



Effects of Warming and Stratospheric Aerosol Injection on Tropical Cyclone Distribution and Frequency in a High-Resolution Global Circulation Model

Andrew Feder¹, David Randall¹, and Donald Dazlich¹

¹Colorado State University

Correspondence: Andrew Feder (andrew.feder@colostate.edu)

Abstract. In recent years, as global circulation models (GCMs) have increased in spatial resolution, increasingly realistic tropical cyclones (TCs) and TC distributions have emerged from them. Where prior research on TC climatologies has relied on proxies like Potential Intensity (PI) and synthetic storm models, the cyclones emerging from the dynamics of newer GCMs can now be analyzed directly, using native model variables.

5 Such direct analysis may be particularly useful in studying possible global storm distributions under radically altered future climates, including high-emissions warming scenarios, and even those shaped by climate interventions. These interventions include various directed changes in global albedo, such as Stratospheric Aerosol Injection (SAI), with only limited precedent in the historical period. GCMs simulating realistic climate intervention scenarios, have not as of yet paired storm-resolving resolution with realistic intervention scenario construction. This has left gaps in our understanding as to how interventions
10 might affect global storm/TC distributions.

In this paper, we utilize a new high-resolution model configuration to conduct experiments examining the effects of SAI, on tropical cyclones and global storm physics more broadly. These experiments are constructed based on prior work on SAI, using the GLENS GCM ensemble. Our analysis centers on 3 10-year experiments conducted using 30-km grid spacing. These include a recent-past calibration run; the Intergovernmental Panel on Climate Change climate pathway SSP 8.5 (IPCC, 2021),
15 for the years 2090-2099, with no SAI; and SSP 8.5, with SAI having begun in 2020 to maintain a global temperature rise of no more than 1.5° C, also simulated for the years 2090-2099. With the resulting data sets, we deploy a novel TC-tracking algorithm to analyze resulting changes in storm tracks and properties. Based on our results for these different scenarios, we find that SAI, while in some ways restoring global storm patterns to a pre-warming state, may also create unique basin-scale TC distribution features and pose novel related hazards.

20 1 Introduction

1.1 TCs, Past and Future

Tropical cyclones (TCs) can be understood as Carnot engines (Emanuel et al., 2023) powered by heat energy from the ocean surface. As such, their occurrence is highly connected to heat and its movement. Fundamentally, TCs are a mechanism by



which the atmosphere transfers heat from the ocean to the upper atmosphere, with other features such as intense cyclonic winds, rain bands, etc, arising from this transfer and thus ultimately fueled by this energy differential. Yet, TCs do not appear wherever they could perform this function, and in fact potentially represent a very small share of the relevant heat transfer budgets (Emanuel, 2022).

TC occurrence is dependent on a host of other variables being conducive to their formation and survival, and overall storm activity is thus much harder to predict than if it were primarily a function of available energy. Over shorter periods, TC populations are highly influenced by chance, linked to the random distribution of seeding events occurring in conjunction with these storm ingredients to take shape into realized cyclones.

As TCs arise stochastically and as a highly contingent, emergent phenomenon, it is difficult to draw direct inferences about changes in TC behavior from long-term climate trends. For purposes of this project, TCs are defined as cyclonic storms with maximum sustained winds of 33+ m/s, categories 1-5, with weaker systems exhibiting tropical storm (TS) and tropical depression (TD) intensity.

The ultimate result of all these epistemological limitations is a dearth of good observational information about how TCs have historically interacted with climate. The era of fairly complete global observational TC records begins ~1990 (Klotzbach et al., 2022), and spans a period of already significant climatic transition. Into this knowledge gap has emerged experimental results from the realm of global circulation models (GCMs).

1.2 TCs in GCMs

Earlier generations of GCMs were generally not run at resolution sufficient to represent the physical structures of TCs, and thus such storms did not meaningfully appear in their outputs (Wehner et al., 2014). However, in recent years, models run at grid spacings approaching ~25km (Roberts et al., 2020) have produced outputs containing TCs in numbers and/or intensities resembling those in best-track archives.

Simulated TCs are counted and analyzed via tracking algorithms, which identify TC-like features in wind, pressure and other variable fields and capture their movements. Despite sharing basic physical underpinnings, model-generated storms and real life ones have major differences in morphology and intensity, which motivated the Pressure-based Hybrid Algorithm for Storm Tracking (PHAST), developed for this research (see Methods).

We see the promise of studying TCs in high resolution GCMs, even as compared to similar methods like localized model downscaling (Knutson et al., 2015), in its parsimonious relationship to native model dynamics. TC behavior in high-resolution runs is a function of overall model skill, dependent on what models predict about the specific weather systems necessary for TC formation and development. Direct tracking could be capable of incorporating the effects of unknown or poorly understood influences on TC behavior, including non-canonical cyclogenesis, and changes in TC formation areas with shifting global temperatures.

Consequences of this dependence of tracked storm behavior on small-scale model dynamics, however, include the possibility of systematic errors arising from model behaviors not yet well understood as we enter the high-resolution modeling era. But in turn, studying TC behavior in this new class of models has the potential to help elucidate model biases: Davis (2018) found



that, given observed TC wind distributions and resolution limitations, strictly physically realistic $\sim .25^\circ$ GCMs cannot possibly produce realistic numbers of category 4 and 5 storms. Even given otherwise perfect model physics, maximum TC winds occur over such small horizontal areas, that averaging over such large cell areas will necessarily smooth out surface wind maxima considerably. Thus, GCMs at this resolution that do generate significant numbers of major storms, must suffer from biases leading to intensity exaggerations.

In this way, direct TC tracking, though dependent on the strength of existing model physics, can recursively help inform future model development.

Davis further suggests that evaluating modeled storm intensities based on wind speed is "not optimal." In light of this, we have developed a novel TC tracking algorithm with intensities based on central pressure, as described in Methods.

1.3 Climate Change and TCs

Under Kerry Emanuel's Potential Intensity theory, warming oceans can be expected to yield TCs of generally greater intensity, all else constant (Emanuel, 1988; Walsh et al., 2016). However, within the context of chaotic weather/climate systems, it is difficult to extrapolate individual storm behavior from physical first principles alone, and a fair degree of uncertainty exists in regard to a warming climate's effects on TC number, intensity and other behavior.

Globally, Walsh et al. (2016) find in a review of studies of the recent/satellite era historical TC record, broad global trends toward TC distributions migrating poleward; reduced translation/track speeds; and increasing proportions of storms of category 4 and 5. Klotzbach et al. (2022) document a recent historical (1990-2021) decline in global TC frequency, along with rising numbers of category 4 and 5 storms, for a relatively more significant upward trend in such powerful storms' overall proportion.

These observations largely comport with findings, from a strong majority (Knutson et al., 2020) of GCM studies focused on future climate/emissions pathways: in a warming world, average TC intensity will increase, perhaps considerably. In a modeling study review, Knutson et al. (2020) find a mean +5% increase in maximum surface wind speeds given 2° of warming, and including only high-resolution model runs. This occurs alongside robust increases in the overall share of intense storms. Further, consistent with the exponential relationship of saturation humidity and temperature under the Clausius-Clapeyron relation, warmer TCs in a warmer climate are also found to yield mean 14% more precipitation under the same 2° assumptions. Less certain are other modeled, interconnected trends, toward reduced TC number; increasing absolute numbers of category 4 and 5 storms; and reductions in track speeds.

Bhatia et al. (2018) produced TC tracking results somewhat varying from the Knutson et al. (2020) review's lower-certainty reported findings. Using the Geophysical Fluid Dynamics Laboratory's HiFLOR model at $.25^\circ$ resolution, Bhatia et al. (2018) compare TCs in a baseline run representing 1986-2005, to two warming scenarios, 2016-2035 and 2081-2100 under RCP4.5. In each scenario, SSTs were nudged toward mean values for the 20-year period, and coupled atmosphere and land models run for 70 model years. Using direct tracking on HiFLOR's spontaneously arising TCs (including significant numbers of category 4 and 5), the authors find an overall increase in TC frequency in a warming climate. The 2081-2100 scenario is found to generate 9.1% more TCs each year than the baseline, arising from a mix of increased and decreased activity among different basins. This is accompanied by an increase in intense TC numbers and share as in other studies, with, notably, an 85% rise in category

5 storms in the same end of century scenario, and consistent increases in TC Rapid Intensification (RI) across all basins in both warming scenarios.

Assuming early-stage TC genesis is broadly controlled by similar mechanisms to TC intensification, the widening geographic areas over which intensification will become likely (Bhatia et al., 2018) should, under the most parsimonious understanding of TC physics, produce increased frequency alongside increased intensity. Alternatively, in a physics of TCs whereby larger storms locally deplete the large-scale conditions necessary for formation (Emanuel, 2022), a possible result of warming could be fewer storms, but more overall cyclone power as measured by total Accumulated Cyclone Energy (ACE), a greater Power Dissipation Index (PDI) (Emanuel, 2007), and/or other energy-based intensity metrics.

Sobel et al. (2021) write that only some climate-related TC changes predicted by models are understood by existing physical theory. Increased wind speeds and precipitation are found and supported by theory, observations, and model results; these and related findings comprise the most certain predictions we can make about TCs in a warming world. Other findings, such as a poleward shift in TC peak intensities, are supported by observations and some model results, but lack a robust theoretical explanation (Sobel et al., 2021). And finally, the authors argue that TC frequency remains the most poorly bounded major question in understanding the relationship between TCs and climate, with little helpful, strong evidence from any direction of inquiry (Sobel et al., 2021).

The mechanisms controlling TC number remain poorly explained at even a basic physical level (Emanuel, 2022; Walsh et al., 2015), with Sobel et al. (2021) writing of current global TC number, "We have little idea why the total number could not be even an order of magnitude greater or smaller." Observationally, it is broadly understood that TCs emerge in regions of warm sea surface temperatures (SSTs) and high vertical instability, and are limited by a lack of Coriolis vorticity at the equator itself. Cyclogenesis is further dependent on local vorticity and convergence conditions, and easily inhibited by vertical wind shear (Frank and Ritchie, 2001). These factors have been incorporated into the indexes, like GPI (Emanuel and Nolan, 2004) or TCG (Tippett et al., 2011), used to estimate TC occurrence operationally and in low resolution modeling. But these are basically relative measures, calibrated to historical observations, and they may not hold in climates that are radically different from present day.

In line with these observed large-scale controls, Walsh et al. (2015) do find a robust correlation in a suite of high-resolution models between TC formation and seasonal 500-hPa mean vertical velocity, consistent across models with different convection parameterization schemes and much stronger than for any other studied variables. A warming climate may result in a more stable tropical vertical atmospheric structure, making it more difficult to achieve the "deep convection" (Walsh et al., 2015) necessary to create TC seeds. In this understanding, regardless of the overall mechanisms controlling TC formation and development with respect to climate, TC occurrence may be fundamentally limited by seeding, as opposed to, say, available energy or storm packing in time and space, alternatives discussed by Emanuel (2022) and also found by him to be relatively lacking.

On shorter time scales, ENSO and other cycles affecting SSTs are known to substantially affect TC frequency in individual basins, with En Niño corresponding to substantial decreases in frequency in the Atlantic and Australia regions, and increases in some others (Sobel et al., 2021). Slightly different correlations may apply to other TC power/distribution measures.



1.4 Climate Intervention Technologies/Scenarios

Climate Intervention (or "Geoengineering" (Bellamy et al., 2012)) consists of proposed methods to mitigate the effects of climate change, apart from emissions reductions. The most studied form of Climate Intervention in the research literature is Stratospheric Aerosol Injection (SAI) (Bellamy et al., 2012), intended to offset greenhouse warming effects through reflection of incoming solar radiation.

As proposed, SAI would involve dispersal of sulfur dioxide (SO₂)/sulfuric acid aerosols into the stratosphere, several kilometers above the tropopause. To meaningfully reduce global temperatures, aerosol releases would represent tens of gigatons of SO₂ annually, deployed according to feedback algorithms intended to meet multiple independent temperature pattern, or other climatic goals (Zhang et al., 2022; Tilmes et al., 2020).

Due to its potential to regulate the climate quickly, effectively and at relatively low cost, SAI has been the focus of significant ensemble modeling projects, including the GLENS and ARISE SAI ensemble projects (Tilmes et al., 2018; Richter et al., 2022).

These and similar SAI modeling research at the National Center for Atmospheric Research include simulations described in "Reaching 1.5 and 2.0°C global surface temperature targets using stratospheric aerosol geoengineering," (Tilmes et al., 2020). This paper presents results of a series of SAI modeling experiments conducted with CESM2, using the Whole Atmosphere Community Climate Model (WACCM6) configuration. The ensemble members are based on differing global emissions scenarios paired with more or less ambitious SAI temperature control goals. These emissions scenarios, based on CMIP6 scenario protocols, are run with and without SAI intervention to explore the climate and weather effects over the studied period for each run, 2020-2100.

GLENS and Tilmes et al. (2020), respectively, include experiments with high-emissions pathways (RCP 8.5/SSP5-8.5), with substantial sulfur quantities necessary to maintain temperature targets based on 2020 conditions, or temperatures 1.5/2.0° above pre-industrial conditions. This in contrast to much more modest interventions studied in ARISE. Such large-deployment scenarios are preferable for studying effects on high noise-to-signal phenomena like seasonal TC behavior, in which small effects could be obscured by random variation. However, RCP 8.5-type scenarios may be unrealistic in light of recent progress in climate policy (Richter et al., 2022).

The SSP/RCP climate pathways used in Tilmes et al. (2020) are based on the findings of successive IPCC reports on consequences of climate change, assuming various future trajectories of GHG emissions (IPCC, 2021). In this framework, SSP5-8.5 represents a high emissions pathway, at the upper end of what may be plausible by the end of the century. The experiment "GEO SSP5-8.5 1.5," in Tilmes et al. (2020), is the forcing for one of our experiments, with SSTs and other variable fields from this extreme intervention case acting on dynamic atmosphere and land models. With SAI deployment beginning in 2020, the SSP5-8.5 based scenario is modified toward achieving 3 temperature goals: global temperatures 1.5° above pre-industrial conditions (L0); maintaining present inter-hemispheric temperature gradients (L1); and maintaining present pole-to-equator temperature gradients (L2). This is achieved with the feedback control algorithm also utilized in GLENS and ARISE, with sulfur injections 5km above the tropopause, split among deployment locations at 15° and 30° north and south. Sulfur released at each latitude is adjusted based on temperature distributions achieved the previous year, with more or less at each



160 to correct for prior imbalances. At this altitude, aerosols quickly diffuse to even distribution within their latitude bands, while more slowly migrating poleward through the Brewer-Dobson Circulation (Richter et al., 2022).

Given fundamental uncertainties in the specifics of any future SAI program, the outcomes of any modeled climate intervention scenario serve mainly to outline potential action mechanisms and consequences of different technologies, rather than predict future climate conditions per se. As such, in the absence of large-scale intervention actually in progress, at best we can
 165 now analyze general tendencies and constraints of our possible climate futures.

1.5 Natural Analogues to SAI

SAI has drawn attention as a possible climate intervention due in large part to the effects of volcanic eruptions seen in the observational record, which similarly loft SOO_2 into the stratosphere along with an array of other aerosols and gases. These events, notably including the 1991 eruption of Mt. Pinatubo, have caused measurable reductions in average global temperatures
 170 lasting several years (Aquila et al., 2021).

Significant disagreement remains as to the effects of volcanic eruptions on El Niño/La Niña (Khodri et al., 2017). Paleoclimate reconstructions and perturbation modeling indicate that ENSO response may depend on the latitude of volcanic events (Liu et al., 2018), but with large tropical eruptions more certainly tending to yield ENSO patterns that are more El Niño-like (Aquila et al., 2021; Liu et al., 2018).

175 Based on the heat engine understanding of TC formation and propagation, the most parsimonious relationship between volcanism/sulfur injection and TC activity is some sort of antagonistic effect. Given the dependence of TC genesis on SST thresholds hypothesized/observed to range from $25.5\text{--}27^\circ\text{C}$ (Tory and Dare, 2015), cooler oceans with smaller potential TC genesis areas should yield fewer storms of more equatorial latitude. However, to the extent TC number and power may not be limited by formation area or heat budgets (Emanuel, 2022), other unexpected mechanisms could disrupt any simple SST-storm
 180 relationship that might otherwise be valid.

Haywood et al. (2013), through observations and modeling, show that cooling in one hemisphere will tend to shift the ITCZ toward the opposite hemisphere by changing the behavior of the Hadley cell. They show that this phenomena, when driven by Northern Hemisphere volcanic eruptions, has contributed to drought events in the Sahel region in recent decades. This movement of the ITCZ changes patterns of convection and precipitation associated with the feature, and is also seen in further
 185 modeling exploring the effects of hemisphere-asymmetric SAI injections (Haywood et al., 2013).

This sensitivity of low-latitude rainfall patterns to stratospheric aerosol distributions could also present a possible constraint/area of concern in considering SAI deployment. Avoiding significant shifts in the latitude of the ITCZ may thus be an important priority in constructing any SAI scheme (Lockley et al., 2022), and comprises an implicit goal of the GLENS/ARISE feedback algorithms, in the implementation of the interhemispheric temperature gradient (L1) constraint (Tilmes et al., 2020).

190 Benton et al. (2022) note observational studies of North Atlantic TCs following eruptions to suggest that this aerosol-ITCZ mechanism may extend robustly to TC activity. In modeling single-hemisphere SAI deployment, described as "analogous" to eruptions, Jones et al. (2017) hypothesize that shifts in the ITCZ southward away from the North Atlantic Main Development Region (MDR) will increase wind shear and impede TC formation, while a more northern ITCZ will promote such. Using



climatological proxies, direct TC tracking (at 1.25° by 1.875° resolution), and statistical-dynamical downscaling, the authors study simulated North Atlantic TC frequency in RCP4.5, and scenarios representing both global and single-hemisphere SAI deployments. Obtaining somewhat contradictory results among the different approaches, Southern Hemisphere injections consistently yield greater North Atlantic basin activity than balanced or Northern Hemisphere alternatives; and based on direct storm tracking and index correlations, may - in spite of heat-engine effects - produce significantly more North Atlantic storms than even non-intervention RCP 4.5.

These mechanisms should remain important regardless of the causes of any hemispherically differential cooling (Jones et al., 2017), and apply to both volcanic eruptions and any albedo-based means of climate intervention.

While overall TC formation/frequency constraints remain poorly understood, we can begin to try to predict storm responses to SAI based on observed responses to current global warming and past episodes of volcanic cooling. These can be supplemented by effects and relationships found in model scenarios. Based on the existing literature, we can outline 5 varyingly well-described potential mechanisms affecting TC distribution under warming scenarios as mitigated by SAI. These include: (1) overall global SST reductions, via heat engine effects; (2) amelioration of polar amplification, with any concurrent shifts in basin area; (3) the emergence or prevention of changes in mean ENSO index; (4) shifts in the ITCZ driven by hemispheric temperature asymmetries; and (5) relative increases in TC seeding rates brought about by halting shifts toward greater atmospheric vertical stability. In the Results and Discussion sections of this paper, we will attempt to link any model-observed changes in TC statistics to one or more of these theorized mechanisms. These will provide a framework for understanding how SAI, relative to unmodified warming, may shift regional and global patterns of storm occurrence; and allow us to assess the certainty level of storm activity forecasts obtained from our models.

Through this process of comparing scenario results and drawing causal connections, we can begin to help illuminate the relative degrees of local and global TC hazards arising from both climate change, and intervention to ameliorate it. At different scales, SAI could bring storm patterns back into line with those in a pre-warming/historical climate, or could push global and regional tempestologies in directions largely without precedent. By identifying which control mechanisms may dominate storm development and evolution under SAI, we can create outlines of potential TC hazard profiles with salience extending well beyond the results of these specific runs.

In this paper, we compare TC distributions and properties arising in the EarthWorks model given three different climate states, representing historical conditions, unmitigated warming, and warming with SAI. We develop new techniques to track TCs occurring in this and other GCMs, and compare the performance of the resulting model-tracker combination to real-world storm data. After establishing the fidelity of model TC representation based on our historical run data, we use this baseline to evaluate changes in storm behavior given either advanced climate change or the global climate patterns created by SAI. This includes overall storm number, latitude/basin distributions, life cycle changes, and changes in typical TC intensities. Finally, we examine possible intermediate mechanisms, such as El Niño and changes in regional vertical shear, through which climate and TC formation may interact.



2 METHODS

2.1 Model Configuration

Our experiments are run within the EarthWorks model currently under development in a collaboration between Colorado State
 230 University, the National Science Foundation (NSF), and other research institutions. Intended to bridge modeling of climate
 and weather phenomena at the largest and the smallest scales, project goals include runs at a $<4\text{km}$ horizontal grid spacing. At
 this and similar grid spacings, EarthWorks will serve as a Global Storm-Resolving Model (GSRM), capable of representing
 global climate behaviors while also capturing small scale phenomena resulting from and contributing to climate processes. In
 this way, problems at the intersection of climate and weather, including TC responses to climate change, can be addressed
 235 comprehensively across scales and domains.

EarthWorks is built on a foundation provided by the Community Earth System Model (CESM), an open source model main-
 tained by the atmospheric science research community and utilized in a range of global and large-scale experiments. CESM
 includes components representing physics and chemistry of the oceans, land surface, and atmosphere. However, having been
 developed for large-scale simulations at relatively lower resolution, CESM is reliant on parameterizations to represent phenom-
 240 ena that at storm-resolving resolution should be directly simulated. However, as model resolutions grow finer, phenomena that
 were once best represented through parameterization may eventually be directly simulated. Among the goals of the EarthWorks
 project, is to address new biases and errors as CESM physics is brought to GSRM scope.

Another notable feature of EarthWorks with respect to TC modeling is its use of the MPAS dynamical cores, based on
 hexagonal Voronoi meshes for atmospheric, ocean and ice components (MPAS-A, MPAS-O, MPAS-I) (Randall et al., 2019).
 245 Our experiments in this paper are conducted using $\sim 30\text{km}$ diameter grid spacing, with 58 vertical levels up to 40km height.
 GCMs with this horizontal spacing can be understood as representing the edge of the GSRM resolution range. Based on prior
 model outputs, this is fine enough to yield realistic numbers of TCs with a realistic distribution of central pressures, and is
 comparable to earlier global TC modeling studies conducted at $\sim .25^\circ$ resolution with other grid geometries (Bhatia et al.,
 2018; Bacmeister et al., 2018; Irvine et al., 2019).

250 2.2 SAI/Forcings

Forcings for our experiments are based on outputs from the WACCM model described in Tilmes et al. (2020), as discussed in
 Introduction. While maintaining EarthWorks' dynamical simulation properties otherwise, data from WACCM ensemble mem-
 bers is used to force SSTs, sea ice cover, and SO_2 sources, with GHG concentrations taken from corresponding EarthWorks
 historical/SSP scenario presets. SST and sea ice are forced on a daily basis, while SO_2 production (rendered in 3 dimensions)
 255 is forced monthly. All three variable fields must be interpolated onto the EarthWorks hexagonal grid. These forcings create
 atmospheric conditions in line with Tilmes et al. (2020)'s studied climatologies, with SSTs themselves directly comprising an
 important element of TC formation conditions.

Given the self-limiting effect of storm-driven surface ocean cooling, models with fixed SSTs may be missing an important
 factor limiting storm intensity. However, given the range of storm intensities (Wehner et al., 2014; Irvine et al., 2019) reported



260 in GSRMs with and without fixed ocean temperatures, and inherent limitations of representing storm intensity at resolutions like ours (Davis, 2018), this effect is likely second-order.

With our forcings from Tilmes et al. (2020) and related NCAR-conducted experiments in CESM2-WACCM, we have constructed three climate scenarios intended to establish baselines for TC behavior in EarthWorks, and study the tempestological effects of both severe global warming and potential SAI responses. These are:

- 265 – **Control Run**, with forcings based on the years 1990-1999 (Danabasoglu, 2019a) (ensemble member r1i1p1f1) in CMIP6. This is well within the era of satellite TC observations, but likely before most appreciable change in climatic TC influences.
- **SSP5-8.5**, with forcings based on the years 2090-2099 in CMIP6 ScenarioMIP SSP5-8.5 (Danabasoglu, 2019b) (ensemble member r1i1p1f1). Extremely strong warming signal that should make clear any significant TC-climate relationships
 270 of significance.
- **SSP5-8.5-Intervention**, with forcings data for the years 2090-2099 from Tilmes et al. (2020) scenario "Geo SSP5-8.5 1.5" (ensemble member 001). Based on SSP5-8.5 trajectory, but with SAI deployment beginning in 2020 sufficient to keep global mean temperatures at 1.5° above pre-industrial conditions as well as meet secondary climate goals.*

The first part of our Analysis consists of comparing TC tracking results from our Control Run against best-track data for the
 275 same time period from IBTrACS (Knapp et al., 2023). To the extent our combined model/tracking algorithm system is able to faithfully reproduce the observed contours of global tempestology as they existed in the 1990s, it will build confidence in our experimental results.

Our two future scenarios will allow us to interpret differences in TC properties in light of significant changes to related climate variables. We will seek to examine changes in ENSO and the distribution of storm-generating SSTs, among other
 280 possible mechanisms, to determine if SAI has the potential to significantly reduce/alter TC risks. As well, our SSP5-8.5-Intervention scenario constitutes among the first attempts to directly model tropical storms in high resolution under climate intervention (Irvine et al., 2019), and the first to so utilizing a realistic SAI regime.

2.3 PHAST Tracking Algorithm

As discussed in the Introduction, TC-like features appearing in the outputs of models at lower-end storm-generating resolutions
 285 either do not, or should not (Davis, 2018) generate winds with a full range of realistic intensities. Based on model native wind speed, storms tracked in our Control Run scenarios very rarely achieve CAT 3, and never attain intensities any greater.

Seeking alternative means of diagnosing the intensity of model storms as they would manifest in the physical world, we turned to the literature quantifying empirical relationships between TC category/wind speed and other variables. The literature on constructing Wind Pressure Relationships (WPRs) demonstrates tight correlations between TC central pressure/-

*Includes 5 days of interpolated SST data, September 26-30 2097, as patch to data error.



290 pressure deficit and max observed wind speed (Knaff and Zehr, 2007, figure 5). This allows minimum central pressure, which is often easier to observe than maximum winds, to serve as a stand-in for such and for overall storm intensity.

Similarly, in EarthWorks model outputs, minimum and near-minimum pressures occur over a much larger area within each storm eye than wind maxima outside of such, creating a more robustly measurable feature. TC central pressures in EarthWorks outputs map more closely to real-world distributions than do max winds, with pressure minima arising equivalent to even strong
 295 CAT 5 storms.

In light of this contrast in the model properties of these possible intensity measures, we decided to update an existing tracking algorithm, TSTORMS (Vitart et al., 1997; Zhao et al., 2009), to take advantage of mapping pressure data onto wind-based storm categories through interpretation of pressure minima via a WPR relation.

As part of our modifications to TSTORMS, after candidate vortex features at each time step are stitched together into
 300 candidate TC tracks, storm intensity minimum requirements are applied based a mix of native wind and pressure constraints. Rather than requiring a minimum 17 m/s V_{max} across three model days, PHAST utilizes a dual requirement of native winds of 10 m/s, and central pressures corresponding to 17 m/s in our chosen WPR (see Appendix) across the same span(s). After this initial intensity filtering, measured intensity is then based entire on mapping PSL onto calculated wind speeds and resulting Saffir-Simpson categories.

305 Other adjustments to TSTORMS include changes in variable window sizes and requirements for maxima/minima identification based on the possibility of storms occurring closer together in space than the 6° in latitude/longitude allowed previously. A number of TCs in EarthWorks output at our ~ 30 km resolution have passed close enough to each other for TSTORMS tracking to start to treat them as a single storm despite maintaining distinct geometries, creating phantom storm deaths/births, which we have significantly remedied through adjusting minima/maxima consideration areas.

310 Finally, as in other configurations of model outputs and storm trackers (Han and Ullrich, 2024), PHAST initially misidentified subtropical systems, particularly off the coast of South America and in the Mediterranean, as TCs. Broadly, TC genesis is extremely rare outside the world's main tropical cyclone basins, and detected storms in these other areas are in fact subtropical systems with important differences from TCs in structure and smaller ranges of intensity.

To quickly distinguish TCs from other convective systems, we impose a storm-center SST requirement to ensure that storms
 315 are occurring in conditions consistent with tropical storm climatology. To be identified as a valid TC in PHAST, a candidate convective system's pressure-center track is matched with SST outputs for the same grid positions in time and space. Each point on the track is tested for whether it represents a storm-SST conjunction with surface temperatures of at least 27° C, not on/over land. Valid TCs meet these conditions for at least one time step over their lifetime.

This temperature threshold comes from the literature on thermodynamic bounds on cyclogenesis (Tory and Dare, 2015).
 320 It represents a highly conservative lower bound on TC formation temperatures, which effectively removes virtually all false positives in our storm track data. A few valid model TCs may be disqualified under this filtering, but track numbers in the world's main TC basins appear virtually unchanged, and the main group of false negatives arising here likely represent low intensity TS/TD storms that do not factor into our main analysis.



2.4 Best Track Data/Method Calibration

325 To compare to/evaluate the realism of our Control Run results, we use the all-basins tropical storm track data from the IBTrACS database (Knapp et al., 2023, 2010), a global compendium of satellite and in-situ observations/interpretations.

Unless otherwise noted, all analysis of TC tracks between both model and best-track data is limited to storms CAT 1+ (IBTrACS categories taken from "USA_SSHS" variable). This increases the reliability of best-track data for the studied period, and limits the rate of false positives in PHAST. This choice has the downside of reducing our effective sample sizes and
330 statistical significance. But overall, we feel that a focus on hurricane strength TC-intensity storms allows us to exclude enough observational and methodological artifacts to justify this reduction in scope.

3 Control Run vs. IBTrACS Comparison

3.1 Storm Numbers and Intensities

Initial track analysis of our Control Run shows high fidelity for historical TC behavior. Using forcings for the 1990-1999
335 period, similar numbers of tracked storms are generated and detected as compared to IBTrACS (605 vs 517, respectively). Storms occur across a range of intensities mirroring real-world distributions, albeit with significantly fewer major storms (CAT3+) (figure 2). This could be a result of resolution effects, with highly localized convection extrema necessary to resolve to create realistic TC central pressures. Alternatively, some other artifact of our model physics, such as its parameterization of turbulence (Nardi et al., 2022) or some other small-scale process, may be creating systemic errors especially apparent in the
340 TC context.

The lowest TC central pressure recorded in our 1990s Control Run, 899.2 hPa, corresponds to a WPR wind speed of 82.3 m/s (296 km/h). This is toward the upper end of observed TC intensities, and demonstrates that our model and method can yield a full spectrum of such intensities, if not a balanced distribution. This indicates that our downward intensity biases are either not fully consistent across model time and space, or are partially balanced by occasional variable biases in the other
345 direction.

3.2 Basin and Latitude Distribution

Using basin geometries from Bhatia et al. (2018), and dividing both IBTrACS and EarthWorks track data by storm origin, we find fairly similar historical distributions of TCs among the world's basins (figures 4, 6). Some IBTrACS categories data may be affected by observational data rounding (Nayak et al., 2024), although applying the same rounding to EarthWorks data
350 shows this affect is likely minimal overall. Broadly, our Control Run has a somewhat lower share of storms occurring in the Pacific. But overall, the basin geometry of storm trackways, origins and directions of movement are represented with great affinity. TCs occur with great density at their cyclogenesis region in the East Pacific, and along much of their range in the West Pacific.



Major differences in basin geometry between these data sets occur as a function of detection lifetime; the lengths of time
 355 TCs are tracked very early in cyclogenesis, and following extratropical transition. Lifetime effects are perhaps most clearly
 visible at the start of the North Atlantic trackway, with pre-TC features in EarthWorks forming the start of storm tracks over
 West Africa, well before/east of where they do so in IBTrACS.

Although tracked storms in our Control Run cover sometimes much longer distances than their best-track counterparts, their
 lifetimes are similar. EarthWorks storms that achieve CAT1 at any point, are alive for a mean of 11.2 days, while the mean
 360 CAT1+ IBTrACS storm occurs over 3-hour steps comprising 11.0 days. In contrast, such EarthWorks storms achieve a mean
 translational velocity, based on 6-hour time steps, of 20.5 km/h, while every two 3-hour steps, equivalent IBTrACS features
 on mean have travelled at 17.5 km/h. Given that our EarthWorks/PHAST tracks appear to include earlier and/or later stages of
 storm evolution (figure 4), these higher velocities and longer tracks with equivalent lifetimes indicate a faster TC life cycle;
 altogether, EarthWorks storms form, move along their trackways and then dissipate consistently faster than in reality. Only some
 365 of the translational speed difference seen here is due to intensity-related effects, as our EarthWorks and IBTrACS translational
 velocities while storms are actively CAT1+ are, respectively, 20.0 km/h and 17.7 km/h. Rather, storm translation occurs faster
 in our simulation across development stages, leading TCs to progress through their evolution from tropical disturbance to post-
 tropical storm more quickly as well. This may also have the effect of reducing peak storm intensities, as systems spend less
 time over patches of ideal SSTs.

370 3.3 Storm Properties

Storms seen in EarthWorks, like those in other GCMs (Nardi et al., 2022) can be broadly described as "donuts."* That is,
 in magnitude 10 meter wind (U10), outgoing longwave radiation and other variable fields, fundamental convection processes
 will create an eye geometry broadly corresponding to that expected from fundamental storm physics (see figure 1). Central
 pressure and eye wall wind speeds vary inversely on curves similar to those derived from observations. But partly due to
 375 resolution limitations, and partly due to biases in model dynamics/parameterization (Nardi et al., 2022), finer scale features
 seen in the real world may not be apparent. Thus, GCM-generated TCs, even when yielding accurate population-level features,
 bear important differences on a storm-level basis with observations.

Given the largely correct basin distribution patterns and macro behavior exhibited by EarthWorks, CAM, HiFLOR, etc
 (Bacmeister et al., 2018; Bhatia et al., 2018), it is likely that most of the fundamental controls on TC distribution can be found
 380 at scales $\sim .25^\circ$ and above. We therefore feel confident in analysis of overall GCM storm trends at this resolution relating to
 such, if perhaps less so with respect to precipitation and other properties more closely tied to exact storm geometry.

Bhatia et al. (2018) discuss observations of storms undergoing rapid intensification (RI) in HiFLOR, and compare rates
 of such to those seen in IBTrACS and ADT-HURSAT databases. Similarly defining RI as storm intensity change of +30kts
 (15.43 m/s) in 24 hours, we find that using the PHAST pressure-intensity relation to evaluate storm evolution, 92.9% of CAT1+
 385 Control Run storms undergo RI over their lifetimes, including 96.5% of major storms that do so. Expanding in this instance to
 include sub-CAT1 storms, we still find an overwhelming majority, 80.2% (795/991) experiencing RI.

*Personal correspondence with Colin Zarzycki and others.

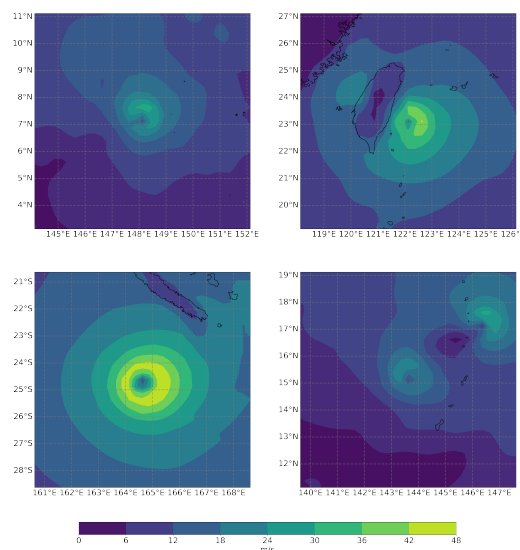


Figure 1. Model-native U10 contour plots for selected TCs, Control Run. Clockwise from top left: West Pacific storm with PHAST-calculated TS intensity; CAT3 storm making landfall on Taiwan; TS experiencing Fujiwhara effect rotation relative to another system; CAT5 TC south of New Caledonia.

These findings are similar to those for major ADT-HURSAT storms as analyzed by Bhatia et al. (2018), and reflect reality insofar as most intense TCs are observed to experience RI. But as compared to the IBTrACS and HiFLOR data sets, and compared to RI lifetime shares for all three Bhatia et al. (2018) historical period data sets, significantly overstate the speed at which most storms generally intensify.

However, such figures may partly reflect the geometry of our WPR curve. Using an alternative NHC definition of RI as a drop in minimum pressure of 42 hPa over 24 hours (Holliday and Thompson, 1979), we find that all Control Run TS/TC storms, CAT1+ TCs, and major storms, respectively, experience RI 15.4%, 25.3%, and 50.4% of the time. The all-Control Run storms see a boost in mean max WPR intensity from 39.0 m/s to 56.5 m/s, with RI vs. without, and in median max intensity from 36.6 m/s to 56.8 m/s. The magnitude of this effect however is still much smaller than those seen by Bhatia et al. (2018) [figure 4] both in best-track data sets and in their HiFLOR experiments.

These pressure-based RI figures are in line with the overall lower frequency of major storms, and lower intensity of such, in our EarthWorks-PHAST outputs as compared to best-track data. And we do see a significant correlation between RI and lifetime maximum intensity here, albeit not to the same extent as observed in the physical world. These exploratory RI findings for our Control Run data set potentially point to the overall preferability of pressure-based metrics for evaluating TCs at this and similar model resolutions. Overall, rapid intensification may not be driving storm development as much in EarthWorks as it does in observations or in Bhatia et al. (2018)'s model native-wind evaluations.



4 Warming, with and without Intervention

4.1 Storm Numbers and Intensities

In line with the bulk of prior modeling/earlier literature, severe warming in EarthWorks yields a world with fewer TCs, but a greater number of CAT5 and outlier/extreme intensity storms. The highest PHAST WPR wind speed observed in SSP5-8.5 is 97.5 m/s, and the scenario includes 8 storms tracks with speeds above the Control Run max, 82.3 m/s. Increasing in number, maximum intensity, and time spent in CAT5 intensity range, the most powerful storms in this warming scenario could represent a significant, disproportionate increase in natural disaster risk, on account of the exponential relationship observed between storm intensity and damage (NOAA, 2024).

Notably, though both future scenarios do represent significant shifts in climate from historical conditions, global TC counts only change substantially with warming that's unmodified (461 in the SSP5-8.5 run, vs. 606 in SSP5-8.5-Intervention). SAI returns global storm number roughly to current observed levels, in spite of important climatological differences between SAI-cooled climates and same-temperature unmodified ones (Tilmes et al., 2020).

The most parsimonious explanation of global trends toward increased storm intensity and reduced storm number with warming, is a combination of higher vertical stability and/or vertical shear inhibiting cyclogenesis, combined with higher SSTs fueling more powerful heat engines. Comparing the scenarios' intensity curves, however (figure 3), while our Intervention experiment roughly matches up with our Control Run distribution, the occurrence of CAT5 and stronger CAT4 storms more closely resembles the magnification seen in SSP5-8.5.

Our Intervention scenario, then, does not represent a linear part-way state between our warming and historical runs in terms of intensity distribution, but rather includes elements of both. Possible explanations for this apparent linear independence include basin-scale effects, physical non-linearity in stability or heat engine mechanisms, or changes in global SST patterns not present in either unmodified scenario. Given that introduced SO₂ in our model should largely precipitate out of the stratosphere over the poles via the Brewer-Dobson circulation, and comprise a fairly small share of overall global aerosols, it is highly unlikely that direct aerosol effects play any major role here at the surface level.

Potentially, our results may be confounded by sample size effects, given the stochastic nature of storm number in any given year, especially taking into account the systemic effects of oscillations/cycles including ENSO. Large-scale cyclogenesis-related variable outputs and ENSO indices are explored to examine potential mechanisms for this unexpected result, in Chapter 5.

4.2 Basin and Latitude Distribution

The most notable basin-scale feature of our SSP5-8.5 scenario is a substantial reduction in Atlantic basin TC activity vs. our Control Run. The share of storms occurring in this basin roughly halves, on top of overall reductions in global activity, yielding a net 61% reduction in Atlantic basin storm count (96 vs. 37). This confirms results of similar magnitude found by Bacmeister et al. (2018) in their RCP8.5 experiment as compared with their present day baselines. Notably however, this contradicts the findings of Bhatia et al. (2018), who report somewhat increasing numbers of both major storms and overall storm numbers

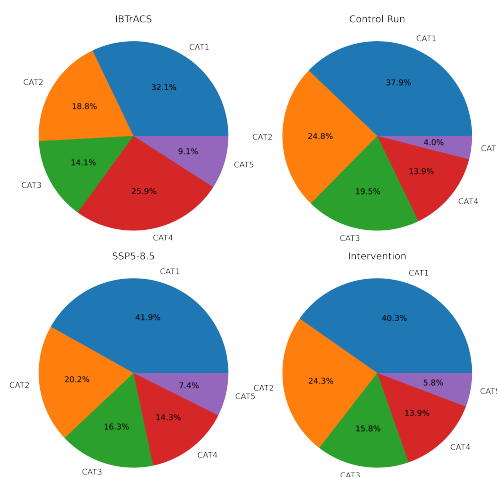


Figure 2. All Scenario Category Distributions (max lifetime intensity)

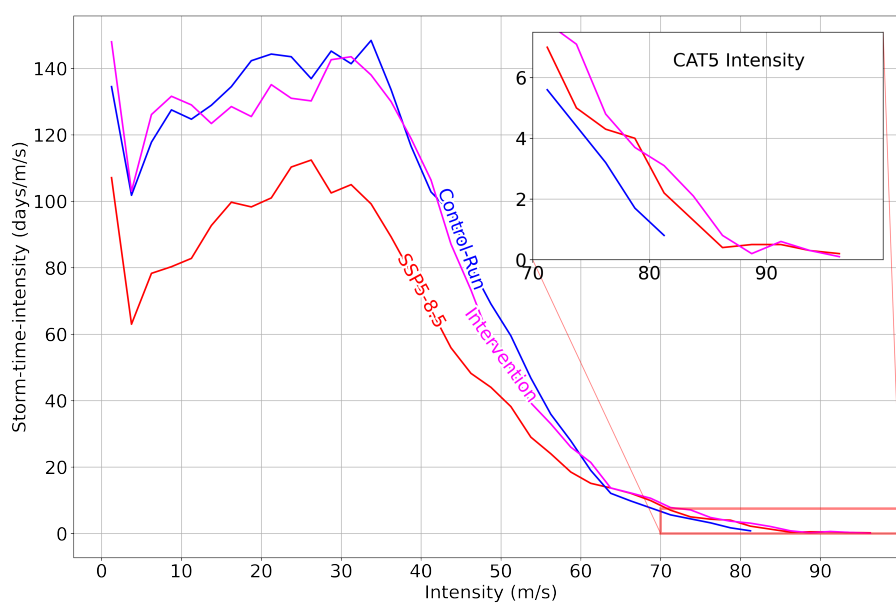


Figure 3. Distribution of WPR-calculated wind intensities for PHAST-generated TC storm tracks (CAT1+). Each storm at each time step constitutes 6 hours of storm-time at its current intensity. Curves extend to maximum observed intensity for each run. Bins are 2.5 m/s wide, with values adjusted to density per m/s unit.



in the Atlantic basin, in both near future and end of century simulations, even as frequency does either decrease or remain steady in other regions.

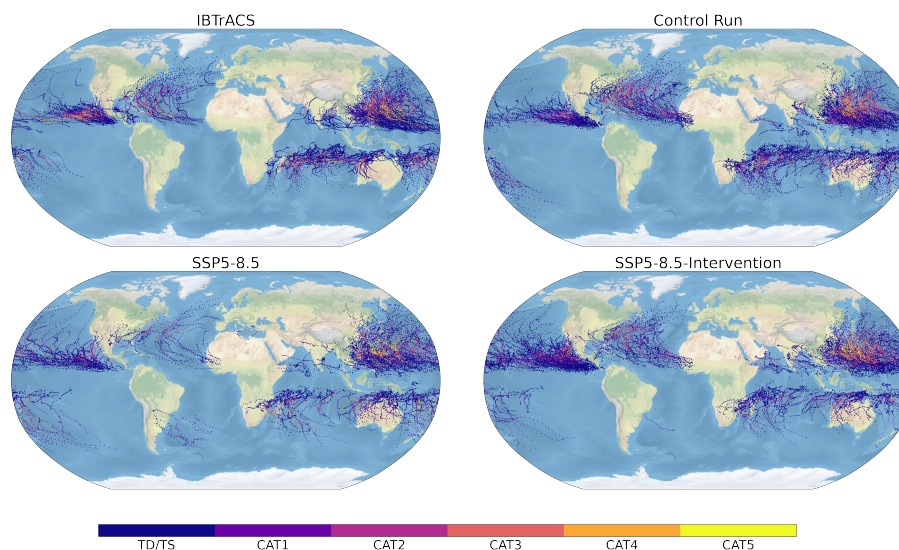


Figure 4. PHAST-generated scenario TC tracks with 1990s IBTrACS comparison map. Excludes systems that never achieve CAT1+ intensity based on PHAST WPR.

Bacmeister et al. (2018) tentatively attribute the decrease in Atlantic TC activity to El-Niño-type warming exhibited in both their RCP 4.5 and RCP 8.5 experiments, characterized by a significantly warmer east Pacific SST field, and accompanied by enhancements in NW Pacific storms as well. If warming may potentially generate strongly positive mean ENSO states ("permanent El Niño"), this mechanism may then constitute the most significant pathway by which global climate effects global storm distribution.

Also notable in our SSP5-8.5 results is the emergence of activity in the south Atlantic basin absent from our Control Run (and Intervention) data. This novel basin behavior corresponds to increased south Atlantic TC activity seen by Bacmeister et al. (2018) [figure 2]. TCs form in this region very rarely in the observational record, and only once at CAT1+ (Pezza and Simmonds, 2006). TCs are generally accepted to not form in this region on account of high tropospheric vertical wind shear, and SSTs below necessary cyclogenesis thresholds.

PHAST's detection of storms here may be related to its misattribution of subtropical systems before the introduction of an SST threshold (Methods). But, given that these warming scenario storms are contained firmly in the region where South American TCs occur in real life; and that ocean conditions are significantly more amenable to TC formation than in the present climate, it seems plausible that this result may correspond to a genuinely enhanced risk of TC formation further from the equator than previously, and in regions of the world typically not now associated with such.

Our SSP5-8.5 track data, additionally, includes a very small number of storms meeting TC detection requirements in the Mediterranean. This region already sees TC-like storms, "medicanes" (Lagouvardos et al., 2022), otherwise excluded by our



455 TC SST threshold. However, the detection of valid TCs in this region with warming may indicate the possibility of more truly hurricane-like systems emerging here in the future, or at least highlight possible dangers arising from medicanes forming under conditions with more available thermal energy.

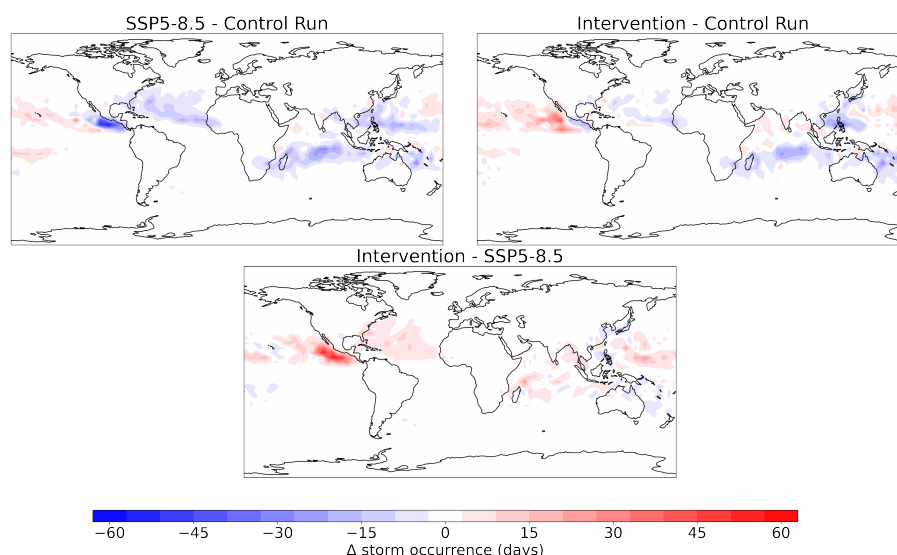


Figure 5. Contour plots of scenario differences in TC (CAT1+) track density. Storm occurrence days are counted on a 4° by 4° grid, based on 6-hour step track positions. Density changes <3 storm days/decade not shown.

Otherwise, between our Control Run and SSP5-8.5, our global reduction in TC number occurs fairly evenly across the world's major TC basins, with the south Indian basin seeing an especially strong reduction, and very few places observing any increase in TC number (see figure 5).

Figure 5 also shows major differences between SSP5-8.5-Intervention and both other runs. In magnitude of total warming relative to historical conditions, differences between SSP5-8.5 and SSP5-8.5-Intervention correspond greatly with the BRACE signal explored by Bacmeister et al. (2018) and others, seeking differences in climate/weather risk between RCP8.5 and RCP4.5. Albeit, given the calibration of our chosen SAI paradigm to maintaining important features of the present/pre-industrial climate (Tilmes et al., 2020), important differences will exist in SST and atmospheric temperature patterns between a largely GHG-driven warming of this magnitude, and one achieved through a GHG overshoot paired with any radiation modification scheme.

As compared with unmodified warming, intervention yields higher TC occurrence virtually wherever it exists with any significant density (figures 4, 5). The number of Atlantic basin storms under intervention is partially restored to historical numbers (69 over the decade), though still represents a significant shift from historical conditions. The most notable basin-scale feature of SSP5-8.5-Intervention, however, is a doubling of storm number in the east Pacific, particularly in waters southwest of the Baja California peninsula. This seemingly leads to substantially increased TC landfall in this general region, and if robust, comprises the most significant enhanced TC hazard posed by this regime of SAI.



Like Atlantic basin suppression, such enhanced eastern Pacific activity, particularly in the basin's western development
 475 region, is consistent with strongly positive ENSO (Jien et al., 2015). However, the fact that both of these El Niño responses
 occur substantially with intervention, but don't consistently correlate across scenarios, indicates a need to examine intermediate
 mechanisms between ENSO and storm activity, further discussed in Bulk Variable Analysis.

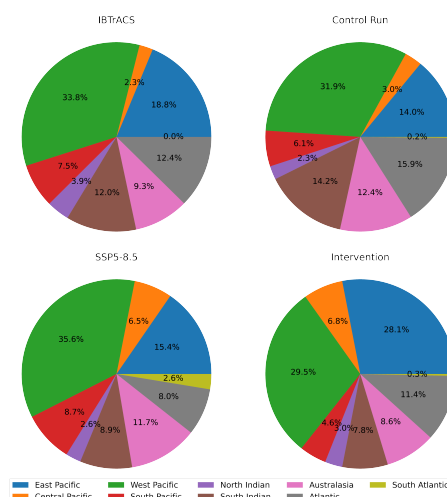


Figure 6. Basin Distributions (system origin)

All three of our simulations share roughly similar relative global storm distribution patterns between the northern and south-
 ern hemispheres. However, our Intervention case possesses a significantly greater share of NH storms, in line with enhanced
 480 east Pacific and north Atlantic activity relative to SSP5-8.5, paired with nearly across the board suppression in SH basins
 roughly in line with such. The emergence of a south Atlantic basin in SSP5-8.5 creates a more significant poleward tail in SH
 track locations, matching a small shift northward in mean NH track positions from the 1990s (20.1° to 20.9°). Expansion of
 regions conducive to maintaining TC convection should expand track ranges poleward, but storms travelling to temperate zones
 may experience preexisting or newly powerful shear leading to their dissolution, regardless of changes in initial cyclogenesis.
 485 Translational speeds in our two future scenarios are largely unchanged from our historical run, with SSP5-8.5 and SSP5-8.5-
 Intervention having mean TC track speeds of 20.4 and 20.6 km/h, respectively. Mean storm lifetimes however, reduce from
 11.2 days in our Control Run to 10.3 and 10.9 days. The reduction in lifetime and thus overall track length with unmodified
 warming appears to occur largely as a result of more poleward cyclogenesis, unpaired with any significant expansion in where
 TCs/TC remnants can survive in colder regions. Southern Hemisphere cyclogenesis statistics are changed non-linearly with
 490 warming by the enabling of successful south Atlantic cyclogenesis, but mean NH starting TC storm track latitude in the NH
 shifts from 12.4° in the historical scenario, to 14.5° and 11.8° , respectively, in our warming and intervention cases. Thus,



storms forming more poleward will tend to be extinguished by latitudinal/continental features relatively sooner, combining with lowered TC numbers to further reduce global TC occurrence time, if not necessarily storm-related coastal hazards.

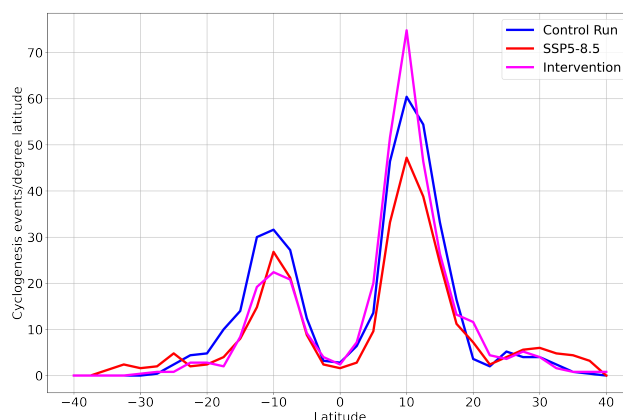


Figure 7. Distribution of starting latitudes of all PHAST-tracked storms (max intensity TS+). Bins are 2.5 ° latitude wide, with values adjusted to density per ° latitude unit.

Expanding our analysis momentarily to include max-intensity TS tracks (figure 7), we see that even as the number of cyclogenesis events total declines with warming (from 991 in our historical scenario to 773 and 921 in our warming and intervention cases), there are greater absolute numbers of such events starting around $\pm 25^\circ$ in each hemisphere. By contrast, storm formation is still about equally suppressed near the equator.

Overall, warming will tend to act on TC latitude distributions within basins and/or apart from more specific teleconnections, through changes in cyclogenesis. Despite polar amplification and other developments that could make the mid-latitudes more like the tropics, TC systems are seemingly not able to survive significantly further from the equator than in the historical record, likely on account of persistent limiting factors like mid-latitude shear.

4.3 Rapid Intensification

Notably, in contrast to Bhatia et al. (2018), our warming scenario produces small, consistent decreases in the share of observed TCs undergoing RI, from 25.3% and 50.4% for CAT1+ and major storms, respectively; to 20.0% and 44.0% in SSP5-8.5; and 23.9% and 51.6% in the Intervention case. The max intensities of CAT1+ storms without and with RI, however, stay roughly the same or increase (in both future scenarios), to means of 48.1 m/s and 62.4 m/s in SSP5-8.5 (WPR-calculated); and 47.7 m/s and 61.3 m/s with Intervention, in contrast to 47.4 m/s and 56.5 m/s in the historical data.

This is somewhat counterintuitive, given the association of RI with increasing storm intensity, and the overall greater share of storms under warming reaching major storm status. However, RI processes may operate through distinct mechanisms/modalities vs. other intensification processes (Judt et al., 2023), and thus storms could in fact grow more intense on average without any increasing frequency of RI. Features like changes in shear may reduce rates of RI significantly more than they effect inten-



sification overall, reflecting the multiple competing mechanisms by which shear, cyclogenesis and heat engine effects combine to yield new patterns of storm occurrence and intensity.

4.4 Seasonality

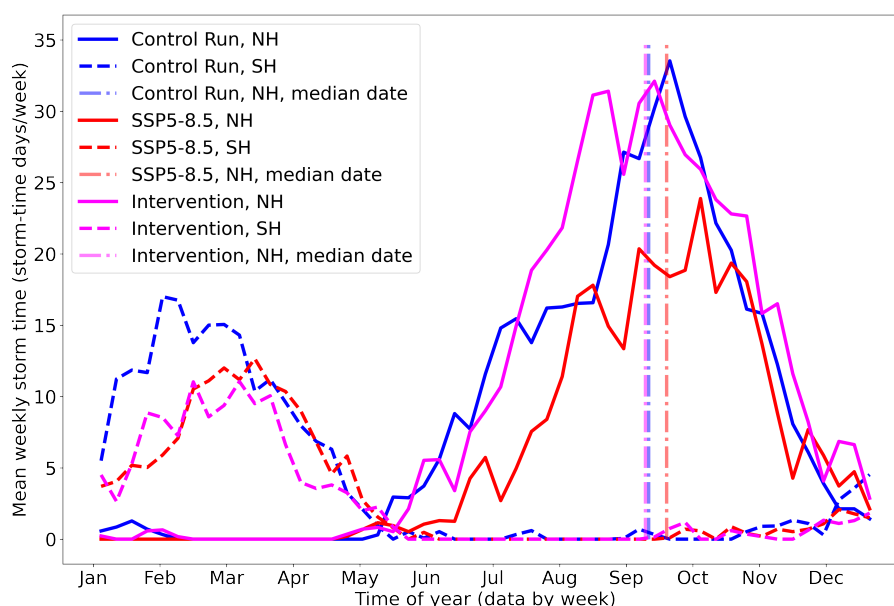


Figure 8. Storm occurrence density by time of year, cumulative over full scenario run periods. Binned approximately by week (365 days/52 weeks). Storm occurrences counted in 6-hour intervals.

515 Broadly, in all scenarios, NH and SH TC occurrence maintain the same basic relationships with hemispheric seasonality. TC formation remains dependent on meeting minimum threshold SSTs, which are most present in late summer/early autumn.

With warming, mean and median storm occurrence time are delayed further in each hemispheric storm season (discussed further in Global Temperature Patterns). This change in timing however cannot be completely disentangled from basin-scale effects, given differing basin seasonal patterns paired with relative changes in basin TC share. Given the data limitations of
 520 this study, and the high variability of storm track time-occurrence within a given basin in any given year, any such regional seasonality findings will necessarily be low-confidence. But, overall hemispheric trends reveal that despite rising global SSTs, under warming it becomes increasingly difficult for early-season TCs to arise and intensify across the world. By contrast, late-season TC occurrence in both hemispheres may be largely unaffected by warming or warming limited by intervention, or even increase despite sharp drops in all-season activity overall.

525 Given that storm lifetimes are not, on net, increasing, this shift must be driven in large part by changes in cyclogenesis favorability, in particular by those in limiting factors acting counter to rising SSTs, explored further in Chapter 5.



5 Bulk Variable Analysis

5.1 Global Temperature Patterns

Forced by our WACCM-provided SSTs, but with dynamically calculated land temperature patterns, our Control Run, SSP5-8.5 and SSP5-8.5-Intervention scenarios see mean global temperatures over their respective decade runs of 15.3°, 20.9°, and 16.3° C. By itself, changes in global temperature patterns between our Control Run and SSP5-8.5 scenarios would likely yield significant increases in global storm activity. The number of monthly location-time points on our interpolated .25° grid exceeding the 27° threshold increases X1.9 with warming, and regions of ocean with cyclogenesis-enabling temperatures expand in both time and space.

In SSP5-8.5, the mean date of such NH storms' place-time occurrences is delayed 10.7 days further into the season compared to our Control Run, from September 6th to September 17th, and the median date is delayed 8.25 days, from September 10th to September 18th. Higher SSTs combined with lower overall storm numbers, especially/largely early in each hemispheric season, indicate higher SST thresholds typically reached later in the season perhaps becoming necessary to break through greater cyclogenesis barriers. Seemingly, rising SSTs in our warming world are acting counter to changes in vertical stability or other factors acting to suppress TC activity, and overall shifts in global storm patterns arise from a balance of these.

The clearest example of SST-driven changes in cyclogenesis is likely in our newly populated south Atlantic basin in SSP5-8.5. Despite local increases in stability and intensification of already strong shear, TC activity rises from virtually nothing in the other two cases, to on the order of 1 CAT1+ storm per year. Given its sharp divergence from current tempestologies, this result is necessarily low certainty in the absence of corroborating non-model evidence. But it is in line with our overall understanding of cyclogenesis, and presents perhaps the most novel potential hazard arising from TCs in a warming climate.

As discussed in Introduction, it is possible that climate change may give rise to shifts in current ENSO patterns (Callahan et al., 2021), which may be a primary mechanism by which climate interacts with TCs.

Given the relatively short spans of our model runs, and their non-continuity in time from each other, we have chosen here to use a history-agnostic ENSO index, the ENSO Longitudinal Index (ELI) (Williams and Patricola, 2018). For each month of our climatological data, we have computed ELI by finding the mean longitude of Pacific SST points warm enough to permit convection, occurring between +/- 5° latitude, as defined by Williams and Patricola (2018). This index allows us to compare ENSO behavior between radically different climate regimes, regardless of shifts in baseline SSTs that may otherwise obscure important new modalities.

From the perspective of mean SST changes between our Control Run and two future scenarios (figure 9), the Niño 3.4 and broader equatorial cold tongue region warms at a substantially higher rate than adjacent regions of ocean, including relative to the western Pacific. This is in line with a substantial weakening of ocean upwelling in the cold tongue region, and indicates a version of permanent El Niño occurring by the end of the century with both unmitigated warming and warming offset by SAI.

Through the lens of our ELI index (figure 9, figure 10), while mean ENSO intensity does substantially increase between our Control Run and both future scenarios, this is driven by a shift toward much more powerful positive-ENSO (El Niño) events. These events regularly push the calculated mean longitude of convection in the Pacific well east of anything observed in the

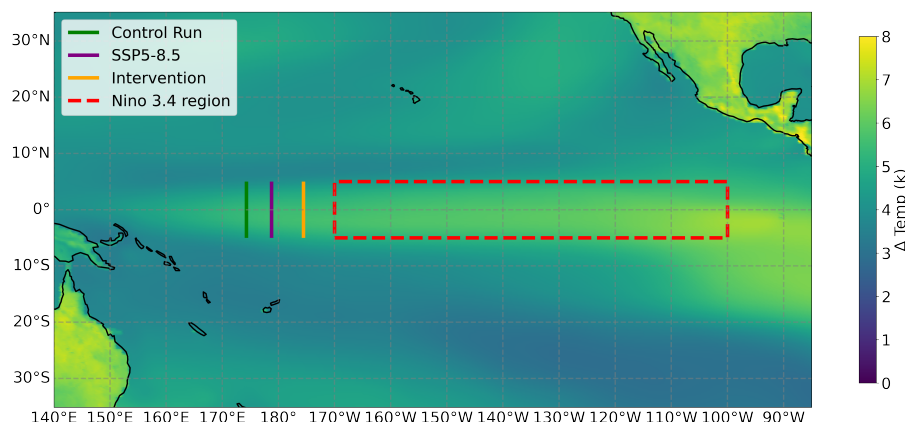


Figure 9. Mean all-run ELI longitude for each scenario, mapped against Niño 3.4 region used in calculating ONI based on SST anomalies.

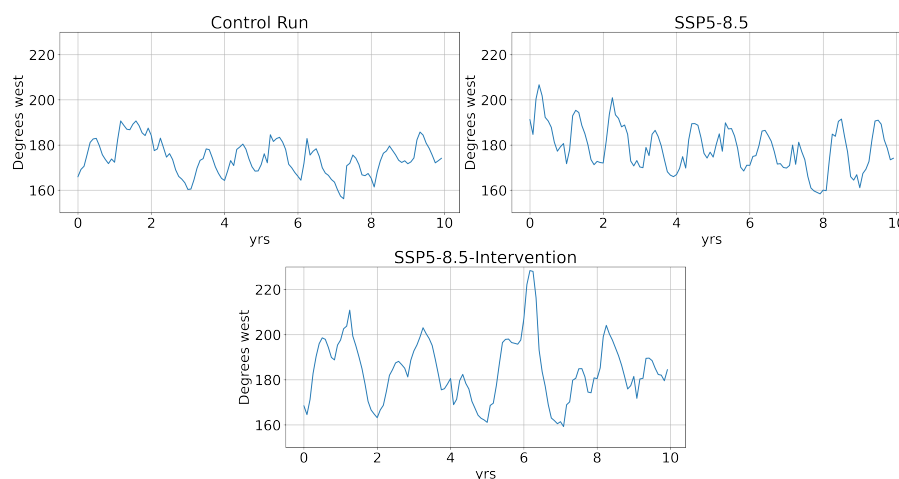


Figure 10. Monthly ELI longitudes, indexed from start of each scenario

historical simulation, and through El Niño's effects on vertical wind shear and stability measures (Arpe and Leroy, 2009), could perhaps entirely explain our observed future drops in Atlantic TC activity.

The degree of storm activity enhancement in the east Pacific with intervention could potentially be a function of the much greater strength of El Niño events observed in that climate trajectory as compared with SSP5-8.5 (figure 10), including unprecedentedly powerful El Niño events in simulated 2091 and 2096 (compare to long-term historical index values in Williams and Patricola (2018)). These may interact non-linearly with other climate features to create periods of higher storm activity, or higher ENSO intensities may merely be less damped in their effect on this basin by separately arising changes in other cyclogenesis variables. ENSO may particularly influence TC activity in this region through higher SSTs and changes in vertical shear



(Jien et al., 2015), which occur on top of mean climatologies and thus provide an opportunity for this difference in scenario responses.

Work by Mueller et al. (2024) using a direct TC modeling approach in WRF, finds that even in an overall more El Niño-like future climate, year-to-year variations in ENSO indices are still predictive of Atlantic TC activity, even as long-term conditions further suppress such. Thus, whether our ENSO results are interpreted as a shift toward permanent El Niño conditions, as a tendency toward substantially stronger El Niño events, or some combination of such, ENSO and its effects on Atlantic basin shear and vertical stability are consistent with our TC observations, with intermediate mechanics discussed in Vertical Stability and Shear.

5.2 Vertical Stability

We have focused our analysis of vertical stability on Convective Inhibition (CIN), a measure of the energy required for surface parcels to reach the level of free convection. For purposes of studying shifts in CIN as they relate to cyclogenesis, we have produced maps of monthly mean values for the three months comprising peak hemisphere-wide TC occurrence in both the NH and SH, when cyclogenesis is most likely to occur.

Our most notable NH season finding is a profound intensification in mean CIN values in the eastern Atlantic basin area, extending prohibitive CIN levels to large new parts of the basin's main cyclogenesis areas. This occurs in both future scenarios, albeit much more strongly without intervention. Given the contributions of CIN-related terms in formulations like the Genesis Potential Index (Camargo et al., 2007), the profound changes in such observed here are likely to be the primary, directly controlling variable in determining Atlantic TC activity in our experiments.

Additionally, changes in CIN off western North America may serve to enhance/suppress TC intensification on intersecting tracks, likely reflected in differences in east Pacific storm activity between SS5-8.5 and SSP5-8.5-Intervention. But given how different storm activity is in this region between our Control Run and Intervention cases, despite similar CIN patterns, this is likely not the full story of primary TC controls here.

In the west Pacific, though changes in CIN are substantially smaller than in the Atlantic and elsewhere (figure 13), significant increases can be seen in the main development region between our SSP5-8.5 and other two scenarios. Given SSP5-8.5's relative dearth of storms here in the world's most significant basin, and the lack of a strong local forcing created by vertical shear, this tongue of newly increased CIN generated by warming SSTs is likely responsible for much of the reduction in global storm numbers in this scenario overall.

Future changes in CIN during the SH season may potentially intersect with parts of the broader Australasia storm development region, particularly in SSP5-8.5. But this appears unlikely to be a significant determinant of SH activity, with our CIN results here likely pointing to other factors being dominant.

5.3 Shear

Looking first at NH shear (magnitude 200 hPa - 850 hPa vectors) (figure 14), there are major differences in east Pacific basin shear between our Control Run and SSP5-8.5 scenarios, and between SSP5-8.5 with and without intervention. These

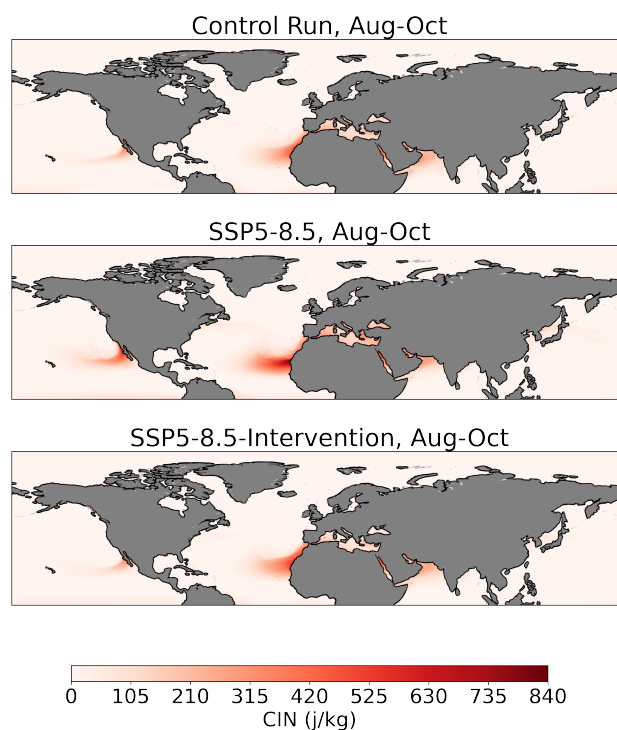


Figure 11. Mean decadal, storm-season mean CIN values for the NH.

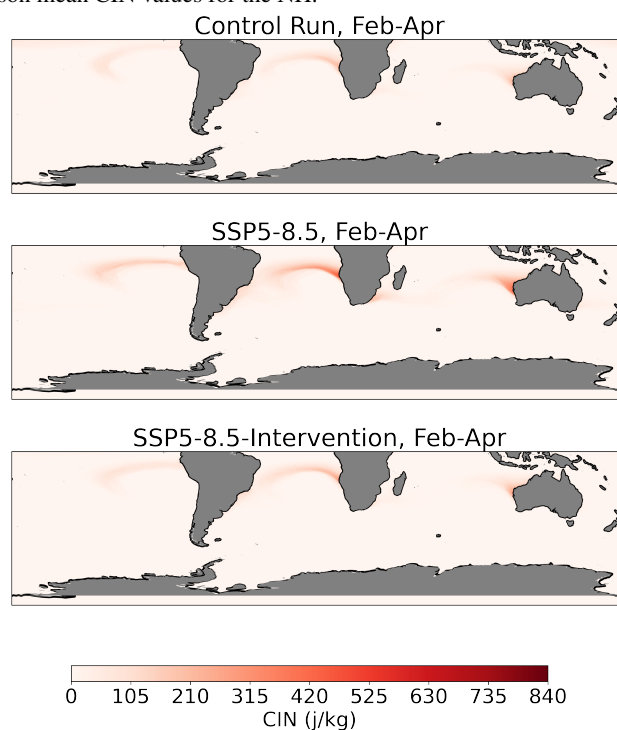


Figure 12. Mean decadal, storm-season mean CIN values for the SH. Colorbar calibrated to NH all-scenario maximum.

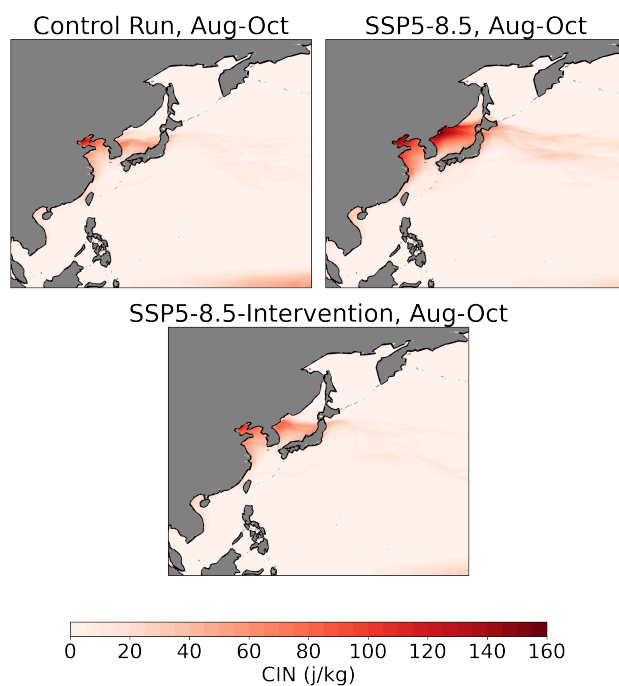


Figure 13. Mean decadal, storm-season mean CIN values for the west Pacific region. Note eastward tongue of higher inhibition in SSP5-8.5. Colorbar calibrated to local all-scenario maximum.

occur in the main development region, are likely influenced by ENSO, and in interaction with shifts in SST and vertical stability (discussed further in East Pacific Synthesis). Altogether, this result, along with higher trackway CIN in SSP5-8.5, likely explains the greater incidence of storms here with SAI in spite of higher SSTs otherwise.

605 Increases in Atlantic development area shear in both future scenarios are in line with expectations given highly increased ENSO indices. These operate in the same direction as CIN in influencing future activity in the basin, and help explain the extreme degree of Atlantic TC suppression seen here and ultimately driven through these intermediate mechanisms by permanent El Niño.

In the SH, given already high levels of vertical shear across basins, substantial increases in such, and the predicted exponential nature of genesis suppression with shear (Camargo et al., 2007), can more than explain substantial reduction in SH storm activity in both future scenarios, including the sharp NH-SH divergence in activity levels seen in SSP5-8.5-Intervention.

5.4 East Pacific Synthesis

Trends between our scenarios in the east Pacific TC basin potentially most exemplify the complexity of cyclogenesis controlling factors, and thus the inherent uncertainties in predicting TC behavior with warming.

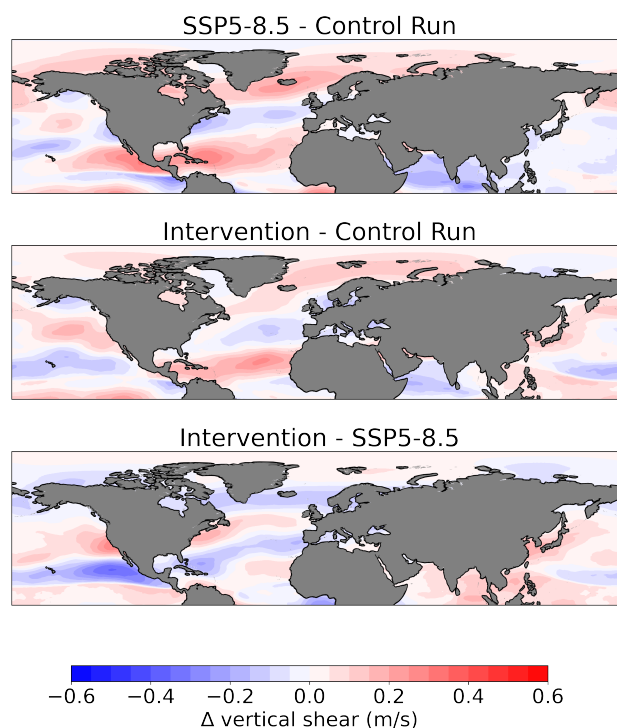


Figure 14. Change in mean decadal, NH storm-season shear magnitude between pairs of scenarios. Magnitudes calculated based on monthly mean U, V values for 200, 850 hPa, differences taken between magnitudes.

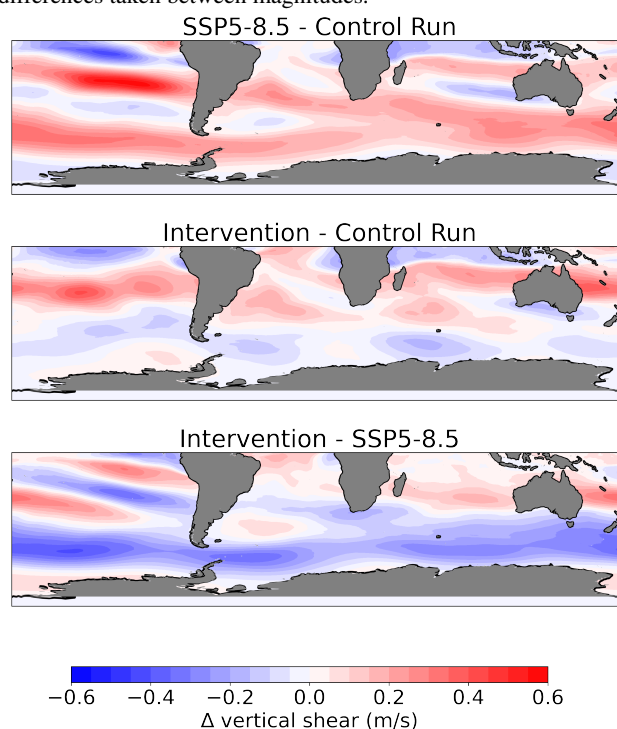


Figure 15. Change in mean decadal, SH storm-season shear magnitude between pairs of scenarios.



615 Despite observed associations between El Niño events, which occur powerfully in SSP5-8.5, and east Pacific storm activity (Jien et al., 2015), this simulation sees an overall reduction in storm number in this basin. Warming with intervention, by contrast yields substantial increases in activity putting this basin on par with the western Pacific in global TC share.

As shown by a close-in view of main-season SSTs in this region, temperatures are already, in historical data, consistently above theoretical thresholds for TC formation, and in both future scenarios well exceed these. This is partly a function of
 620 overall global temperature increases, and partly a result of strongly elevated ENSO indices in both. In either future, all else being equal, this would constitute a positive forcing on TC number.

In terms of local vertical stability changes, in line with parts of other NH basins, SSP5-8.5 sees a substantial expansion of the high-CIN region in the northern part of many typical storm tracks here. By contrast, despite its own local (substantially weaker) SST increases, our Intervention case does not experience a similar CIN effect.

625 The largest differentiating factor here, however, appears likely to be distinct patterns of shear. On top of already fairly significant shear levels in this region, SSP5-8.5 sees very large increases in shear (by NH standards) in the main cyclogenesis region, while between our historical and intervention runs, there's almost no change. Given what's theoretically understood about cyclogenesis, this increase in shear with climate change could more than cancel out any enhancements due to increased SSTs and ENSO effects more broadly, and is likely the primary explanation for our divergence between climate futures here.

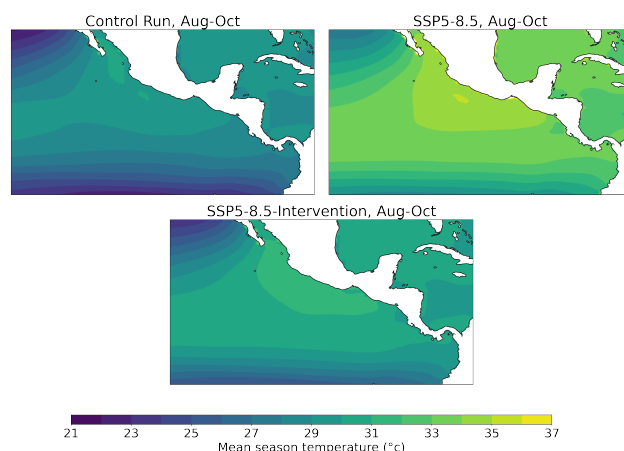


Figure 16. Mean decadal SSTs for east Pacific main development region. Note intensification of Eastern Pacific Warm Pool in future scenarios.

630 While ENSO is a dominant explanation for many changes in TC distribution going into our future scenarios, competing climate effects may serve to interfere with this signal. In making predictions about strong basin-scale TC activity changes for any given climate trajectory, the strength of forecasts may be highly dependent on the robustness of ENSO modeling. Yet, ENSO indices are not fully determinative even in high-sensitivity regions. And given multiple competing effects, our understanding of climate-TC dynamics for the east Pacific basin, home as it is to many of the world's most powerful storm
 635 systems, may necessarily remain more contingent than elsewhere.



6 Conclusions

TCs comprise perhaps the most destructive mesoscale weather phenomenon, and thus represent an important target for GSRM-based research occurring at the intersection of climate and weather. With advances in high-resolution modeling, it has become possible to directly model TCs in global simulations in ways that capture important aspects of their relationship with climate, as well as important elements of their internal dynamics.

In this paper, we have applied paradigms and existing data sets (Tilmes et al., 2020) from the study of climate interventions, and paired them in new ways with techniques to track TCs occurring natively in high-resolution global climate models. In doing so, we have yielded novel results analyzing for the first time resolved TC physics under a realistic, specific climate intervention scenario, algorithmically controlled SAI.

In the course of trying to quantify TC behavior in GCM runs at our chosen resolution, and compare such to real-world observations, we have significantly adapted and borrowed from established TC-tracking algorithms (Vitart et al., 1997; Han and Ullrich, 2024). This has involved moving away from a focus on model native wind speeds as a measure of intensity and development state, given inherent resolution limitations on such (Davis, 2018). Instead other properties, like central pressure and SSTs with more gradual variation in time and space, have proven much stronger as fundamental diagnostics of storm nature.

We have found that, with such pressure- and temperature-based TC tracking heuristics, tropical storm behavior in Earth-Works exhibits high fidelity with best-track data. Our model captures important controls on TC number and intensity, and this work helps demonstrate the potential value of studying mesoscale climate-weather interactions using GCMs at this and even finer resolutions.

Perhaps our most notable finding is that, given a realistic, targeted implementation of climate intervention through algorithmically-controlled SAI, TC occurrence outcomes in each basin can behave in a highly non-linear fashion given different degrees of net warming. That is, the properties and distribution of storms in our SAI climate should not be seen as intermediate between those in historical and advanced warming scenarios. Such intervention may actually yield significant novel risks (say, extremely magnified east Pacific storm activity), even while bringing local climate variables back below thresholds for others (the emergence of a significant south Atlantic basin in SSP5-8.5).

Among the principal limitations of this work has been that presented by available computational power. Going forward, future research studying the impact of SAI and other climate interventions on TCs and other mesoscale features would potentially gain considerable robustness from longer simulation run times and/or finer grid spacings. This is especially true if these are combined with model dynamics/parameterization improvements that create more realistic TCs and other mesoscale features (Nardi et al., 2022), allowing us to study GSRM storms in greater individual detail and output small-scale metrics like TC precipitation and internal dynamics more grounded in reality.

The other main avenues for further work include broadening the range of climate intervention scenarios considered. Different strategies for implementing SAI with alternate climate priorities may yield substantially distinct SST patterns. Different intervention technologies could induce such, while also introducing geochemical (Kravitz et al., 2013) or other effects that



act on TC distribution beyond the mechanisms considered here. Of particular value for understanding future Atlantic basin behavior would be model runs either dynamically exhibiting or forced with significantly lower ENSO indices than arose in our future scenarios.

Given the scale and persistence of other hazards at play in considering advanced warming scenarios and possible interventions, including sea level rise, heat waves, drought, etc., TCs are unlikely to comprise a determinative factor in informing specific geoengineering/emissions policy. Yet they represent an important locus through which global climate can have severe local impacts, with their stochastic and emergent nature substantially complicating our ability to predict and adapt to their behavior in the long term. And thus, as our future climate trajectory is actually realized, it remains important to remember that TCs and other emergent phenomena may behave unexpectedly, and non-linear shifts in such may constitute important contours of the climate future.

Code and data availability. PHAST algorithm and corresponding TC track files can be found at: github.com/afeder17/PHAST

Appendix A

The Pressure-based Hybrid Algorithm for Storm Tracking (PHAST) represents a novel application of known empirical relationships between TC central pressures and wind intensity/category. Based in part on research directions suggested at the close of Davis (2018), and in light of the shortcomings of current GSRM's in representing storm intensity and convection (Judt et al., 2021), we have sought alternative means of quantifying modeled TC intensity distributions.

In the PHAST process, elements of the TSTORMS algorithm (Vitart et al., 1997; Zhao et al., 2009) are adjusted to account for high-resolution grid spacing (including the occurrence of storms close together in space), and paired with storm strength estimation using a wind-pressure relationship (WPR) adapted by Knaff and Zehr (2007) from work by Atkinson and Holliday (1977), with correction for storm intensity biases. Central TC minimum pressures (in hPa) at each time step are plugged into a form of this adapted WPR taken from Holland (2008) (equation 4):

$$V_{max} = 2.3(1010 - P_c)^{.76}$$

This relation yields equivalent maximum 1-minute sustained wind speeds. Thus, model outputs that represent real-world central TC pressures (P_c) more realistically than they do maximum wind speed (V_{max}), can yield TC tracking data with a more realistic range of storm categories.

The algorithm is implemented on (natively hexagonal) Earthworks outputs interpolated to a quadrilateral, .25° lat-lon grid. Variables are returned as instantaneous values given at 6-hour intervals, with the relevant fields comprising: 10m wind speed (U10); pressure at sea level (PSL); vorticity at 850 hPa height (vorticity850); and mean temperature between the 300-500 hPa pressure levels (T300-500). PHAST can be re-tuned to analyze data at other spatial and temporal resolutions as well.



700 The creation of storm tracks from variable fields by PHAST involves detecting candidate vortexes, stitching them together into trajectories, and filtering out extratropical cyclones and other edge cases, as outlined below.

With proximity defined as the greater of the difference in latitude or difference in longitude, in degrees, between two grid points:

1. Candidate Vortexes

- 705
- At each time step, globally, scan for local vorticity850 maxima above threshold of $1.6e-4$, with no other vorticity850 values higher within proximity 2 degrees.
 - Find lowest PSL within proximity 2 degrees of vorticity maxima, the pressure center
 - Find highest U10 value within proximity 2 degrees of pressure center
 - Find the warm core center, the warmest individual T300-500 value within proximity 4 degrees of pressure center.
- 710 There is only a valid candidate TC vortex when this highest temperature value is found within proximity 2 degrees of the pressure center, and is at least 1°C greater than the mean of the proximity 4 degree proximity box.
- Pressure centers arising from vorticity850, PSL, and T300-500 maxima/minima meeting these requirements are added to a list of vortex candidate positions, with accompanying properties, for the given time step.

2. Making Trajectories

- 715
- Initialize two arrays, for dead_storms and living_storms.
 - Load every candidate vortex from the first output time step into living_storms.
 - For each subsequent time step, for every storm in living_storms, if there is a candidate vortex in the new time step within 400km, the storm continues on living, taking on the properties/position of the closest candidate vortex. Older living storms take priority in being matched with candidate vortexes.
- 720 If two or more candidate vortexes are equidistant from a living storm, tie is broken by sum of how relatively northern and westward pressure centers are by degrees lat-lon.
- Living storms with no successor candidate vortex die, and are moved to dead_storms. Candidate vortexes unmatched with a current living storm become new living storms.
 - At the end of each storm's lifetime, storm is identified as a valid TC if, on at least 3 model days, it achieved TS or
- 725 TC intensity. For at least one time step on each of 3 days, the storm's direct model wind max must be at least 10 m/s, and WPR predicted wind max must be at least 17 m/s. Overall storm lifetime must be at least 72 hours.
- Storm category at each time step is based on WPR predicted wind max, plugged into Saffir-Simpson scale.

3. Filtering Edge Cases



- 730 – To distinguish tropical storms from extratropical storms and other TC-like convective systems not a part of TC
best track data, restrict valid storm tracks to those with pressure centers occurring over SST's of $\geq 27^{\circ}$ C for at
least one time step. This does not exclude TC's later undergoing extratropical transition, but does exclude entirely
continental/cold water systems from our consideration.

735 *Author contributions.* AF, DR and DD designed the experimental setup. DD executed the corresponding EarthWorks model runs and asso-
ciated processing. AF designed the PHAST tracking algorithm, and performed storm track and climate analysis. AF wrote the manuscript
draft. DR reviewed and edited the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

740 *Acknowledgements.* The advice of John Knaff and Christopher Slocum have been invaluable in developing the PHAST algorithm and
implementing other TC analysis metrics. They and Yushan Han at UC Davis, prompted Andrew Feder to reconsider our persistent sub-
tropical cyclone misidentification issue, and pointed him toward possible solutions and important limitations of TC tracking algorithms more
broadly.

Michael Bell, over the course of many meetings, was incredibly helpful in deciding on metrics to use in analyzing possible future climates,
particularly with respect to ENSO fluctuations.



References

- Aquila, V., Baldwin, C., Mukherjee, N., Hackert, E., Li, F., Marshak, J., Molod, A., and Pawson, S.: Impacts of the Eruption of Mount Pinatubo on Surface Temperatures and Precipitation Forecasts With the NASA GEOS Subseasonal-to-Seasonal System, *Journal of Geophysical Research: Atmospheres*, 126, e2021JD034 830, 2021.
- Arpe, K. and Leroy, S. A.: Atlantic hurricanes—Testing impacts of local SSTs, ENSO, stratospheric QBO—Implications for global warming, *Quaternary International*, 195, 4–14, 2009.
- Atkinson, G. D. and Holliday, C. R.: Tropical Cyclone Minimum Sea Level Pressure/Maximum Sustained Wind Relationship for the Western North Pacific, *Monthly Weather Review*, 105, 421 – 427, 1977.
- Bacmeister, J. T., Reed, K. A., Hannay, C., Lawrence, P., Bates, S., Truesdale, J. E., Rosenbloom, N., and Levy, M.: Projected changes in tropical cyclone activity under future warming scenarios using a high-resolution climate model, *Climatic Change*, 146, 547–560, 2018.
- Bellamy, R., Chilvers, J., Vaughan, N. E., and Lenton, T. M.: A review of climate geoengineering appraisals, *WIREs Climate Change*, 3, 597–615, 2012.
- Benton, B. N., Alessi, M. J., Herrera, D. A., Li, X., Carrillo, C. M., and Ault, T. R.: Minor impacts of major volcanic eruptions on hurricanes in dynamically-downscaled last millennium simulations, *Climate Dynamics*, 59, 1597–1615, 2022.
- Bhatia, K., Vecchi, G., Murakami, H., Underwood, S., and Kossin, J.: Projected Response of Tropical Cyclone Intensity and Intensification in a Global Climate Model, *Journal of Climate*, 31, 8281 – 8303, 2018.
- Callahan, C. W., Chen, C., Rugenstein, M., Bloch-Johnson, J., Yang, S., and Moyer, E. J.: Robust decrease in El Niño/Southern Oscillation amplitude under long-term warming, *Nature Climate Change*, 11, 752–757, 2021.
- Camargo, S. J., Emanuel, K. A., and Sobel, A. H.: Use of a Genesis Potential Index to Diagnose ENSO Effects on Tropical Cyclone Genesis, *Journal of Climate*, 20, 4819 – 4834, 2007.
- Danabasoglu, G.: NCAR CESM2-WACCM-FV2 model output prepared for CMIP6 CMIP historical, <https://doi.org/10.22033/ESGF/CMIP6.11298>, 2019a.
- Danabasoglu, G.: NCAR CESM2-WACCM model output prepared for CMIP6 ScenarioMIP ssp585, <https://doi.org/10.22033/ESGF/CMIP6.10115>, 2019b.
- Davis, C. A.: Resolving Tropical Cyclone Intensity in Models, *Geophysical Research Letters*, 45, 2082–2087, 2018.
- Emanuel, K.: Environmental Factors Affecting Tropical Cyclone Power Dissipation, *Journal of Climate*, 20, 5497 – 5509, 2007.
- Emanuel, K.: The Enduring Enigma of Tropical Cyclone Formation (session 3, 1:39:00), Live Webcast/Video Archive, <https://web.mit.edu/webcast/eaps/s22/2/>, 2022.
- Emanuel, K. and Nolan, D.: Tropical cyclone activity and the global climate system, in: 26th Conference on Hurricanes and Tropical Meteorology, AMS, 2004.
- Emanuel, K., Velez-Pardo, M., and Cronin, T. W.: The Surprising Roles of Turbulence in Tropical Cyclone Physics, *Atmosphere*, 14, 2023.
- Emanuel, K. A.: The Maximum Intensity of Hurricanes, *Journal of Atmospheric Sciences*, 45, 1143 – 1155, 1988.
- Frank, W. M. and Ritchie, E. A.: Effects of Vertical Wind Shear on the Intensity and Structure of Numerically Simulated Hurricanes, *Monthly Weather Review*, 129, 2249 – 2269, 2001.
- Han, Y. and Ullrich, P.: The System for Classification of Low-Pressure Systems (SyCLoPS): An All-in-One Objective Framework for Large-scale Datasets, *ESS Open Archive*, 2024.



- Haywood, J. M., Jones, A., Bellouin, N., and Stephenson, D.: Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall,
 780 Nature Climate Change, 3, 660–665, 2013.
- Holland, G.: A Revised Hurricane Pressure–Wind Model, Monthly Weather Review, 136, 3432 – 3445, 2008.
- Holliday, C. R. and Thompson, A. H.: Climatological Characteristics of Rapidly Intensifying Typhoons, Monthly Weather Review, 107, 1022
 – 1034, 1979.
- IPCC: Summary for Policymakers, p. 3–32, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,
 785 https://doi.org/10.1017/9781009157896.001, 2021.
- Irvine, P., Emanuel, K., He, J., Horowitz, L. W., Vecchi, G., and Keith, D.: Halving warming with idealized solar geoengineering moderates
 key climate hazards, Nature Climate Change, 9, 295–299, 2019.
- Jien, J. Y., Gough, W. A., and Butler, K.: The Influence of El Niño–Southern Oscillation on Tropical Cyclone Activity in the Eastern North
 Pacific Basin, Journal of Climate, 28, 2459 – 2474, 2015.
- 790 Jones, A. C., Haywood, J. M., Dunstone, N., Emanuel, K., Hawcroft, M. K., Hodges, K. I., and Jones, A.: Impacts of hemispheric solar
 geoengineering on tropical cyclone frequency, Nature Communications, 8, 1382, 2017.
- Judt, F., Klocke, D., Rios-Berrios, R., Vanni  re, B., Ziemer, F., AUGER, L., BIERCAMP, J., BRETHERTON, C., Chen, X., D  ben, P.,
 HOHENEGGER, C., Khairoutdinov, M., KODAMA, C., Kornbl  h, L., Lin, S.-J., Nakano, M., Neumann, P., PUTMAN, W., R  ber, N.,
 and ZHOU, L.: Tropical Cyclones in Global Storm-Resolving Models, Journal of the Meteorological Society of Japan. Ser. II, 99, 579 –
 795 602, 2021.
- Judt, F., Rios-Berrios, R., and Bryan, G. H.: Marathon versus Sprint: Two Modes of Tropical Cyclone Rapid Intensification in a Global
 Convection-Permitting Simulation, Monthly Weather Review, 151, 2683 – 2699, 2023.
- Khodri, M., Izumo, T., Vialard, J., Janicot, S., Cassou, C., Lengaigne, M., Mignot, J., Gastineau, G., Guilyardi, E., Lebas, N., Robock, A.,
 and McPhaden, M. J.: Tropical explosive volcanic eruptions can trigger El Ni  o by cooling tropical Africa, Nature Communications, 8,
 800 778, 2017.
- Klotzbach, P. J., Wood, K. M., Schreck III, C. J., Bowen, S. G., Patricola, C. M., and Bell, M. M.: Trends in Global Tropical Cyclone Activity:
 1990–2021, Geophysical Research Letters, 49, e2021GL095 774, 2022.
- Knaff, J. A. and Zehr, R. M.: Reexamination of Tropical Cyclone Wind–Pressure Relationships, Weather and Forecasting, 22, 71 – 88, 2007.
- Knapp, K. R., Kruk, M. C., Levinson, D. H., Diamond, H. J., and Neumann, C. J.: The International Best Track Archive for Climate
 805 Stewardship (IBTrACS): Unifying Tropical Cyclone Data, Bulletin of the American Meteorological Society, 91, 363 – 376, 2010.
- Knapp, K. R., Diamond, H. J., Kossin, J. P., Kruk, M. C., and Schreck, C. J.: International Best Track Archive for Climate Stewardship
 (IBTrACS) Project, Version 4 [since1980], 2023.
- Knutson, T., Camargo, S. J., Chan, J. C. L., Emanuel, K., Ho, C.-H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., and Wu, L.:
 Tropical Cyclones and Climate Change Assessment: Part II: Projected Response to Anthropogenic Warming, Bulletin of the American
 810 Meteorological Society, 101, E303 – E322, 2020.
- Knutson, T. R., Sirutis, J. J., Zhao, M., Tuleya, R. E., Bender, M., Vecchi, G. A., Villarini, G., and Chavas, D.: Global Projections of Intense
 Tropical Cyclone Activity for the Late Twenty-First Century from Dynamical Downscaling of CMIP5/RCP4.5 Scenarios, Journal of
 Climate, 28, 7203 – 7224, 2015.
- Kravitz, B., Forster, P. M., Jones, A., Robock, A., Alterskj  r, K., Boucher, O., Jenkins, A. K. L., Korhonen, H., Kristj  nsson, J. E., Muri,
 815 H., Niemeier, U., Partanen, A.-I., Rasch, P. J., Wang, H., and Watanabe, S.: Sea spray geoengineering experiments in the geoengineering



- model intercomparison project (GeoMIP): Experimental design and preliminary results, *Journal of Geophysical Research: Atmospheres*, 118, 11,175–11,186, 2013.
- Lagouvardos, K., Karagiannidis, A., Dafis, S., Kalimeris, A., and Kotroni, V.: Ianos—A Hurricane in the Mediterranean, *Bulletin of the American Meteorological Society*, 103, E1621 – E1636, 2022.
- 820 Liu, F., Li, J., Wang, B., Liu, J., Li, T., Huang, G., and Wang, Z.: Divergent El Niño responses to volcanic eruptions at different latitudes over the past millennium, *Climate Dynamics*, 50, 3799–3812, 2018.
- Lockley, A., Xu, Y., Tilmes, S., Sugiyama, M., Rothman, D., and Hindes, A.: 18 Politically relevant solar geoengineering scenarios, *Socio-Environmental Systems Modelling*, 4, 18 127, 2022.
- Mueller, T. J., Patricola, C. M., and Bercos-Hickey, E.: The Influence of ENSO Diversity on Future Atlantic Tropical Cyclone Activity, 825 *Journal of Climate*, 37, 3959 – 3975, 2024.
- Nardi, K. M., Zarzycki, C. M., Larson, V. E., and Bryan, G. H.: Assessing the Sensitivity of the Tropical Cyclone Boundary Layer to the Parameterization of Momentum Flux in the Community Earth System Model, *Monthly Weather Review*, 150, 883 – 906, 2022.
- Nayak, C., Bulusu, J., Vichare, G., and Dimri, A. P.: Effects of Solar Variability on Tropical Cyclone Activity, *Earth and Space Science*, 11, e2023EA003 500, 2024.
- 830 NOAA: Hurricane Damage Potential, <https://www.noaa.gov/jetstream/tc-potential>, 2024.
- Pezza, A. B. and Simmonds, I.: Catarina: The first South Atlantic hurricane and its association with vertical wind shear and high latitude blocking, in: *International Conference on Southern Hemisphere Meteorology and Oceanography (ICSHMO)*, vol. 8, pp. 353–364, 2006.
- Randall, D. A., Hurrell, J., Gettelman, A., Loft, R., and Skamarock, W.: Proposal to the National Science Foundation’s Program for Cyber-
 infrastructure for Sustained Scientific Innovation for Collaborative Research: Frameworks: Community-Based Weather and Climate Sim-
 835 ulation with a Global Storm-Resolving Model, <https://hogback.atmos.colostate.edu/earthworks/pdf/EarthWorks-proposal.enhanced.pdf>, 2019.
- Richter, J. H., Visioni, D., MacMartin, D. G., Bailey, D. A., Rosenbloom, N., Dobbins, B., Lee, W. R., Tye, M., and Lamarque, J.-F.: Assessing Responses and Impacts of Solar climate intervention on the Earth system with stratospheric aerosol injection (ARISE-SAI): protocol and initial results from the first simulations, *Geoscientific Model Development*, 15, 8221–8243, 2022.
- 840 Roberts, M. J., Camp, J., Seddon, J., Vidale, P. L., Hodges, K., Vannière, B., Mecking, J., Haarsma, R., Bellucci, A., Scoccimarro, E., Caron, L.-P., Chauvin, F., Terray, L., Valcke, S., Moine, M.-P., Putrasahan, D., Roberts, C. D., Senan, R., Zarzycki, C., Ullrich, P., Yamada, Y., Mizuta, R., Kodama, C., Fu, D., Zhang, Q., Danabasoglu, G., Rosenbloom, N., Wang, H., and Wu, L.: Projected Future Changes in Tropical Cyclones Using the CMIP6 HighResMIP Multimodel Ensemble, *Geophysical Research Letters*, 47, e2020GL088 662, 2020.
- Sobel, A. H., Wing, A. A., Camargo, S. J., Patricola, C. M., Vecchi, G. A., Lee, C.-Y., and Tippett, M. K.: Tropical Cyclone Frequency, 845 *Earth’s Future*, 9, e2021EF002 275, 2021.
- Tilmes, S., Richter, J. H., Kravitz, B., MacMartin, D. G., Mills, M. J., Simpson, I. R., Glanville, A. S., Fasullo, J. T., Phillips, A. S., Lamarque, J.-F., Tribbia, J., Edwards, J., Mickelson, S., and Ghosh, S.: CESM1(WACCM) Stratospheric Aerosol Geoengineering Large Ensemble Project, *Bulletin of the American Meteorological Society*, 99, 2361 – 2371, 2018.
- Tilmes, S., MacMartin, D. G., Lenaerts, J. T. M., van Kampenhout, L., Muntjewerf, L., Xia, L., Harrison, C. S., Krumhardt, K. M., Mills, 850 M. J., Kravitz, B., and Robock, A.: Reaching 1.5 and 2.0 °C global surface temperature targets using stratospheric aerosol geoengineering, *Earth System Dynamics*, 11, 579–601, 2020.
- Tippett, M. K., Camargo, S. J., and Sobel, A. H.: A Poisson Regression Index for Tropical Cyclone Genesis and the Role of Large-Scale Vorticity in Genesis, *Journal of Climate*, 24, 2335 – 2357, 2011.



- Tory, K. J. and Dare, R. A.: Sea Surface Temperature Thresholds for Tropical Cyclone Formation, *Journal of Climate*, 28, 8171 – 8183, 2015.
- 855 Vitart, F., Anderson, J. L., and Stern, W. F.: Simulation of Interannual Variability of Tropical Storm Frequency in an Ensemble of GCM Integrations, *Journal of Climate*, 10, 745 – 760, 1997.
- Walsh, K. J., McBride, J. L., Klotzbach, P. J., Balachandran, S., Camargo, S. J., Holland, G., Knutson, T. R., Kossin, J. P., Lee, T.-c., Sobel, A., and Sugi, M.: Tropical cyclones and climate change, *WIREs Climate Change*, 7, 65–89, 2016.
- Walsh, K. J. E., Camargo, S. J., Vecchi, G. A., Daloz, A. S., Elsner, J., Emanuel, K., Horn, M., Lim, Y.-K., Roberts, M., Patricola, C.,
 860 Scoccimarro, E., Sobel, A. H., Strazzo, S., Villarini, G., Wehner, M., Zhao, M., Kossin, J. P., LaRow, T., Oouchi, K., Schubert, S., Wang, H., Bacmeister, J., Chang, P., Chauvin, F., Jablonowski, C., Kumar, A., Murakami, H., Ose, T., Reed, K. A., Saravanan, R., Yamada, Y., Zarzycki, C. M., Vidale, P. L., Jonas, J. A., and Henderson, N.: Hurricanes and Climate: The U.S. CLIVAR Working Group on Hurricanes, *Bulletin of the American Meteorological Society*, 96, 997 – 1017, 2015.
- Wehner, M. F., Reed, K. A., Li, F., Prabhat, Bacmeister, J., Chen, C.-T., Paciorek, C., Gleckler, P. J., Sperber, K. R., Collins, W. D., Gettelman,
 865 A., and Jablonowski, C.: The effect of horizontal resolution on simulation quality in the Community Atmospheric Model, CAM5.1, *Journal of Advances in Modeling Earth Systems*, 6, 980–997, 2014.
- Williams, I. N. and Patricola, C. M.: Diversity of ENSO Events Unified by Convective Threshold Sea Surface Temperature: A Nonlinear ENSO Index, *Geophysical Research Letters*, 45, 9236–9244, 2018.
- Zhang, Y., MacMartin, D. G., Vioni, D., and Kravitz, B.: How large is the design space for stratospheric aerosol geoengineering?, *Earth
 870 System Dynamics*, 13, 201–217, 2022.
- Zhao, M., Held, I. M., Lin, S.-J., and Vecchi, G. A.: Simulations of Global Hurricane Climatology, Interannual Variability, and Response to Global Warming Using a 50-km Resolution GCM, *Journal of Climate*, 22, 6653 – 6678, 2009.