ENVIRONMENTAL RESEARCH
LETTERS

ACCEPTED MANUSCRIPT • OPEN ACCESS

Increasing tropical cyclone intensity and potential intensity in the subtropical Atlantic around Bermuda from an ocean heat content perspective 1955- 2019

To cite this article before publication: Samantha Hallam *et al* 2021 *Environ. Res. Lett.* in press https://doi.org/10.1088/1748-9326/abe493

Increasing tropical cyclone intensity and potential intensity in the subtropical Atlantic around Bermuda from an ocean heat content perspective 1955- 2019

Samantha Hallam* [1,2], Mark Guishard[3,4], Simon A. Josey[1], Pat Hyder[5], Joel Hirschi[1]

1. National Oceanography Centre, European Way, Southampton, SO14 3ZH
2. University of Southampton, National Oceanography Centre, European Way, Southampton, SO14 3ZH
3. Bermuda Institute of Ocean Sciences, 17 Biological Station, St. George's GE 01, Bermuda
4. Bermuda Weather Service, Bermuda Airport Authority, St. George's DD03, Bermuda
5. Met Office, Fitzroy Road, Exeter, EX1 3PB

*Corresponding Author: Samantha Hallam, University of Southampton, National Oceanography Centre, European Way, Southampton, SO14 3ZH, s.hallam@noc.soton.ac.uk

Abstract

We investigate tropical cyclone (TC) activity and intensity within a 100km radius of Bermuda between 1955 and 2019. The results show a more easterly genesis over time and significant increasing trends in tropical cyclone intensity (maximum wind speed (Vmax)) with a decadal Vmax median value increase of 30kts from 33 to 63kts ($r=0.94$, $p=0.02$), together with significant increasing August, September, October (ASO) sea surface temperature (SST) of 1.1°C (0.17 °C per decade) $r= 0.4$ ($p<0.01$) and increasing average ocean temperature between 0.5–0.7°C (0.08-0.1°C per decade) $r=0.3$($p<0.01$) in the depth range 0-300m. The strongest correlation is found between TC intensity and ocean temperature averaged through the top 50m ocean layer ($\overline{T_{50m}}$) $r=0.37$ ($p<0.01$).

We show how tropical cyclone potential intensity estimates are closer to actual intensity by using $\overline{T_{50m}}$ as opposed to SST using the Bermuda Atlantic Timeseries Hydrostation S dataset. We modify the widely used sea surface temperature potential intensity index by using $\overline{T_{50m}}$ to provide a closer estimate of the observed minimum sea level pressure (MSLP), and associated Vmax than by using SST, creating a $\overline{T_{50m}}$ potential intensity ($\overline{T_{50m}}$_PI) index. The average MSLP difference is reduced by 12mb and proportional ($r=0.74$, $p<0.01$) to the SST/$\overline{T_{50m}}$ temperature difference. We also suggest the index could be used over a wider area of the subtropical/tropical Atlantic where there is a shallow mixed layer depth.

1. Introduction

In September 2019 Hurricane Humberto was the latest Category 3 hurricane to impact Bermuda, with 100 knot winds and causing power outage to over 80% of the island, and there have been several other intense hurricanes impacting the island in the recent past: Fabian (2003), Gonzalo (2014), Nicole (2016) and Paulette (2020).

Observed Atlantic hurricane frequency has been found to correlate with the variability of sea surface temperatures on seasonal (Hallam et al., 2019) to multidecadal timescales, particularly as measured by the Atlantic Multi-decadal Variability (AMV) index (Goldenberg et al., 2001), which is the North Atlantic area-averaged (0–60°N, 0–

80°W) Sea Surface Temperature Anomaly (SSTA). Greater hurricane frequency during warm years of the AMV is also likely due to reduced vertical wind shear and lower sea-level pressure patterns, which are correlated with positive SSTA (through greater ocean-air heat fluxes) (Klotzbach, 2007). As hurricanes intensify by extracting energy from the warm ocean surface via air-sea sensible and latent heat fluxes, the underlying SSTs and upper ocean thermal structure are critical for their development and intensification (Emanuel, 1999, Emanuel, 1987, Shay et al., 2000, Huang et al., 2015, Lloyd and Vecchi, 2011, Domingues et al., 2019, Mainelli et al., 2008). When a TC intensifies the SST reduces through surface cooling by evaporation and associated convection, vertical mixing and upwelling of cooler subsurface water. Price (2009) find that the depth averaged ocean temperature preceding the passage of the TC, averaged from the surface to the expected cyclone induced mixing depth, is a good indication of SST during TC intensification and better reflects the layer which supplies the heat for evaporation. How the initial upper ocean thermal profile impacts on intensification is also a function of TC intensity, translation speed and size, sometimes referred as ocean coupling effect (OCE) (Lloyd and Vecchi, 2011, Huang et al., 2015). Other studies have found rising SSTs increase TC maximum potential intensity (Emanuel, 1987, Webster et al., 2005, Villarini and Vecchi, 2013) and positive Ocean Heat Content (OHC) anomalies increase the hurricane intensity and track length (Mainelli et al., 2008, Balaguru et al., 2018, Trenberth et al., 2018, Lin et al., 2014).

Tropical cyclone (TC) intensity, defined by the minimum sea level pressure (MSLP) at the TC centre and the maximum sustained wind speed (MSW) at 10m, can be affected by internal physical processes and the storm's interaction with the environment. Although predicting individual tropical cyclone intensity remains difficult, it is accepted that thermodynamic limits to intensity exist, provided that there is no negative interaction between a storm and its environment (Emanuel, 1999). Limit calculations (potential intensity) are fairly straightforward as they are based on SST and the vertical structure of the atmosphere (Emanuel, 1995). The upper limit is based on the maximum heat input from the ocean to the atmosphere and the thermodynamic efficiency related to the difference between the SST and the temperature at the level of neutral buoyancy. While PI is a good predictor of TC maximum intensity, it is a poor predictor of actual TC intensity as most TCs fail to obtain intensities near their PI (Lin et al. (2013), Bender et al. (2007), Wang and Wu (2004)). Bender et al. (2007) found upper ocean coupling significantly improved TC intensity predictions measured by MSLP. Here we use the widely accepted potential intensity (PI) estimate based on SST (SST_PI)(Emanuel, 1999) but also adapt it to create an average ocean temperature PI index based on initial ocean temperature through the top 50m layer, to estimate TC $\overline{T_{50m}}$_PI.

Oceanographic measurements from the Bermuda Atlantic Times series (BATS) Hydrostation S (Michaels and Knap, 1996, Phillips and Joyce, 2007), tropical cyclone data from HURDAT2 (Landsea and Franklin, 2013) and atmospheric radiosonde soundings from the Bermuda Weather Service are used to investigate the tropical cyclone activity and intensity around Bermuda for the period 1880 to 2019. GODAS ocean re-analysis data (Behringer et al., 1998) provide SST and sub surface temperatures for the wider North Atlantic.

2. Data and methodology

Tropical cyclones were analysed within a radius of 100km from Bermuda with a search centre at 32.4N and 64.8W, on the basis the storms could impact Bermuda (Bell and Ray, 2004). The observed Atlantic tropical cyclone and hurricane track data for the years 1880 to 2019 were obtained from HURDAT2, the revised Atlantic hurricane database (Landsea and Franklin, 2013). The data includes 6 hourly information on location, MSLP and MSW, although data availability is more limited in the early part of the record. In the data interpretation we are mindful that in the presatellite era (between 1878 and 1965) an upward adjustment of hurricane counts (and associated intensity adjustment) may be needed due to the sparse density of reporting ship traffic (Vecchi and Knutson, 2011).

The BATS Hydrostation S Time-Series Site is located in the oligotrophic northern Sargasso Sea gyre about 26 km southeast of the island of Bermuda (32 °10′N, 64° 30′W) and provides hydrographic parameters since 1954. We use the surface and sub surface temperature profiles (0-300m), which are collected on a biweekly to monthly basis, to calculate surface temperature and $\overline{T_n}$(average ocean temperature over the depth) for the period. For each tropical cyclone, the temperature and depth data were obtained from conductivity, temperature and depth (CTD) instruments preceding its passage into the Bermuda area, which ranged from 1 to 33 days.

TC maximum potential intensity based on SST, which provides an estimate of the theoretical upper limit of TC intensity, was calculated based on the method and code (http://emanuel.mit.edu/products) developed by Emanuel (1999) which uses the energy cycle of the storm to estimate the maximum possible surface wind speed and also the minimum central pressure. It can be written in convective available potential energy (CAPE) terms (Emanuel, 1994, Bister and Emanuel, 2002)

$$V^2 = \frac{C_k}{C_D}\frac{T_s}{T_0}\,(CAPE^* - CAPE) \qquad (1)$$

where V is the maximum surface wind speed, C_k and C_D are the exchange coefficients for enthalpy and drag, T_s and T_0 are the temperatures at the sea surface and mean outflow temperature, CAPE* is the convective available potential energy of air lifted from saturation at sea level in reference to the environmental sounding, and CAPE represents the sounding at the radius of the maximum winds. A positive difference $(CAPE^* - CAPE)$ indicates a significant air-sea enthalpy flux into the atmosphere (mostly driven by latent heat flux) and is the environment required to assist tropical cyclone maintenance.

In the evaluation of (1) the surface pressure at the radius of the maximum winds is calculated to provide the saturation mixing ratio necessary for CAPE* using equation (6) of Emanuel (1995)

$$c_p\, T_s \ln\frac{p_0}{p_m} = \frac{1}{2}\,V^2 + CAPE \qquad (2)$$

c_p is the heat capacity at constant pressure, p_0 is the ambient surface pressure and p_m is the surface pressure at the radius of the maximum winds. CAPE is calculated using the mixing ratio and vertical temperature profile. Radiosonde soundings from the Bermuda

Weather Service Station at LF Wade International Airport (WMO station identifier code 78016), were used to provide the vertical temperature profile and mixing ratio data. The atmospheric profiles preceded the passage of the storm to represent the undisturbed environment (Emanuel et al., 2004). For comparison to the potential intensity estimates, actual V and minimum central pressure of the TC were taken from the HURDAT2 data.

3. Results

Hurricane season activity and intensity

There were 93 tropical cyclone tracks which passed within 100km of Bermuda between 1880 and 2019 (Fig. 1). The majority of these tracks originate in the North Atlantic main development region (10-20°N, 20-80°W). There is a difference in the TC genesis area between 1980 -1999 (Fig. 1(ii)) where the majority of tracks originate west of 50°W, whereas between 2000 – 2019 the majority of tracks originated further east just off Africa around 20-30°W (Fig. 1(iii)). The different genesis pattern between the 2 periods is consistent with the all Atlantic track trend which shows a 62% increase in TC genesis (from 26 to 42 tracks) off Africa (10-20N, 0-30W) in the period 2000-2019 compared to 1980-1999 (Fig. 1(iv) and (v)). In an attempt to understand the more easterly genesis in the later period, from an ocean perspective, the difference in the prevalent ASO SSTs between the 1980s and 2010s was assessed Fig. 2 (upper). An SST warming is shown in the later period of up to 0.9°C off the west coast of Africa at 20°N 20°W, in addition there is an $\overline{T_{50m}}$ warming, Fig. 2 (lower), off the coast of Africa (10-20N, 10-15W) of up to 1.1°C, potentially related to a reduced upwelling. The SST increase results in a northward shift in the 26-28°C SST isotherms, which is consistent with increasing the potential for TC genesis in the eastern part of the Atlantic which requires a minimum SST of 26°C (Defforge and Merlis (2017), Crnivec et al. (2016), Gray (1968)). The more easterly genesis may also be associated with changes in atmospheric variables (not explored here), such as vertical wind shear, mid-level moisture or African easterly waves (AEW). In the Atlantic, weak vertical wind shear favourable for tropical cyclone development is associated with warmer SSTs (Klotzbach et al., 2018, Klotzbach, 2007, Hallam et al., 2019). Warmer SSTs weaken the subsidence associated with the subtropical high which consequently weakens the trade winds and associated vertical shear (Klotzbach, 2007). In terms of AEW, Patricola et al. (2018) suggest that AEW may not influence basin wide TC variability and instead AEW and TC variability may both be driven by ocean variability. Kouadio et al. (2010) also find that a dipole in SST could contribute to enhanced continental convergence. In combination these factors may help explain the more easterly TC genesis observed.

In terms of tropical cyclone intensity, Fig. 3a shows the tropical cyclones within 100km of Bermuda from 1880-2019. However, the work of Vecchi and Knutson (2011) highlights that in the pre-satellite era (between 1878 and 1965) a significant upward adjustment of hurricane counts may be needed before 1965 to account for the low density of reporting ship traffic. The research indicates that the under recording is most likely to relate to weaker tropical cyclones which are less likely to have been reported by ships (and would reduce the average intensity). More reliable is the significant increasing trend (Fig. 3a) in tropical cyclone intensity between 1955 and 2019, r=0.4 (p=0.02) (when oceanographic data is also available from the BATS Hydrostation S site), where an increase in MSW of 34 kts over the period is observed (5.2 kts per decade). The rate of increase in MSW between 1980-2019 is higher with an increase

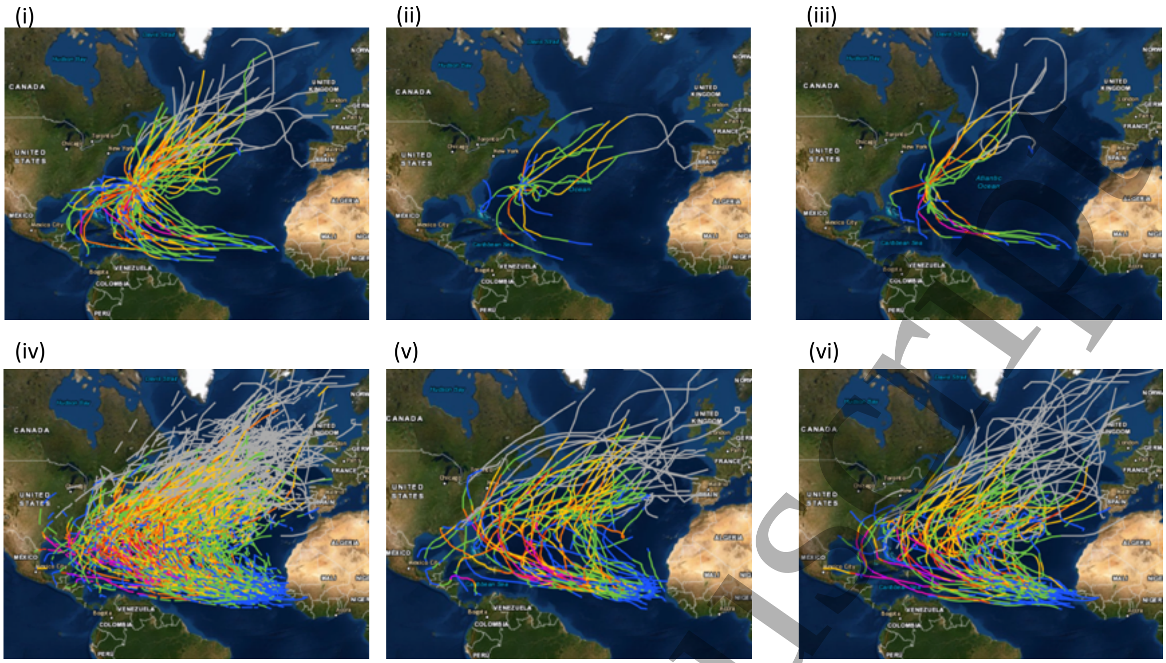

Fig. 1 Tropical cyclone tracks within 100km of Bermuda. (i) 1880 – 2019, (ii) 1980 – 1999, (iii) 2000 – 2019. Atlantic tropical cyclone tracks (iv) 1880-2019 (v) 1980-1999 (vi) 2000 – 2019

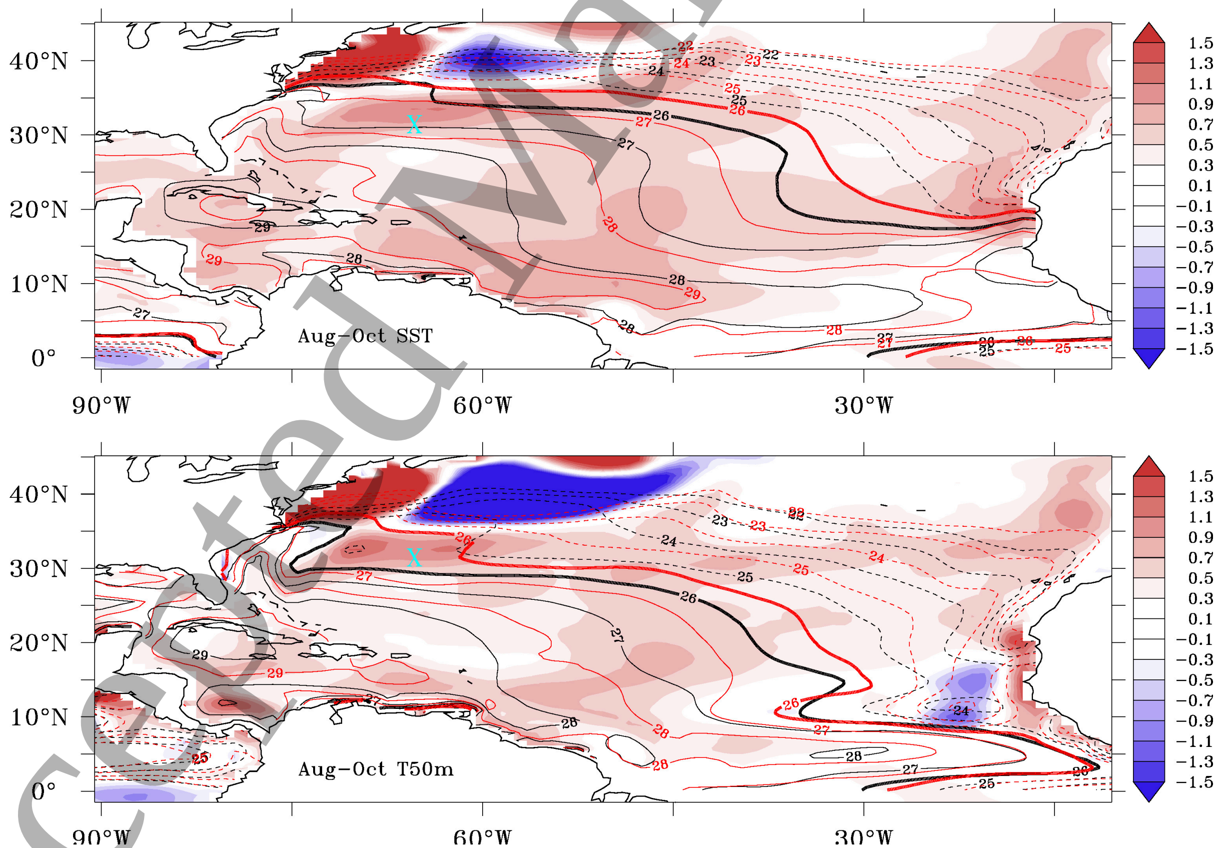

Fig. 2 ASO SST difference for the period 2010-2019 compared to 1980-1990 (upper), contours show the ASO SSTs for the 1980s (black) and 2010s (red), ASO $\overline{T_{50m}}$ temperature difference for the period 2010-2019 compared to 1980-1990 (lower) contours show the ASO $\overline{T_{50m}}$ for the 1980s (black) and 2010s (red) X indicates the location of Bermuda.

from 42 to 72 kts observed (7.7kts per decade), r=0.4 (p=0.01). The box plot for the period 1955-2019 also highlights the increasing trend in intensity (Fig. 3b) where there is a significant increasing trend in the decadal Vmax median value (r=0.94, p=0.02) of 30kts (4.9kts per decade) from 33 to 63kts (1955-2019). The Vmax trend has also been analysed comparing the Atlantic Multidecadal Oscillation AMO cold period (1970 - 1994) to the AMO warm period (1995-2019) where we find an increase of 18kts from 45 to 63kts (Supplementary Fig. 1).

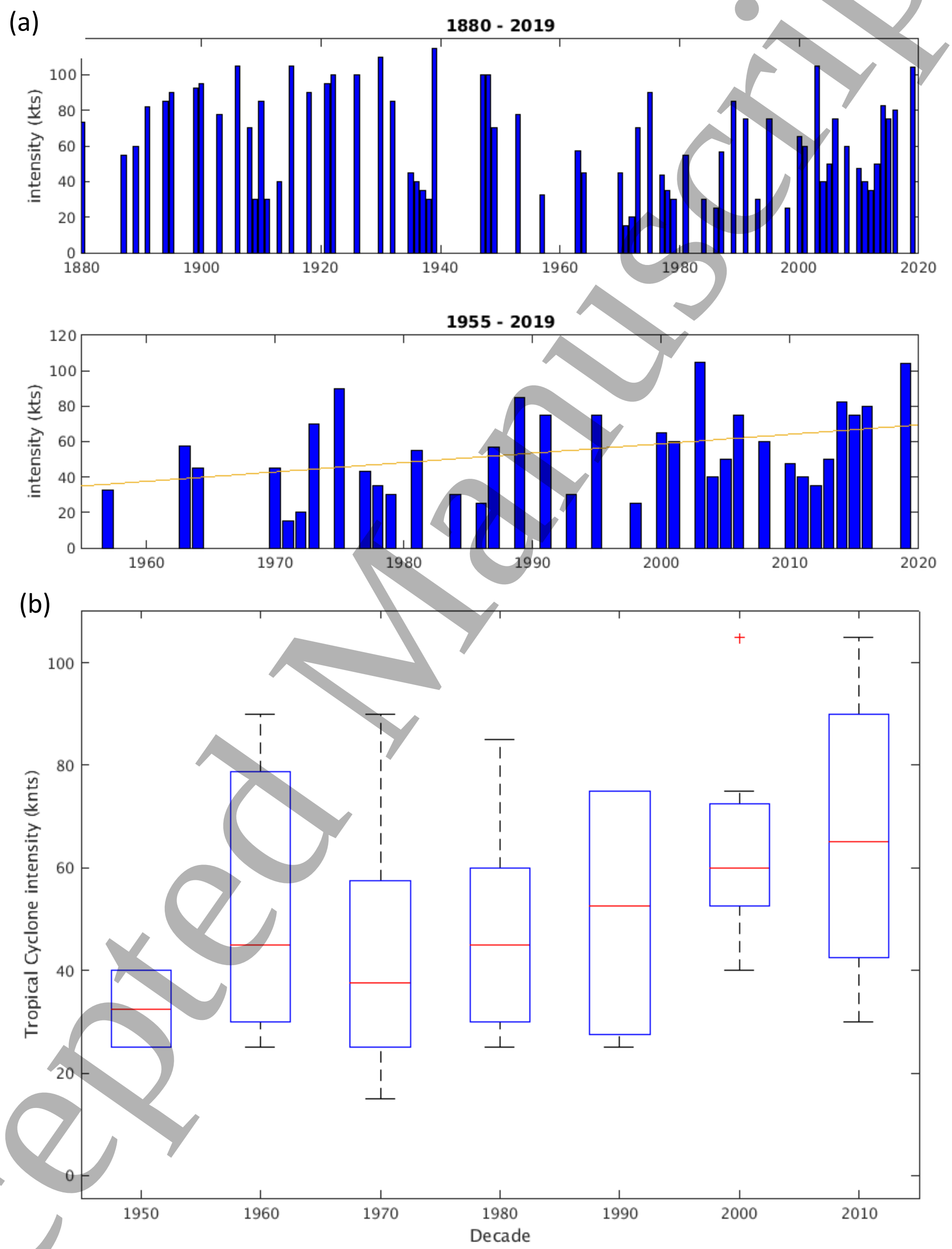

Fig. 3 (a)Tropical Cyclone intensity for tracks within 100km of Bermuda for the periods 1880 – 2019 and 1955 – 2019. Orange line indicates linear trend for the period. (b) Tropical Cyclone intensity box plot for tracks within 100km of Bermuda from 1955 to 2019.

Bermuda Atlantic Time Series

To understand the changes in the August, September, October (ASO) SST and average ocean temperature ($\overline{T_n}$) in the Bermuda area a timeseries of the BATS Hydrostation S data is used for the period 1955 to 2016 (Fig. 4). Interannual variability is evident for SST and across all the $\overline{T_n}$ levels from 25m to 300m which are evaluated here. $\overline{T_n}$ is calculated as the average temperature across the depth profile from the surface. Increasing trends are highlighted via the 5 year running means. The largest significant increase in temperature between 1955 and 2016 is seen in the ASO SST of 1.1°C (0.17 °C per decade) r= 0.4 (p<0.01) where there has been an increase from 26.6°C to 27.7°C. Significant increases are also seen in all the ASO $\overline{T_n}$ levels with an increase between 0.5 – 0.7°C (0.08-0.1°C per decade), with increases for $\overline{T_{50m}}$ from 25.4°C to 26°C, r=0.3 (p<0.01), and for $\overline{T_{200m}}$ 22.0°C to 22.6°C, r=0.31 (p<0.02). The trends are higher if the period 1980-2016 is considered where there is a increase from 0.32°C to 0.27°C per decade between the surface and $\overline{T_{300m}}$ respectively, r=0.4 (p<0.01). Pearson correlation coefficient was used to assess statistical significance.

GODAS reanalysis data for the North Atlantic (Fig. 2), also shows increasing temperatures of over 0.9°C in the ASO SST and $\overline{T_{50m}}$ layers between the 1980s and 2010s, in the western part of the subtropical gyre (30-35N,60-70W), an area characterised by clockwise circulation. The increasing temperatures led to a 1500km ENE movement in the $\overline{T_{50m}}$ 26°C isotherm, from the south to the north of Bermuda, in the latter period (2010-2019). Stevens et al. (2020) also find an increase in the OHC in the upper ocean in the western subtropical gyre between 2010-2018 which is anti-correlated with a reduction in subtropical mode water formation, a vertically homogeneous water mass. Around 35-40N, 50-70W (Fig. 2) there is southward shift in the 22-25°C isotherms (2010-2019), most pronounced at the $\overline{T_{50m}}$ level, potentially associated with a shift in the inter gyre location and likely contributor to the convergence of heat observed further south.

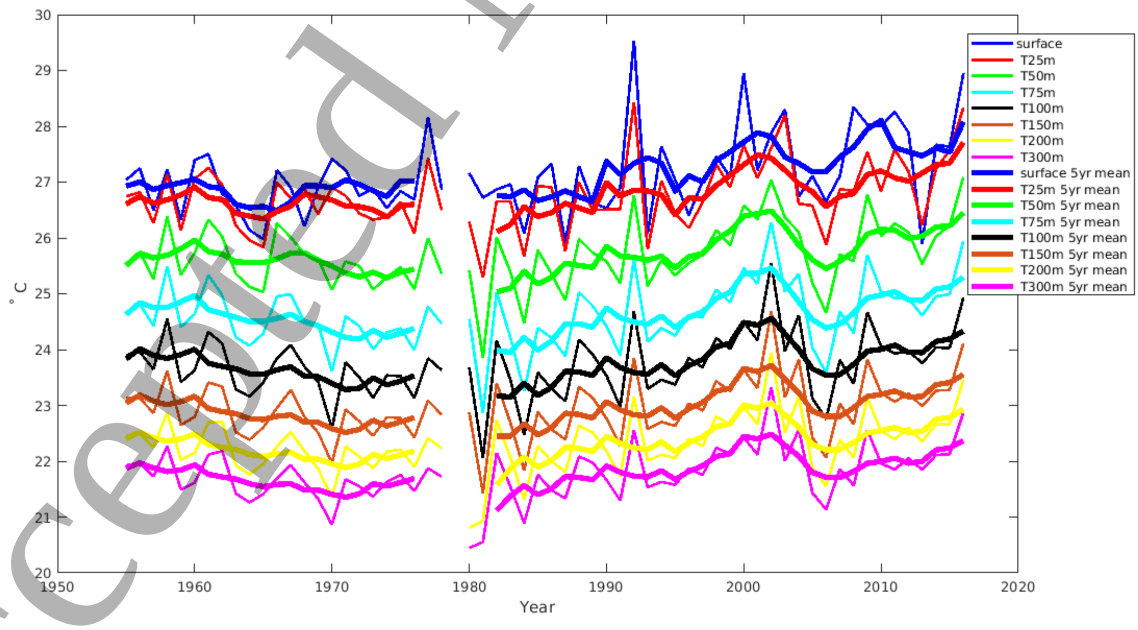

Fig. 4 ASO SST and $\overline{T_n}$ timeseries from the Bermuda Atlantic Time series Hydrostation S for the period 1955 – 2016

When the ASO SST and $\overline{T_n}$ BATS timeseries is then correlated with TC intensity in the Bermuda area (supplementary Fig. 2a) significant correlations are seen at all levels with the strongest correlation at $\overline{T_{50m}}$, $\overline{T_{100m}}$ and $\overline{T_{150m}}$ r=0.38 (p<0.01), based on the 41 TC observations. SST has the weakest but still significant correlation at r=0.3 (p=0.02). These results highlight the importance of upper ocean temperature profile ($\overline{T_n}$) to TC intensity and suggest that the increasing trend in the ASO SST and $\overline{T_n}$is driving the increase in tropical cyclone intensity seen (Fig. 3) in the subtropical area around Bermuda.

Potential intensity estimates using SST and $\overline{T_n}$

As hurricane intensity is linked to SST and ocean thermal structure, we compare the actual maximum wind speed (Vmax) of each tropical cyclone between 1955 and 2019 with SST and $\overline{T_n}$, as measured at the BATS Hydrostation S site (Fig. 5) from the data immediately preceding the TC event. A significant correlation is seen between SST and Vmax (based on the Vmax for 46 TC observations), and between $\overline{T_n}$ and Vmax at depths(n) of 25m, 50m, 75m (Fig. 5 and supplementary Fig. 2b), with the strongest significant relationship at $\overline{T_{50m}}$, where r=0.37 (p=0.01).

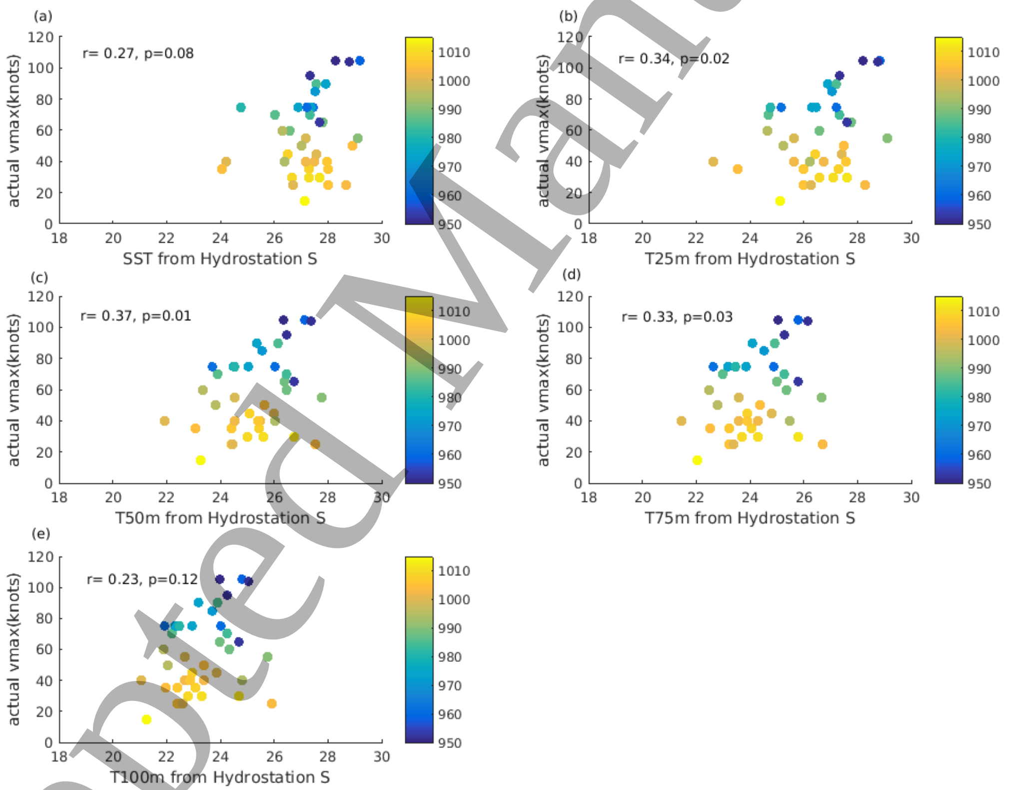

Fig. 5 Tropical Cyclone maximum wind (Vmax) and SST or $\overline{T_n}$, (a) SST, (b) $\overline{T_{25m}}$, (c) $\overline{T_{50m}}$, (d) $\overline{T_{75m}}$, (e) $\overline{T_{100m}}$, for tropical cyclones within a 100km radius of Bermuda 1955 – 2019. Colorbar units MSLP (mb)

The results from Fig. 5 and supplementary Fig. 2 show that $\overline{T_{50m}}$ is most closely correlated with Vmax. This suggests that 50m is the expected cyclone induced mixing depth resulting from vertical mixing and upwelling of cooler subsurface waters, which would be a good indication of SST during TC passage (Price, 2009), and represents the

SST experienced by the TC core. As an example, the ocean temperature profile preceding and after TC Paulette in September 2020 (supplementary Fig. 3) shows a deepening of the mixed layer depth to 50m after the passage of the TC. In line with this, and the approach adopted by Lin et al. (2013) who use an ocean coupling PI in their analysis in the western North Pacific, we have modified the sea surface temperature potential intensity index to create a potential intensity index based on $\overline{T_{50m}}$ ($\overline{T_{50m}}$_PI) (3)

$$V_{\overline{T50m}}{}^{2} = \frac{C_k}{C_D}\frac{\overline{T_{50m}}}{T_0}\left(CAPE^{*} - CAPE\right) \qquad (3)$$

where $\overline{T_{50m}}$ is the average temperature through the top 50m ocean layer and $V_{\overline{T50m}}$ is the maximum wind speed. The main difference between V and $V_{\overline{T50m}}$ however, results from the change in computed CAPE due to the different amounts of moist entropy increase from air-sea fluxes. Replacing Ts with $\overline{T_n}$ (e.g. $\overline{T_{50m}}$) will change the buoyancy of air parcels, resulting in a lower V. Again in the evaluation of (3) the surface pressure at the radius of the maximum winds is calculated to provide the saturation mixing ratio necessary for CAPE* using an adapted version of equation (6) of Emanuel (1995)

$$c_p\,\overline{T_{50m}}\,\ln\frac{p_0}{p_m} = \frac{1}{2}\,V_{\overline{T50m}}{}^{2} + CAPE \qquad (4)$$

We use equation 3 and 4 to estimate potential minimum pressure for the tropical cyclones within 100km of Bermuda between 1955 and 2019 and compare to estimates using SST (Fig. 6).

(a) (b)

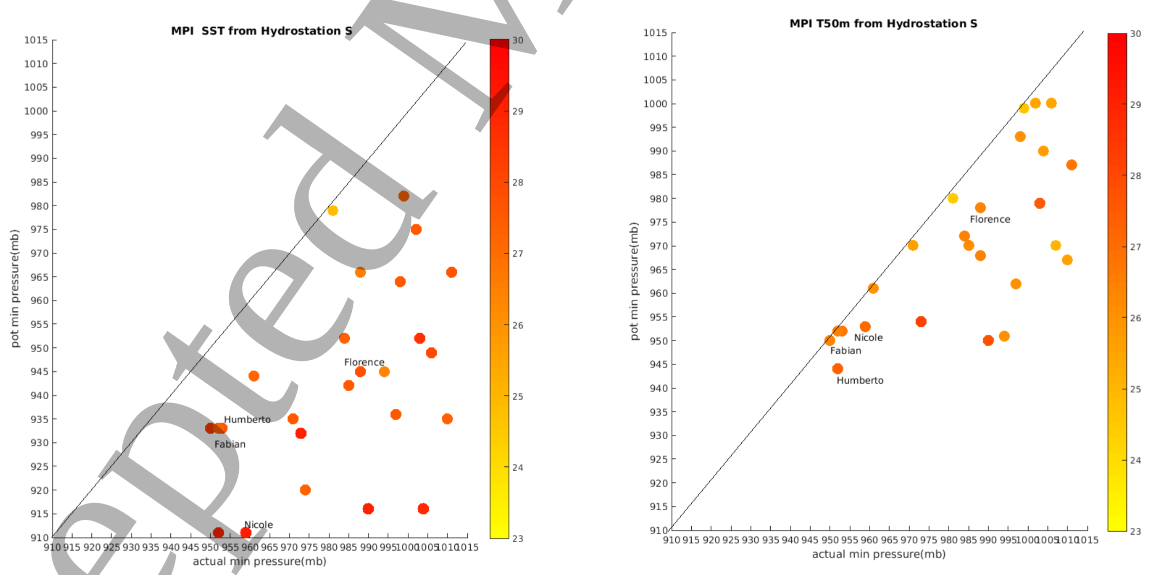

Fig. 6 Tropical cyclone minimum pressure – potential intensity vs actual intensity 1955 – 2019 for tracks passing within 100km radius of Bermuda. (a) SST (b) $\overline{T_{50m}}$. Colorbar units temperature (°C)

The results show that when $\overline{T_{50m}}$(Fig. 6b) is used to calculate the theoretical minimum pressure, the results are closer to the actual minimum pressure recorded than when SST (Fig. 6a) is used. TCs Humberto, Fabian, Nicole and Florence are labelled on Fig. 6 as examples. SST_PI has a correlation (R^2 = 0.22, slope = 0.49) for minimum pressure,

$\overline{T_{50m}}$_PI has a higher correlation (R^2 = 0.49, slope = 0.6) for minimum pressure. As well as explaining 49% of the variance, the $\overline{T_{50m}}$_PI also reduces the TC minimum pressure difference compared to SST_PI from 27mb to 15mb. In all instances the minimum pressure difference between actual and predicted is lower using $\overline{T_{50m}}$compared to SST (supplementary Fig. 4a). There are some instances where $\overline{T_{50m}}$_PI or SST_PI is very close to the actual PI typically where SST or $\overline{T_{50m}}$ is below 25.5C. TC reaching their PI is rare although Emanuel (2000) do find that in the Atlantic the decline of potential intensity can be sudden, associated with sharp SST gradients, and the decline of actual storm intensity cannot keep pace resulting in instances where potential intensity can be close to or lower than actual intensity. The TCs here, where $\overline{T_{50m}}$_PI or SST_PI is close to the actual intensity, had passed their maximum intensity so this may explain what is observed in the results. Overall $\overline{T_{50m}}$_PI provides a closer prediction of actual minimum pressure which could be useful for forecasting purposes.

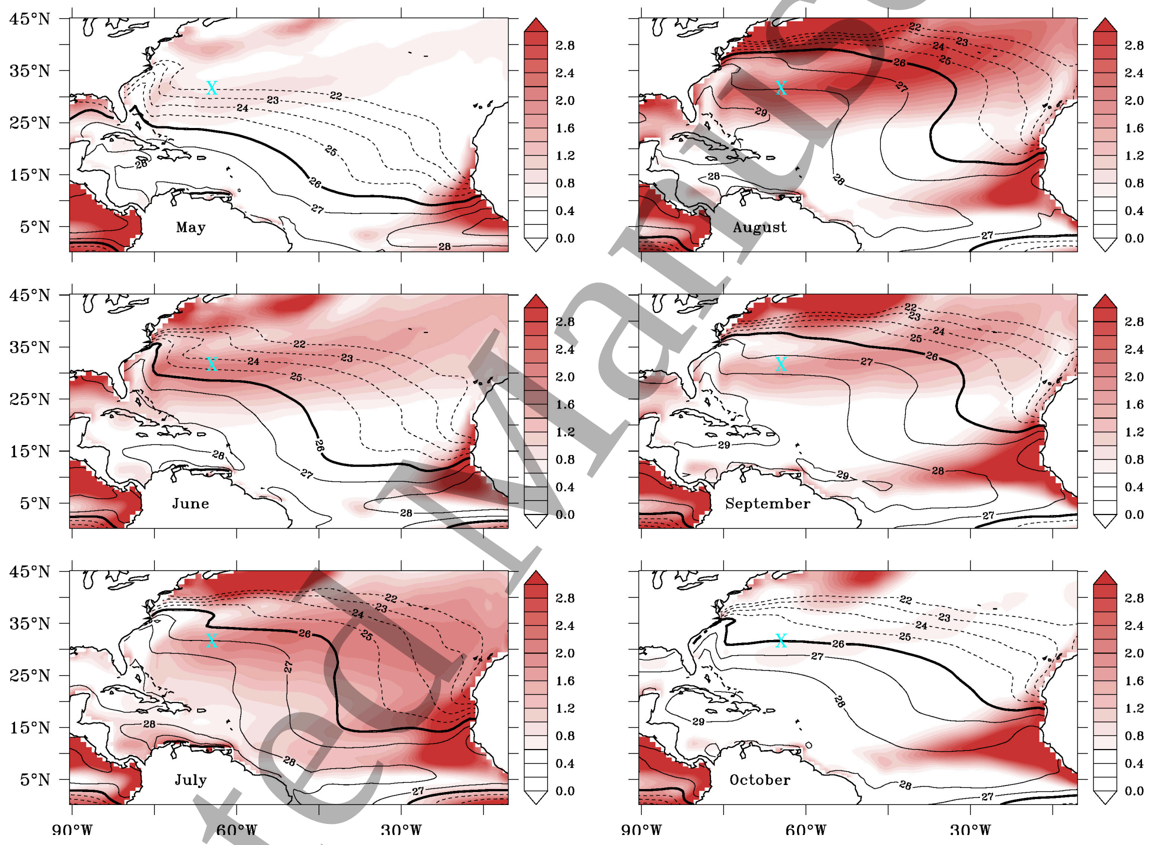

Fig. 7 Monthly averaged SST (contours (°C)) and temperature difference between SST and $\overline{T_{50m}}$(shading (°C)) from May to October for the period 1980-2019. Location of Bermuda (X)

For the TC events between 1955-2019 within 100km of Bermuda the average difference between SST and $\overline{T_{50m}}$ was 1.8°C with a range from 0.1 to 3.89°C and a difference over 0.8°C in 90% of TC instances. Supplementary Fig. 4b illustrates that the reduction in the potential minimum pressure difference using $\overline{T_{50m}}$ is significantly proportional to the difference between SST and $\overline{T_{50m}}$ (r=0.74, $p<0.01$) explaining 54% of the variance. The reduction in the minimum pressure difference observed highlights that where the mixed layer depth is shallow (<50m), $\overline{T_{50m}}$ can play an important role in providing a closer prediction of TC MSLP and associated MSW. Fig. 7 provides further analysis and shows the temperature difference between SST and $\overline{T_{50m}}$ between May and December across the North Atlantic (shading). In the subtropics, north of 25N, the temperature difference is between 1-3°C (pink and red shading) from June to September when the mixed layer depth is shallower due to surface warming. South of 25N the temperature difference between SST and $\overline{T_{50m}}$ is less than 1°C from May to October, except off the west coast of Africa (10-20N, 15-30W) due to coastal upwelling, and during July. Using $\overline{T_{50m}}$ to calculate TC PI where the difference between SST and $\overline{T_{50m}}$ is more than 1°C (Fig. 7 pink and red shading) could reduce the MSLP over prediction by a minimum of 15 mb (supplementary Fig. 4b).

4. Discussion and Summary

In this study we have reviewed TCs in the Bermuda area from 1955 -2019 and highlighted the more easterly genesis of tracks in the period 2000-2019 compared to 1980-1999, in line with the all Atlantic trend, and suggest, from an ocean perspective, that this is related to the increase (up to 0.9°C) in ASO SST and $\overline{T_{50m}}$ in the eastern Atlantic off the west coast of Africa (10-20N, 10-20W). In addition to the more easterly track genesis we have observed a statistically significant increase (r=0.94, p=0.02) in TC intensity in the Bermuda area with an increase in the Vmax median value of 30kts (4.9kts per decade) from 33 to 63kts (1955-2019) and an increased trend observed for the period 1980-2019 of 7.7kts which is in line with the increase of 8kts per decade (1982-2009) observed over the wider Atlantic region by (Kossin et al., 2013, Kossin et al., 2007). We have associated the increase in TC intensity with the increasing SSTs and $\overline{T_n}$ in the Bermuda area as measured by the BATS Hydrostation S timeseries. The significantly increasing SST (1.1°C) and $\overline{T_n}$ (0.5 – 0.7°C) is aligned and correlated with (r=0.37, p<0.01), the increasing TC intensity observed over the time period 1955 – 2019 and consistent with other studies which suggest increasing hurricane intensity with rising ocean temperatures (Kossin et al., 2007, Emanuel, 1987, Kossin et al., 2013, Kossin et al., 2020). In the early part of the record (1960-1980), however, aerosols may have suppressed the SST/OHC and associated TC intensity (Villarini and Vecchi, 2013).

For the time period 1955-2019 we find TC intensity is most closely correlated with $\overline{T_{50m}}$ in the Bermuda area and most likely represents the SST which the TC core experiences. The findings of Huang et al. (2015), Lloyd and Vecchi (2011) and (Price, 2009) also find that the initial upper ocean thermal profile impacts on TC intensification. In the Pacific, Lin et al. (2013) found TC intensity most closely correlated with the ocean temperature profile through the upper 80m, as opposed to the upper 50m found here, possibly related to the fact that their study was conducted at lower latitude (10-30N). Using $\overline{T_{50m}}$ we find the TC MSLP prediction is closer to the actual value with the average prediction difference reduced by 12mb from 27mb to 15mb, and proportional (r=0.74, p<0.01) to the temperature difference between SST and $\overline{T_{50m}}$, a new finding here, and in accordance with Bender et al. (2007) who found ocean coupling improved MSLP predictions. Using $\overline{T_{50m}}$ to predict TC intensity improves TC MSLP prediction in the subtropical Bermuda area, where there is a shallow mixed layer depth from June to September, accordingly we suggest $\overline{T_{50m}}$ would also be useful for TC prediction in the subtropical Atlantic north of 25N and elsewhere in the tropical Atlantic when the SST/$\overline{T_{50m}}$ temperature difference is more than 1°C.

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**,** 4238-4247.

BEHRINGER, D. W., JI, M. & LEETMAA, A. 1998. An Improved Coupled Model for ENSO Prediction and Implications for Ocean Initialization. Part I: The Ocean Data Assimilation System. *Monthly Weather Review,* 126**,** 1013-1021.

BELL, K. & RAY, P. S. 2004. North Atlantic Hurricanes 1977–99: Surface Hurricane-Force Wind Radii. *Monthly Weather Review,* 132**,** 1167-1189.

BENDER, M. A., GINIS, I., TULEYA, R., THOMAS, B. & MARCHOK, T. 2007. The Operational GFDL Coupled Hurricane–Ocean Prediction System and a Summary of Its Performance. *Monthly Weather Review,* 135**,** 3965-3989.

BISTER, M. & EMANUEL, K. A. 2002. Low frequency variability of tropical cyclone potential intensity 1. Interannual to interdecadal variability. *Journal of Geophysical Research: Atmospheres,* 107**,** ACL 26-1-ACL 26-15.

CRNIVEC, N., SMITH, R. K. & KILROY, G. 2016. Dependence of tropical cyclone intensification rate on sea-surface temperature. *Quarterly Journal of the Royal Meteorological Society,* 142**,** 1618-1627.

DEFFORGE, C. L. & MERLIS, T. M. 2017. Evaluating the Evidence of a Global Sea Surface Temperature Threshold for Tropical Cyclone Genesis. *Journal of Climate,* 30**,** 9133-9145.

DOMINGUES, R., KUWANO-YOSHIDA, A., CHARDON-MALDONADO, P., TODD, R. E., HALLIWELL, G., KIM, H. S., LIN, I. I., SATO, K., NARAZAKI, T., SHAY, L. K., MILES, T., GLENN, S., ZHANG, J. A., JAYNE, S. R., CENTURIONI, L., LE HÉNAFF, M., FOLTZ, G. R., BRINGAS, F., ALI, M. M., DIMARCO, S. F., HOSODA, S., FUKUOKA, T., LACOUR, B., MEHRA, A., SANABIA, E. R., GYAKUM, J. R., DONG, J., KNAFF, J. A. & GONI, G. 2019. Ocean Observations in Support of Studies and Forecasts of Tropical and Extratropical Cyclones. *Frontiers in Marine Science,* 6.

EMANUEL, K. 2000. A Statistical Analysis of Tropical Cyclone Intensity. *Monthly Weather Review,* 128**,** 1139-1152.

EMANUEL, K., DESAUTELS, C., HOLLOWAY, C. & KORTY, R. 2004. Environmental Control of Tropical Cyclone Intensity. *Journal of the Atmospheric Sciences,* 61**,** 843-858.

EMANUEL, K. A. 1987. The dependence of hurricane intensity on climate. *Nature,* 326**,** 483-485.

EMANUEL, K. A. 1994. Atmospheric Convection. 580.

EMANUEL, K. A. 1995. Sensitivity of Tropical Cyclones to Surface Exchange Coefficients and a Revised Steady-State Model incorporating Eye Dynamics. *Journal of the Atmospheric Sciences,* 52**,** 3969-3976.

EMANUEL, K. A. 1999. Thermodynamic control of hurricane intensity. *Nature,* 401**,** 665.

GOLDENBERG, S. B., LANDSEA, C. W., MESTAS-NUNEZ, A. M. & GRAY, W. M. 2001. The recent increase in Atlantic hurricane activity: Causes and implications. *Science,* 293**,** 474-479.

GRAY, W. M. 1968. Global view of the origin of tropical disturbances and storms. *Monthly Weather Review,* 96**,** 669-700.

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**,** 896.
HUANG, P., LIN, I. I., CHOU, C. & HUANG, R.-H. 2015. Change in ocean subsurface environment to suppress tropical cyclone intensification under global warming. *Nature Communications,* 6**,** 7188.
KLOTZBACH, P. J. 2007. Revised Prediction of Seasonal Atlantic Basin Tropical Cyclone Activity from 1 August. *Weather and Forecasting,* 22**,** 937-949.
KLOTZBACH, P. J., III, C. J. S., COLLINS, J. M., BELL, M. M., BLAKE, E. S. & ROACHE, D. 2018. The Extremely Active 2017 North Atlantic Hurricane Season. *Monthly Weather Review,* 146**,** 3425-3443.
KOSSIN, J. P., KNAPP, K. R., OLANDER, T. L. & VELDEN, C. S. 2020. Global increase in major tropical cyclone exceedance probability over the past four decades. *Proceedings of the National Academy of Sciences,* 117**,** 11975.
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.
KOSSIN, J. P., OLANDER, T. L. & KNAPP, K. R. 2013. Trend Analysis with a New Global Record of Tropical Cyclone Intensity. *Journal of Climate,* 26**,** 9960-9976.
KOUADIO, Y. K., MACHADO, L. A. T. & SERVAIN, J. 2010. Tropical Atlantic Hurricanes, Easterly Waves, and West African Mesoscale Convective Systems. *Advances in Meteorology,* 2010**,** 284503.
LANDSEA, C. W. & FRANKLIN, J. L. 2013. Atlantic Hurricane Database Uncertainty and Presentation of a New Database Format. *Monthly Weather Review,* 141**,** 3576-3592.
LIN, I.-I., BLACK, P., PRICE, J. F., YANG, C.-Y., CHEN, S. S., LIEN, C.-C., HARR, P., CHI, N.-H., WU, C.-C. & D'ASARO, E. A. 2013. An ocean coupling potential intensity index for tropical cyclones. *Geophysical Research Letters,* 40**,** 1878-1882.
LIN, I. I., PUN, I.-F. & LIEN, C.-C. 2014. “Category-6” supertyphoon Haiyan in global warming hiatus: Contribution from subsurface ocean warming. *Geophysical Research Letters,* 41**,** 8547-8553.
LLOYD, I. D. & VECCHI, G. A. 2011. Observational Evidence for Oceanic Controls on Hurricane Intensity. *Journal of Climate,* 24**,** 1138-1153.
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**,** 3-16.
MICHAELS, A. F. & KNAP, A. H. 1996. Overview of the U.S. JGOFS Bermuda Atlantic Time-series Study and the Hydrostation S program. *Deep Sea Research Part II: Topical Studies in Oceanography,* 43**,** 157-198.
PATRICOLA, C. M., SARAVANAN, R. & CHANG, P. 2018. The Response of Atlantic Tropical Cyclones to Suppression of African Easterly Waves. *Geophysical Research Letters,* 45**,** 471-479.
PHILLIPS, H. E. & JOYCE, T. M. 2007. Bermuda’s Tale of Two Time Series: Hydrostation S and BATS. *Journal of Physical Oceanography,* 37**,** 554-571.
PRICE, J. F. 2009. Metrics of hurricane-ocean interaction: Vertically-integrated or vertically averaged ocean temperature? *Ocean Sciences,* 5**,** 351-368.
SHAY, L. K., GONI, G. J. & BLACK, P. G. 2000. Effects of a Warm Oceanic Feature on Hurricane Opal. *Monthly Weather Review,* 128**,** 1366-1383.

STEVENS, S. W., JOHNSON, R. J., MAZE, G. & BATES, N. R. 2020. A recent decline in North Atlantic subtropical mode water formation. *Nature Climate Change,* 10**,** 335-341.

TRENBERTH, K. E., CHENG, L., JACOBS, P., ZHANG, Y. & FASULLO, J. 2018. Hurricane Harvey links to Ocean Heat Content and Climate Change Adaptation. *Earth's Future*.

VECCHI, G. A. & KNUTSON, T. R. 2011. Estimating Annual Numbers of Atlantic Hurricanes Missing from the HURDAT Database (1878–1965) Using Ship Track Density. *Journal of Climate,* 24**,** 1736-1746.

VILLARINI, G. & VECCHI, G. A. 2013. Projected Increases in North Atlantic Tropical Cyclone Intensity from CMIP5 Models. *Journal of Climate,* 26**,** 3231-3240.

WANG, Y. & WU, C. C. 2004. Current understanding of tropical cyclone structure and intensity changes – a review. *Meteorology and Atmospheric Physics,* 87**,** 257-278.

WEBSTER, P. J., HOLLAND, G. J., CURRY, J. A. & CHANG, H. R. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science,* 309**,** 1844-1846.