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Future Changes in Active and Inactive Atlantic Hurricane Seasons in the Energy Exascale Earth System Model

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Key Points:

- We project future change in active and inactive Atlantic hurricane seasons driven by ENSO and the Atlantic Meridional Mode.
- Future Atlantic tropical cyclone (TC) frequency increases during active and inactive seasons, with greater increases in the active season.
- Increased potential intensity and relative humidity and decreased shear support stronger and more frequent TCs in the future.

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Abstract

North Atlantic tropical cyclones (TCs) have considerable interannual variability, with La Niña and the positive phase of the Atlantic Meridional Mode (AMM) tending to drive active hurricane seasons, and El Niño and the negative AMM often driving inactive seasons. Here, we analyze how active and inactive Atlantic hurricane seasons may change in the future using the high resolution Energy Exascale Earth System Model (E3SM). We performed atmosphere-only simulations forced by sea-surface temperature patterns characteristic of La Niña and the positive AMM jointly, and El Niño and the negative AMM jointly, in historical and future climates. Projected Atlantic TCs become more frequent in the future by approximately 34% during El Niño and negative AMM and by 66% during La Niña and positive AMM, with a significant increase in the portion of intense TCs. Warmer SSTs increase TC potential intensity, with reduced wind shear and increased mid-tropospheric humidity further supporting TC activity.

Plain Language Summary

Tropical cyclones (TCs) are among the most destructive natural disasters worldwide. Here, we assess how the frequency and intensity of TCs in the North Atlantic are projected to change in a warming climate. We performed high resolution global climate model simulations in which sea surface temperature patterns associated with active and inactive Atlantic hurricane seasons were applied in both historical and future climate scenarios. We found that Atlantic TCs are projected to become more frequent and intense in the future in both active and inactive seasons, with a greater intensification during active TC seasons. These results shed light on the importance of considering changes not only in the mean, but also in year-to-year variability, when analyzing future projections of TC activity.

1 Introduction

Tropical cyclones (TCs) are among the costliest natural disasters in the world, affecting more than 150 million people globally (Geiger et al., 2021). The frequency of TCs in the North Atlantic, as well as their corresponding impacts, have a considerable interannual variability. While the average Atlantic hurricane season produced 12.1 named tropical storms per year during 1981-2010 (Blunden & Boyer, 2021; Landsea & Franklin, 2013), the 2020 season produced 30 named storms, the most active on record (Blunden & Boyer, 2021). Meanwhile, only 4 named storms formed in the North Atlantic in 1983 (Landsea & Franklin, 2013), which was one of the least active seasons in recent decades. The large interannual variability of Atlantic TCs is often explained by the influence of large scale modes of climate variability both in the North Atlantic and remotely.

Two interannual modes of ocean-atmosphere variability that strongly influence Atlantic TC activity include the El Niño - Southern Oscillation (ENSO) and the Atlantic Meridional Mode (AMM). ENSO is characterized by sea-surface temperature anomalies (SSTAs) in the eastern-central equatorial Pacific. During El Niño events, warm eastern-central equatorial Pacific SSTAs shift tropical Pacific deep convection eastward, generating anomalies in the Walker circulation that enhance vertical wind shear in the North Atlantic, resulting in reduced Atlantic TC activity (Goldenberg & Shapiro, 1996; Gray, 1984). The opposite happens during La Niña, which commonly drives active Atlantic hurricane seasons. The ENSO-driven extremes in seasonal Atlantic TC activity have strong implications on TC landfall (Smith et al., 2007; Klotzbach, 2011) and damages, with La Niña causing 20 times greater TC-related damages in the U.S. than El Niño (Pielke & Landsea, 1999). The other primary driver of North Atlantic TC activity is the Atlantic Meridional Mode (AMM), which is characterized by anomalous meridional SST gradients in the tropical Atlantic (Chang et al., 1997; Chiang & Vimont, 2004; Servain et al., 1999). In particular, the positive phase of the AMM is characterized by warm SSTAs in the northern tropical Atlantic and cool SSTAs in the southern tropical Atlantic, and vice versa for the negative phase of the AMM. Positive AMM (AMMp) is associated with active Atlantic hurricane seasons, whereas the negative AMM (AMMn) tends to drive inactive Atlantic hurricane seasons (Kossin & Vimont, 2007; Vimont & Kossin, 2007). Notably, the SSTAs locally and south of the equator more strongly impact Atlantic TC development than local SSTAs alone.

The influence of ENSO and AMM on seasonal Atlantic TC activity can have compounding or compensating effects (Patricola et al., 2014). For example, co-occurring positive AMM and La Niña tend to drive a greater increase in Atlantic TC activity than one of the factors individually. However, either El Niño or negative AMM may be enough to increase the vertical wind shear to a threshold that substantially inhibits Atlantic TC development, leading to a decrease in TC activity. In addition, phases of ENSO and the AMM that individually drive opposing influences on Atlantic TC activity together tend to compensate and produce near-average Atlantic TC activity. Similarly, Klotzbach (2011) found that ENSO and the Atlantic Multidecadal Oscillation (AMO) together better explain Caribbean TC activity than the individual climate modes.

There is evidence that Atlantic TC activity has been changing in recent decades. North Atlantic TCs have been intensifying in observations, and climate models generally agree that this trend is projected to continue in the future (Knutson et al., 2020, 2019; Walsh et al., 2016). There is no consensus on whether TC frequency has been changing in recent decades (Klotzbach, 2006; Klotzbach et al., 2022; K. Emanuel, 2005; Chand et al., 2022; Webster et al., 2005). This is a challenging problem, as part of the observed changes can be attributed to the influence of decadal modes of climate variability, particularly the AMO (K. Emanuel, 2005; Goldenberg et al., 2001), while other studies suggest that the changes in observational methods can account for most of the observed changes in frequency (Landsea et al., 2006; Vecchi et al., 2021; K. Emanuel, 2021). Similarly, there is little consensus regarding future changes in the global number of TCs, and regional trends are even more uncertain (Knutson et al., 2020; Sobel et al., 2021; Vecchi et al., 2019). In the North Atlantic, studies found both increased and decreased projections in TC frequency depending on emissions scenario, spatial resolution, and ocean coupling (Knutson et al., 2020, and references therein).

Previous studies have largely focused on mean changes in TC activity; however, changes in the distribution of seasonal TC activity have received less attention. It is important to understand how the extremes in seasonal TC activity may change in the future, as it is the extremely active seasons that tend to cause societal impacts (Pielke & Landsea, 1998, 1999; Klotzbach et al., 2018). In this study, we examine how the most active and inactive North Atlantic hurricane seasons, which are often modulated by ENSO and AMM in the present climate, may change in a future warmer climate by performing SST-forced experiments in a TC-permitting global climate model. This research helps shed light on the effect of climate change on extreme Atlantic hurricane seasons.

2 Data and Methods

We performed a set of six experiments using the high resolution ($\approx 0.38^\circ$) Energy Exascale Earth System Model (E3SM), version 2 (Caldwell et al., 2019) to explore how the most active and inactive Atlantic hurricane seasons in the present climate may change under projected conditions by the end of the 21st century. We refer to simulations forced by joint La Niña and positive AMM conditions as “active” Atlantic hurricane seasons, and by joint El Niño and negative AMM conditions as “inactive” seasons, based on the typical observed influences of ENSO and the AMM in the historical climate. The atmosphere-only simulations were forced with idealized prescribed monthly SST patterns (Fig. 1), to allow us to systematically test how TCs would respond to ocean variability under a changing climate. The following experiments were performed:

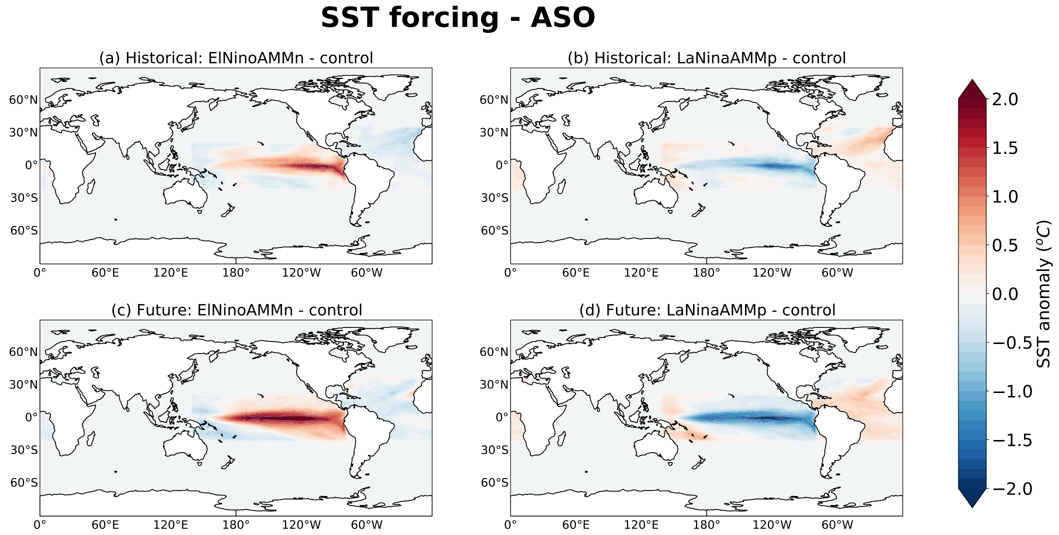

Figure 1. Difference in the SST forcing, averaged in ASO, for: (a) ElNiñoAMMn-hist minus CTL-hist; (b) LaNiñaAMMp-hist minus CTL-hist; (c) ElNiñoAMMn-fut minus CTL-fut and (d) LaNiñaAMMp-fut minus CTL-fut.

1. CTL-hist is an atmosphere-only simulation forced with 1980-2010 monthly mean climatology sea surface temperature (i.e., neutral ENSO and neutral AMM) and sea ice derived from the historical E3SM-DECK experiment (Golaz et al., 2019). External aerosol and greenhouse gas concentrations (GHGs) were prescribed based on the year 2010 of the CMIP6 experiments (Eyring et al., 2016). The monthly SST bias relative to the Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST, Rayner et al., 2003) was removed, in an effort to reduce the influence of the model bias in the simulations, as SST biases can induce substantial errors in simulated TC activity (e.g., Hsu et al., 2019; Vecchi et al., 2019).
2. ElNiñoAMMn-hist used the CTL-hist forcing, but with El Niño conditions over the tropical Pacific ($20^oS - 20^oN$; $140 - 280^oE$) and negative AMM conditions over the tropical Atlantic ($20^oS - 35^oN$; $100^oW - 15^oE$) added to the monthly SST (Fig. S1). The average ASO SST anomalies relative to CTL-hist are shown in Fig. 1a. The forcings were derived based on the monthly bias-corrected E3SM-DECK SST in the historical period (1980-2010), as described in the supporting information. Note that the AMM SSTAs in the southern tropical Atlantic have either a weakly opposite or same sign as in the northern tropical Atlantic, which may be related to biases in the SST and to the method used to define AMM and to attempt to correct for such biases. Since the SSTAs in the northern tropical Atlantic dominate the influence of the AMM on Atlantic TCs (Kossin & Vimont, 2007), we anticipate the southern tropical Atlantic SSTAs may have a secondary influence. Atlantic SSTAs associated with the AMM are weaker than Pacific SSTAs associated with ENSO in both observations and in the SSTAs imposed in the E3SM simulations (e.g., Patricola et al., 2017). For the same magnitude of SSTA, observed and simulated Atlantic TC activity is more sensitive to tropical SSTAs in the Atlantic compared to the Pacific, making the AMM more efficient than ENSO in modulating Atlantic TC activity (Fig. S2; Patricola et al., 2014, 2017). This suggests that both ENSO and AMM contribute to the TC changes simulated by E3SM.
3. LaNiñaAMMp-hist is similar to ElNiñoAMMn-hist, but combines LaNiña conditions calculated in 1980-2010 with the CTL-hist forcing (Fig. 1b).

4. CTL-fut is forced with 2070-2100 monthly mean SST and sea ice derived from the 1pctCO2 (1% CO_2) increase per year) E3SM-DECK experiment. For these experiments, we apply an SST bias correction by assuming that the SST bias calculated for the CTL-hist will remain the same in the future climate. The external aerosol and GHGs forcings are set to the 2100 concentration according to the Representative Concentration Pathway 8.5 (RCP8.5). As discussed in the Supporting Information (SI), the CO_2 concentration for 2100 is similar between the RCP8.5 and 1pctCO2 emissions scenarios. The difference between the CTL-fut and CTL-hist forcings in the ASO period is shown in Fig. S3. The projected SST warming in E3SM is consistent in sign and magnitude with that from other CMIP6 models (Sung et al., 2021).
5. ElNiñoAMMn-fut is similar to ElNiñoAMMn-hist, but with the SST anomalies calculated for the future climate, and paired with the CTL-fut forcings (Fig. 1c)
6. LaNiñaAMMp-fut is similar to LaNiñaAMMp-hist, but for the future climate (Fig. 1d).

Simulations were initialized on 01-April and run for one year. In order to evaluate how substantial the TC response is to the different SST patterns and climate states, and to account for internal atmospheric variability, we performed a 10-member ensemble of each experiment. The ensemble members differ from each other only by a random small perturbation in the initial surface temperature. Further details on the model setup can be found in the SI and are summarized in table S1.

The Toolkit for Extreme Climate Analysis (TECA; Prabhat et al., 2012) was used to identify TC location and intensity in the model output. The TC tracking algorithm in TECA is based on Vitart and Stockdale (2001). Only TCs with a minimum duration of 2 days are evaluated. Accumulated cyclone energy (ACE; 10^4 kt^2), which accounts for TC number, intensity, and duration, is calculated by summing the square of the maximum sustained wind speed every six hours over the TC lifetime (G. D. Bell et al., 2000). The genesis potential index (GPI), which considers factors such as potential intensity (PI), mid-tropospheric relative humidity, and vertical wind shear, was calculated to determine how favorable the environment is to TC activity (Camargo et al., 2007, details in the SI). Anomalies significant at or above the 95% confidence interval in a two-tailed t-student test are considered significant. A climatology of TC activity in observations was obtained to determine how well the characteristics of the ENSO/AMM-TC relationship is reproduced in the model (see SI, text S4).

3 Results

3.1 North Atlantic TCs in E3SM

Compared with observations from the International Best Track Archive for Climate Stewardship, version 4 (Knapp et al., 2010, IBTrACS), E3SM generally simulates observed Atlantic TC activity well. The global TC distribution is well represented in the E3SM historical control simulation, apart from spurious activity over the South Atlantic and southeastern Pacific and a greater number of TCs in the Northeastern Pacific (Fig. S4). Similar to observations, North Atlantic TCs are generated in the eastern tropical North Atlantic and move to the west, often reaching the continental North Atlantic before dissipating. Their seasonality is also well represented in the high resolution E3SM, with the majority of Atlantic TCs simulated during the August-October observed peak of the hurricane season, though a greater percentage of North Atlantic TCs are produced during the boreal winter in the model compared to observations (Fig. S5). However, the TC intensity is underestimated compared to observed, as would be expected given to the model's spatial resolution (Balaguru et al., 2020). The maximum TC intensity reached in the North Atlantic in the control simulation was a category 4 hurricane.

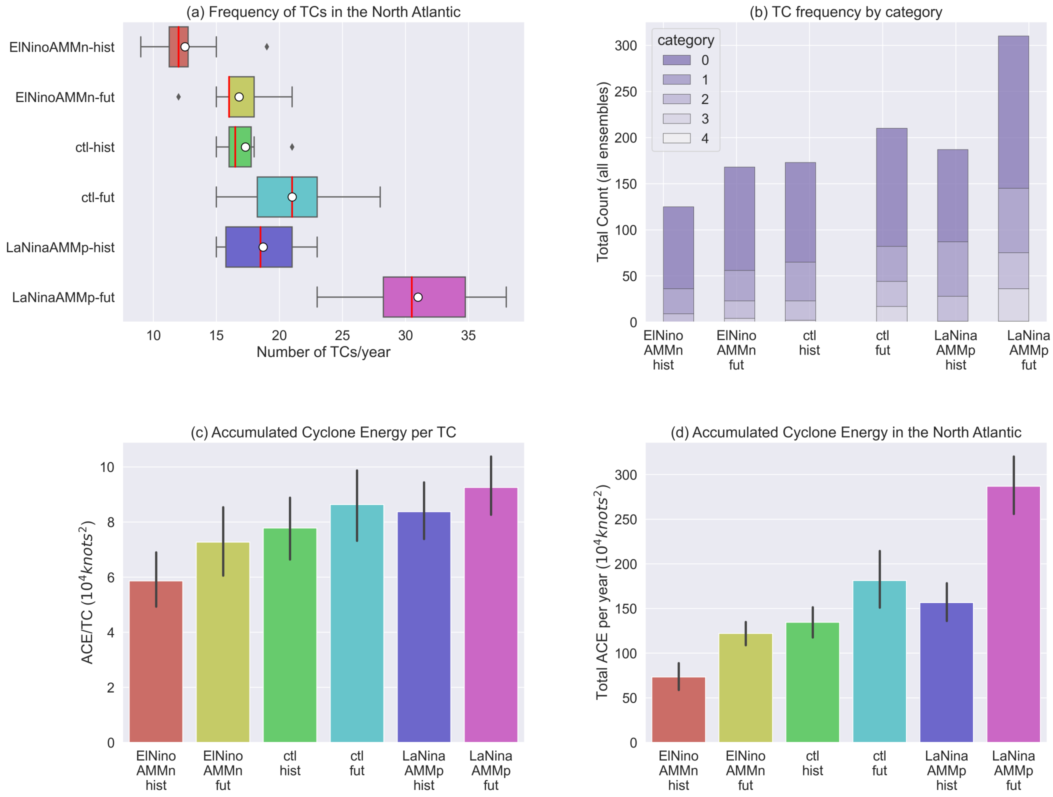

Figure 2. (a) The number of North Atlantic TCs per year from the 10-member ensemble of each E3SM experiment. The boxplot represents the internal atmospheric variability of the experiments. The edges of the boxplots show the 25th and 75th percentiles. Whiskers represent 1.5 the innerquartile range. The median is marked as a straight red line, and the mean is noted by a white circle. (b) Total number of North Atlantic TCs in the 10-member ensemble of each experiment grouped by intensity based on the Saffir-Simpson scale. TCs that do not reach the threshold of hurricane strength are shown in the darkest purple, and denoted by the number 0 in the legend. c) Mean ACE (10^4 kt^2) per TC in the North Atlantic in each experiment. The error bars represent one standard deviation from the mean based on all detected TCs; d) Ensemble mean of the total North Atlantic ACE per year. Error bars represent the ensemble variability.

The observed relationship between ENSO and AMM and the number of North Atlantic TCs (Fig. S6) is generally reproduced in E3SM, with an increase of 1.4 TCs/year, or 8%, in the number of Atlantic TCs in the LaNiñaAMMp-hist simulation (but not significant at the 95% level) and a significant decrease in Atlantic TC frequency of 4.8 TCs/year (28%) in the ElNiñoAMMn-hist simulation (Fig. 2a). Based on these results, we find that the ENSO and AMM-forced experiments in the historical climate are reasonably consistent with observations and suitable for this study.

3.2 North Atlantic TC response to climate change

The total number of North Atlantic TCs significantly increases in the future relative to the historical for all of the ENSO/AMM scenarios analyzed (Fig. 2a and Table S2). For the climatological SST scenarios (i.e., neutral ENSO and neutral AMM), the ensemble-mean frequency of TCs significantly increases by 3.7 TCs/year (a 21% increase) in the future climate. In the ElNiñoAMMn experiment, the number of North Atlantic TCs increases by 4.3 TCs/year (34% increase) in the future when compared to similar historical conditions, and becomes insignificantly different from the historical neutral ENSO and AMM conditions and joint La Niña and positive AMM conditions in the historical climate. The most pronounced increase in TC frequency in the future climate was projected for the concurrent La Niña and positive AMM conditions, with a significant increase of 12.3 TCs/year, or 66%. In this case, the increase is concentrated in the western portions of the North Atlantic and the Gulf of Mexico (Fig. S7).

As North Atlantic TC activity becomes more frequent in the future climate, the intensity distribution shifts toward stronger TCs (Fig. 2b). The frequency of major hurricanes (defined as category 3 hurricane or greater) is expected to increase from historical to future in all of the ENSO/AMM scenarios analyzed, and prominently during the active season (La Niña and positive AMM). The total number of major hurricanes produced in the 10-member ensemble of neutral ENSO/AMM experiments increased substantially from 2 in the historical climate to 17 in the future. Similarly, the experiment representing inactive Atlantic hurricane seasons (El Niño and negative AMM), produced no major hurricanes in the historical climate, while 4 were simulated in the future. Compared with the inactive hurricane season, a greater TC intensification was found during the active season. Specifically, only one major hurricane was simulated in the historical LaNiñaAMMp simulation across all 10 of the ensemble members, whereas 36 major hurricanes were found in the future LaNiñaAMMp simulation, including one category 4 hurricane. The general intensification of the TCs in future climate can also be seen as an increase of the ACE per TC for all of the future simulations (Fig. 2c). In addition, the total ACE per season increases from the historical to the corresponding future climate for given AMM/ENSO conditions, associated with an increase in both Atlantic TC frequency and intensity. The active Atlantic hurricane seasons (La Niña and positive AMM) have the greatest projected increase in seasonal ACE, from 156.6 $\times 10^4 knots^2$ in the historical climate to 286.9 $\times 10^4 knots^2$ in the future, an 83% increase. Meanwhile, seasonal ACE is projected to increase by 66% in the inactive (El Niño and negative AMM) simulations, and by 35% in the control (Fig. 2d).

These results are in agreement with the environment conditions becoming more conducive to TC development. Figure 3 shows the difference in GPI between the future and historical climates for the active and inactive Atlantic hurricane seasons. Under El Niño and negative AMM conditions, the central part of the North Atlantic and the Gulf of Mexico became more favorable to TC development (Fig. 3a). Under La Niña and positive AMM conditions, there is a basin-wide, stronger increase in GPI, agreeing with a greater increase in TC activity during the active season (Fig. 3b).

To understand the contributing factors for this variation, Figure 4 shows the projected future changes in each component of the GPI given La Niña and positive AMM conditions. There is a general increase in the TC potential intensity in the Northern Hemisphere (Fig. 4a), consistent with the general SST warming in the future climate (Fig. S3). During the future climate, the Hadley circulation is projected to expand, generating a poleward shift of the subtropical jet (e.g. Grise & Davis, 2020) As a result, the vertical wind shear in the North Atlantic is reduced (Fig. 4b), creating more favorable conditions for Atlantic TCs. Meanwhile, mid-tropospheric relative humidity increases over much of the central-eastern main development region (Fig. 4d), accompanied by anomalous co-located mid-tropospheric ascent (not shown). Together, these responses suggest less entrainment of more moist air, contributing to the intensification of TCs. Although the same mechanism exists in the inactive seasons (Fig. S8), the future relative humidity increases more in the active season, especially in the Main Development Region (12%) compared to the inactive season (9%) and vertical wind shear decreases are stronger and cover a greater portion of the Atlantic main TC development region for the active season (Fig. 4) compared to the inactive season (Table S3). However, changes in GPI does not fully explain the differences in the TC frequency response in the inactive season and

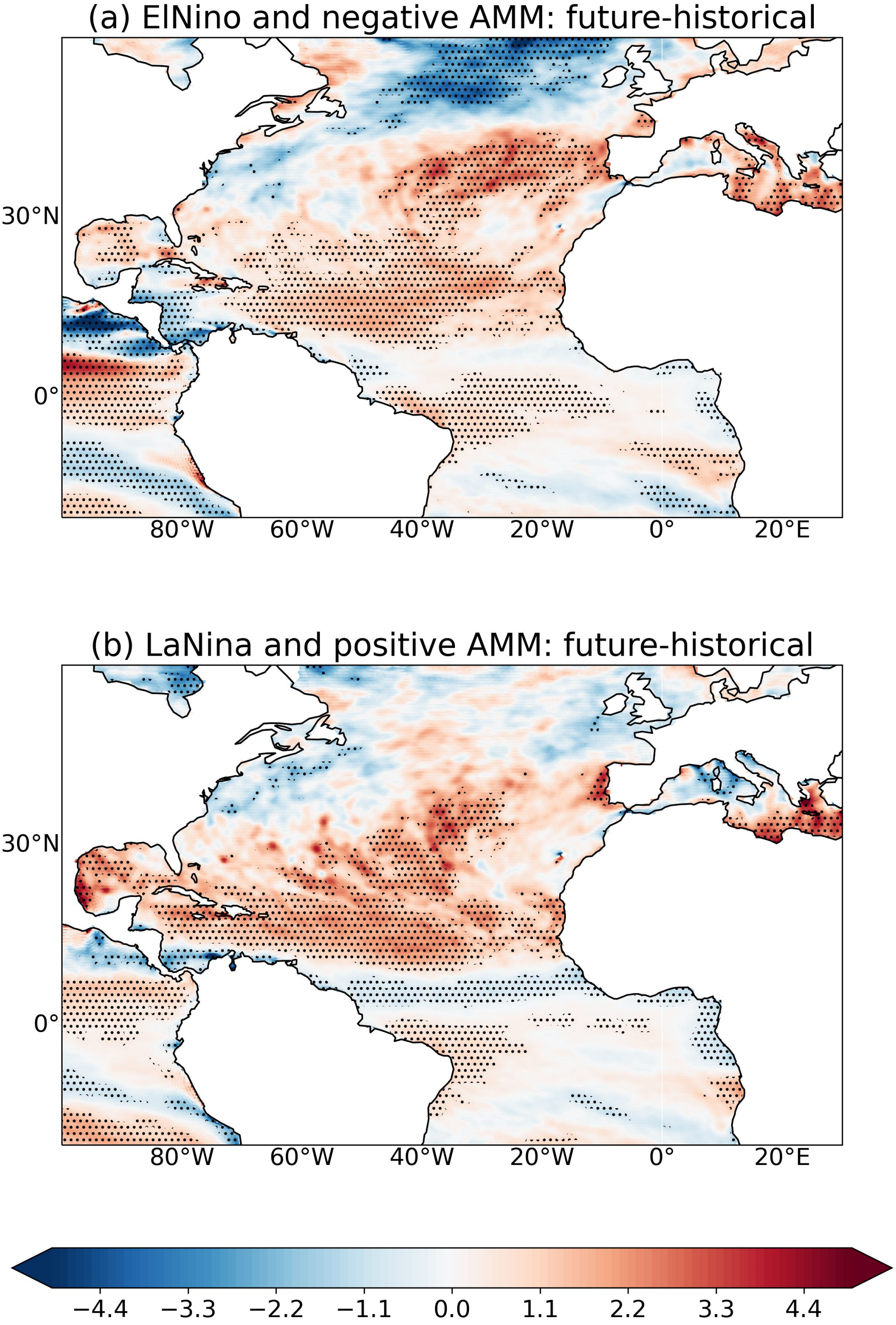

Figure 3. Difference between the ASO-averaged, ensemble-mean genesis potential index (unitless) for the: (a) ElNiñoAMMn-fut minus ElNiñoAMMn-hist (inactive hurricane season) and (b) LaNiñaAMMp-fut minus LaNiñaAMMp-hist experiments (active hurricane season). Stippling indicates significant anomalies at or above the 95% significance level.

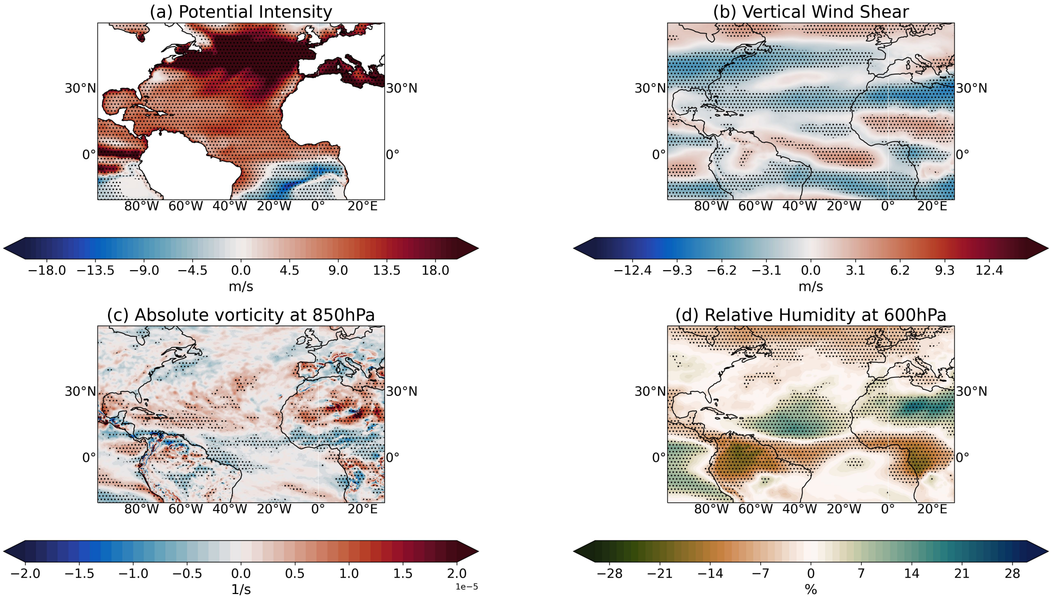

Figure 4. Difference between the ASO-averaged, ensemble-mean of the LaNiñaAMMp-fut minus LaNiñaAMMp-hist experiments (active hurricane season) for (a) potential intensity (m/s); (b) vertical wind shear between 850hPa and 200hPa (m/s); (c) absolute vorticity at 850hPa (s^{-1}) and (d) relative humidity at 600hPa (%). Stippling indicates significant anomalies at or above the 95% significance level.

climatology. While the changes in TC frequency are greater during the inactive season, there is a greater change in GPI during climatology. This may be due to the difficulty of GPI to explain TC activity in future climates (Camargo, 2013) and/or the fact that the relation between vertical wind shear and TC frequency is non-linear. A smaller change in vertical wind shear during the inactive season may cross the threshold to make the environment more conducive to TCs. Note that the vertical wind shear response has opposite signals in the Gulf of Mexico and North Atlantic in the inactive season, a feature common in other climate models(Camargo, 2013).

4 Conclusions

Tropical cyclones (TCs) can cause significant economic and life impacts. Previous studies have typically focused on future projections in mean TC frequency, with little consensus globally and by basin. In this study, we analyzed how active and inactive North Atlantic hurricane seasons may change in the future, since the extreme seasons generally lead to severe impacts or respite from impacts. We used SST-forced high resolution global climate model experiments to investigate active and inactive Atlantic hurricane seasons, which are often associated with joint La Niña and a positive AMM, and with joint El Niño and a negative AMM, respectively, in the current climate.

We found that North Atlantic TCs are projected to become more frequent in both the active and inactive hurricane seasons in the future relative to the historical climate. The greatest increase in Atlantic TC number was simulated during the active season, associated with concurrent La Niña and positive AMM, with the mean number of Atlantic TCs increasing by 66%. During years with concurrent El Niño and negative AMM conditions, currently related to a reduction in North Atlantic TC activity, the number of TCs is also projected to increase, reaching numbers similar to the present climate's climatology and active seasons. We note that while this study focuses on the North Atlantic, there is evidence that the TC response to climate change may also vary according to ENSO in other basins, including the Northwestern Pacific (S. S. Bell et al., 2020; Tu et al., 2022). Along with the shift towards greater Atlantic TC numbers, we found that the TC intensity distribution is projected to shift towards stronger TCs, consistent with what is documented in the literature. This North Atlantic TC intensification is stronger during the active seasons, especially when considering the number of major hurricanes. Altogether, the co-occurring increase in TC number and strength may lead to increased risk to the continental North Atlantic in the future climate. Multiple factors – thermodynamic and dynamic – work together to contribute to more intense Atlantic TC activity in the future climate including: 1) increased TC potential intensity, partially due to warmer SSTs; 2) a reduction in vertical wind shear, leading to a reduction in the entrainment in the TCs, and 3) an increase in mid-tropospheric humidity, leading to less entrainment of dry air.

In order to better constrain future TC projections, further work is needed to reduce the uncertainty around future projections of ENSO. Although we applied a bias-correction to the monthly mean SST, it is possible that mean-state biases may influence the projected changes in ENSO dynamics (Kim et al., 2017; Seager et al., 2019). Furthermore, the global model simulations from which the SST forcings were derived may contain biases in SST variability including ENSO and the AMM. We highlight that there is a lack of consensus regarding future changes in ENSO (e.g., Yeh et al., 2014; Capotondi et al., 2015), which can have important implications for future TC activity. However, as in most climate models (Fredriksen et al., 2020), E3SM projects a future weakening of the equatorial Pacific zonal SST gradient (i.e., a more El Niño-like state). On the other hand, an increase in the tropical Pacific zonal SST gradient, towards a more La Niña-like background state, has been observed in recent decades (Seager et al., 2019). This common discrepancy between the models and observations represents a major uncertainty in projecting future TC activity. The results obtained here suggest that about 21% of the projected increase in TC frequency may be attributed to the global warming effect on the mean state of the atmosphere (CTLfut minus CTLhist), whereas joint changes in ENSO and AMM are responsible for the remaining 13% and 45% of the increase in the TC frequency in the inactive and active experiments, respectively. The greater changes in TC frequency in the active season are associated with a greater increase in basinwide mid-level relative humidity and reduction in vertical wind shear when compared to the inactive season. The dynamic mechanisms for this difference could be further explored in the future. All else similar, we hypothesize that a shift towards a La Niña-like background state could further reduce wind shear in the tropical North Atlantic through changes in the Walker circulation, thus favoring Atlantic TC activity. However, SSTAs in the tropical Pacific could affect tropical north Atlantic SSTs, as well as the magnitude of ENSO teleconnections (e.g. Liu et al., 2021). In addition, simulations that form the basis for future climate projections would ideally include an interactive ocean, which would require improvements in simulated tropical SSTs (Hsu et al., 2019). This would allow for representation of TC-ocean feedbacks in which TC winds can induce ocean mixing and SST cooling, known as SST cold wakes. Such feedbacks are usually negative, and lead to a less favorable ocean environment for the overlying TC, as well as subsequent TCs (Bender & Ginis, 2000; Schade & Emanuel, 1999; Karnauskas et al., 2021; Singh & Roxy, 2022). This study focuses on the combined effect of ENSO and AMM changes on North Atlantic TCs. Additional research is underway to investigate how future changes in ENSO influence future TC frequency.

This research highlights the importance of considering how future change in both the mean climate state and climate variability can influence extreme events. This work has several implications for future risks associated with Atlantic TCs. By focusing on the typical oceanic drivers of active and inactive Atlantic hurricane seasons, we were able to evaluate how the active and inactive tails of the seasonal Atlantic TC activity distribution could change in a future climate. Notably, we found that the patterns of ocean variability that currently drive the most active Atlantic hurricane seasons in the historical record, when paired with climate change, have the potential to produce hurricane seasons that are even more active. In addition, the simulations indicate that the ocean variability patterns that typically help to reduce Atlantic TC impacts by suppressing TCs in the historical climate become less effective at doing so in the future. Altogether, the simulated shift in the future extremes in seasonal Atlantic TC activity represents a potential worsening of Atlantic TC impacts in the future.

Acknowledgments

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Open Research Statement

HadISST data can be accessed at `https://www.metoffice.gov.uk/hadobs/hadisst/`. E3SM version 2 is available at `https://e3sm.org` (DOI: 10.11578/E3SM/dc.20210927.1). TECA is available at `https://teca.readthedocs.io/en/latest/index.html` (DOI: https://doi.org/10.5281/zenodo.6640287). The model output used in this manuscript is published at `https://doi.org/10.5281/zenodo.6633637` (DOI: https://doi.org/10.5281/zenodo.6633637). IBTrACS is available at https://www.ncei.noaa.gov/products/international-best-track-archive?name=ib-v4-access.

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