niu, X., & O'Brien, J. J. (1998). Effect of El Niño on US landfalling hurricanes, revisited. Bulletin of the American Meteorological Society, 79(11), 2477-2482. 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.

Brown, P. T., Lozier, M. S., Zhang, R., & Li, W. (2016). The necessity of cloud feedback for a basin-scale Atlantic Multidecadal Oscillation. Geophysical Research Letters, 43(8), 3955-3963.

Bryden, H. L., King, B. A., McCarthy, G. D., & McDonagh, E. L. (2014). Impact of a 30% reduction in Atlantic meridional overturning during 2009-2010. Ocean Science, 10(4), 683-691.

Bryden, H. L., Johns, W. E., King, B. A., McCarthy, G., McDonagh, E. L., Moat, B. I., & Smeed, D. A. (2020). Reduction in ocean heat transport at 26 N since 2008 cools the eastern subpolar gyre of the North Atlantic Ocean. Journal of Climate, 33(5), 1677-1689.

Dailey, P.S., Zuba, G., Ljung, G., Dima, I.M., Guin, J. (2009), On the Relationship between North Atlantic Sea Surface Temperatures and U.S. Hurricane Landfall Risk. Journal of Applied Meteorology and Climatology 48, 111-129.

DeMaria, M. (1996). The effect of vertical shear on tropical cyclone intensity change. Journal of the atmospheric sciences, 53(14), 2076-2088.

Elsner, J. B., & Jagger, T. H. (2004). A hierarchical Bayesian approach to seasonal hurricane modeling. Journal of Climate, 17(14), 2813-2827. 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.

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.

Gray, W. M., Landsea, C. W., Mielke Jr, P. W., & Berry, K. J. (1992). Predicting Atlantic seasonal hurricane activity 6–11 months in advance. Weather and Forecasting, 7(3), 440-455.

Grist, J. P., S. A. Josey, R. Marsh, Y.-O. Kwon, R. J. Bingham, and A. T. Blaker (2014), The Surface-Forced Overturning of the North Atlantic: Estimates from Modern Era Atmospheric Reanalysis Datasets. J. Climate, 27, 3596-3618. doi: 10.1175/JCLI-D-13-00070.1

Groeskamp, S., Griffies, S.M., Iudicone, D., Marsh, R., Nurser, A.G., and J.D. Zika (2019). The water mass transformation framework for ocean physics and biogeochemistry. *Ann. Rev. Mar. Sci.*, 11 (1), 271-305.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., ... & Zhu, Y. (1996). The NCEP/NCAR 40-year reanalysis project. Bulletin of the American meteorological Society, 77(3), 437-472.

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.

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].

Kossin, J. P., Knapp, K. R., Vimont, D. J., Murnane, R. J., & Harper, B. A. (2007). A globally consistent reanalysis of hurricane variability and trends. Geophysical Research Letters, 34(4).

Kossin, J. P., Camargo, S. J., & Sitkowski, M. (2010). Climate modulation of North Atlantic hurricane tracks. Journal of Climate, 23(11), 3057-3076.

Marsh. R., de Cuevas, B. A., Coward, A. C., Nurser, A. J. G., and S. A. Josey (2005). Water mass transformation in the North Atlantic over 1985-2002 simulated in an eddy-permitting model. *Ocean Science*, 1, 127-144.

Marsh, R., S. A. Josey, B. A. de Cuevas, L. J. Redbourn, and G. D. Quartly (2008). Mechanisms for recent warming of the North Atlantic: Insights gained with an eddy-permitting model, *J. Geophys. Res*., 113, C04031, doi:10.1029/2007JC004096.

NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2020). https://www.ncdc.noaa.gov/billions/, DOI: 10.25921/stkw-7w73

Pasch, R. J., Avila, L. A., and J. L. Guiney (2001). Atlantic Hurricane Season of 1998. *Mon. Wea. Rev.*, 129, 3085-3123.

Shapiro, L. J., & Goldenberg, S. B. (1998). Atlantic sea surface temperatures and tropical cyclone formation. Journal of Climate, 11(4), 578-590.

Smeed, D. A., Josey, S. A., Beaulieu, C., Johns, W. E., Moat, B. I., Frajka-Williams, E., ... & McCarthy, G. D. (2018). The North Atlantic Ocean is in a state of reduced overturning. Geophysical Research Letters, 45(3), 1527-1533.

Walin, G. (1982). On the relation between sea-surface heat flow and thermal circulation in the ocean, *Tellus*, 34, 187-195.

Wang, C., Liu, H., Lee, S. K., & Atlas, R. (2011). Impact of the Atlantic warm pool on United States landfalling hurricanes. *Geophysical Research Letters*, *38*(19).

Wang, C., Dong, S., Evan, A. T., Foltz, G. R., & Lee, S. K. (2012). Multidecadal covariability of North Atlantic sea surface temperature, African dust, Sahel rainfall, and Atlantic hurricanes. Journal of Climate, 25(15), 5404-5415. Walin, G. (1982). On the relation between sea-surface heat flow and thermal circulation in the ocean. Tellus, 34(2), 187-195.

Yuan, T., Oreopoulos, L., Zelinka, M., Yu, H., Norris, J. R., Chin, M., ... & Meyer, K. (2016). Positive low cloud and dust feedbacks amplify tropical North Atlantic Multidecadal Oscillation. Geophysical Research Letters, 43(3), 1349-1356

Zhang, R., & Delworth, T. L. (2006). Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes. Geophysical Research Letters, 33(17).

Zhang, R., Sutton, R., Danabasoglu, G., Kwon, Y.-O., Marsh, R., Yeager, S.G., Amrhein, D.E., and C.M. Little (2019). A review of the role of the Atlantic Meridional Overturning Circulation in Atlantic Multidecadal Variability and associated climate impacts. *Rev. Geophys*., 57. https://doi.org/10.1029/2019RG000644