PNAS PERSPECTIVE

Near-term tropical cyclone risk and coupled Earth system model biases

Adam H. Sobel[a,b,1], Chia-Ying Lee[b], Steven G. Bowen[c], Suzana J. Camargo[b], Mark A. Cane[b], Amy Clement[d], Boniface Fosu[e], Megan Hart[f], Kevin A. Reed[g], Richard Seager[b], and Michael K. Tippett[a]

Edited by Isaac Held, Princeton University, Princeton, NJ; received February 3, 2023; accepted June 14, 2023

Most current climate models predict that the equatorial Pacific will evolve under greenhouse gas–induced warming to a more El Niño-like state over the next several decades, with a reduced zonal sea surface temperature gradient and weakened atmospheric Walker circulation. Yet, observations over the last 50 y show the opposite trend, toward a more La Niña-like state. Recent research provides evidence that the discrepancy cannot be dismissed as due to internal variability but rather that the models are incorrectly simulating the equatorial Pacific response to greenhouse gas warming. This implies that projections of regional tropical cyclone activity may be incorrect as well, perhaps even in the direction of change, in ways that can be understood by analogy to historical El Niño and La Niña events: North Pacific tropical cyclone projections will be too active, North Atlantic ones not active enough, for example. Other perils, including severe convective storms and droughts, will also be projected erroneously. While it can be argued that these errors are transient, such that the models' responses to greenhouse gases may be correct in equilibrium, the transient response is relevant for climate adaptation in the next several decades. Given the urgency of understanding regional patterns of climate risk in the near term, it would be desirable to develop projections that represent a broader range of possible future tropical Pacific warming scenarios—including some in which recent historical trends continue—even if such projections cannot currently be produced using existing coupled earth system models.

climate modeling | tropical cyclones | model biases | tropical Pacific | climate adaptation

Some of the most consequential risks associated with human-induced climate change involve changes in the frequency, severity, or other properties of extreme weather events. The most extreme and destructive events are rare, such that historical observations generally contain too few instances to allow trends to be assessed with confidence, or forced trends to be distinguished from natural variability, using those observations alone. Earth system models (ESMs), on the other hand, can provide detailed, physically based simulations of Earth's climate in the past, present, and future, including ensembles to quantify uncertainty, and counterfactuals (e.g., simulations with no human influence) that can be used to attribute outcomes to forcings. While such models do not, in general, simulate extreme events well enough to use their output directly in risk assessment (e.g., ref. 1), they can be "downscaled" for this purpose.* By using one or more ESMs in conjunction with statistical or dynamical downscaling, scientists can generate assessments of present and future risk that include estimates of changes due to human influence.

Because all downscaling methods start from the ESM climate, however, they inherit any systematic errors, or biases, in that climate. A standard approach to dealing with this is to use multimodel ensembles. To the extent that biases differ between models, and can be considered random, one can obtain a meaningful uncertainty range from the multimodel ensemble spread. Biases that are common to most or all models, on the other hand, are more difficult to address. Here, we discuss the possibility that nearly all models in the multimodel ensembles used in the last several Coupled Model Intercomparison Projects (CMIPs) are simulating the pattern of radiatively forced upper ocean warming in the tropical Pacific incorrectly, with errors of the same type and sign, as recent research suggests (9, 10). This issue has well-documented consequences for estimates of Earth's global climate sensitivity, where the modeled pattern of warming implies greater sensitivity than does either the observed one, or a spatially uniform warming (11–15). The implications for regional climate impacts have been less examined but are in our view arguably even more consequential, at least in the next several decades. To the extent that

Author affiliations: [a]Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY 10027; [b]Lamont Doherty Earth Observatory, Columbia University, Palisades, NY 10964; [c]Private Address, Lake Forest, IL 60045; [d]Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL 33149; [e]Department of Geosciences, Mississippi State University, Mississippi State, MS 39762; [f]Aon, Troy, MI 48084; and [g]School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY 11794

Author contributions: A.H.S., C.-Y.L., S.G.B., S.J.C., M.A.C., A.C., B.F., M.H., K.A.R., R.S., and M.K.T. designed research and contributed input on the manuscript; C.-Y.L., S.J.C., B.F., and R.S. performed research; C.-Y.L., S.J.C., and B.F. analyzed data; R.S. and M.K.T. wrote a section; and A.H.S. wrote the paper.

Competing interest statement: A.H.S. is a member of the Board of Advisors of Jupiter Intelligence, Inc.

This article is a PNAS Direct Submission.

[1]To whom correspondence may be addressed. Email: ahs129@columbia.edu.

This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2209631120/-/DCSupplemental.

Published August 7, 2023.

*Downscaling methods—which can include higher-resolution dynamical models equivalent to individual components of the ESM, e.g., atmosphere-only models (2–5), or computationally lighter statistical or statistical-dynamical (6–8) models—take the ESM climate as given and generate extreme events that are consistent with that climate, yet are more realistic than those generated by the ESM itself.

the modeled pattern of equatorial surface warming in response to greenhouse gas forcing is indeed incorrect, it implies that the models will also simulate patterns of some types of extreme events incorrectly, since the pattern of equatorial sea surface temperature (SST) is known from historical experience to have a strong influence on those types of events. This implies in turn that extreme event risk assessments of the future based on these models—including those obtained by downscaling—are incorrect as well. Here, we focus on tropical cyclones (TCs) but also briefly discuss other types of extreme events.

Projected Tropical Cyclone Trends

To understand projected future trends in TC activity, it is useful to look at them in conjunction with the spatial pattern of projected SST change, as well as global- or tropical-mean aspects of climate change. In Fig. 1, we show two state-of-the-art ways of making future projections of SST (*A* and *B*) and TCs (*C* and *D*). One method uses output from simulations by a limited number of high-resolution models in which the storms (*C*) can be simulated organically along with the climate, represented here by SST (*A*). In another, we take a large number of simulations with many lower-resolution models and use their climate states, represented here by SST (*B*) as inputs to a statistical-dynamical model (CHAZ, refs. 7 and 16) that produces TCs (*D*). The SST trends in both the low-resolution CMIP6 and high-resolution (from the HighResMIP project, 17) models show warming maxima on the equator and in the eastern side of the Pacific basin (CMIP6) and around the dateline (HighResMIP), with minima in the southeast Pacific. The CHAZ track density trends show reductions in the Gulf of Mexico, Caribbean, and North Atlantic main TC development region, strong increases in almost the entire Pacific, a southward shift in the south Indian Ocean, and a westward and equatorward shift in the south Pacific. The trends in HighResMIP are much noisier due to a much smaller sample size of available data from that ensemble compared to CMIP6 but are in some respects consistent with those in CHAZ, particularly in the planetary-scale contrast between the more active Pacific and less active Atlantic.

The spatial patterns of simulated SST change shown in Fig. 1 bear a broad resemblance to those associated with El Niño events. The El Niño-Southern Oscillation (ENSO) phenomenon, of which El Niño and La Niña are the climatic events with oppositely signed SST anomalies centered on the equatorial eastern Pacific, are known to influence TC activity strongly on interannual time scales. El Niños, in which the equatorial eastern Pacific is anomalously warm, suppress TC activity over the North Atlantic and enhance it over the eastern and central North Pacific. In the western North Pacific, the region of TC genesis shifts eastward and equatorward, and TC intensities increase, during El Niño events. The changes observed during La Niña events are generally of opposite sign to those during El Niño events. These changes in TC activity are relatively well understood as consequences of specific changes in the large-scale environment for TC genesis and intensification, e.g., SST and vertical wind shear (e.g., refs. 18 and 19). Empirical "genesis indices" are computed from local climate variables at any given space-time point to predict the probability of TC formation at that point, based on historical relationships between those climate variables and TC genesis frequency. These, for example, capture the anomalous global patterns in genesis associated with ENSO, even when the indices are trained only on the climatological annual cycle (e.g., ref. 20). ENSO is by no means the only mode of climate variability that affects TCs; others include the Atlantic and Pacific meridional modes, the Pacific decadal oscillation, and Atlantic multidecadal oscillation (e.g., ref. 21). However, ENSO has a powerful global influence.

It is plausible that, to the extent that long-term trends in the mean state of the tropical Pacific resemble those that occur during ENSO events, they will influence TC activity in future projections in ways that are similar to those observed

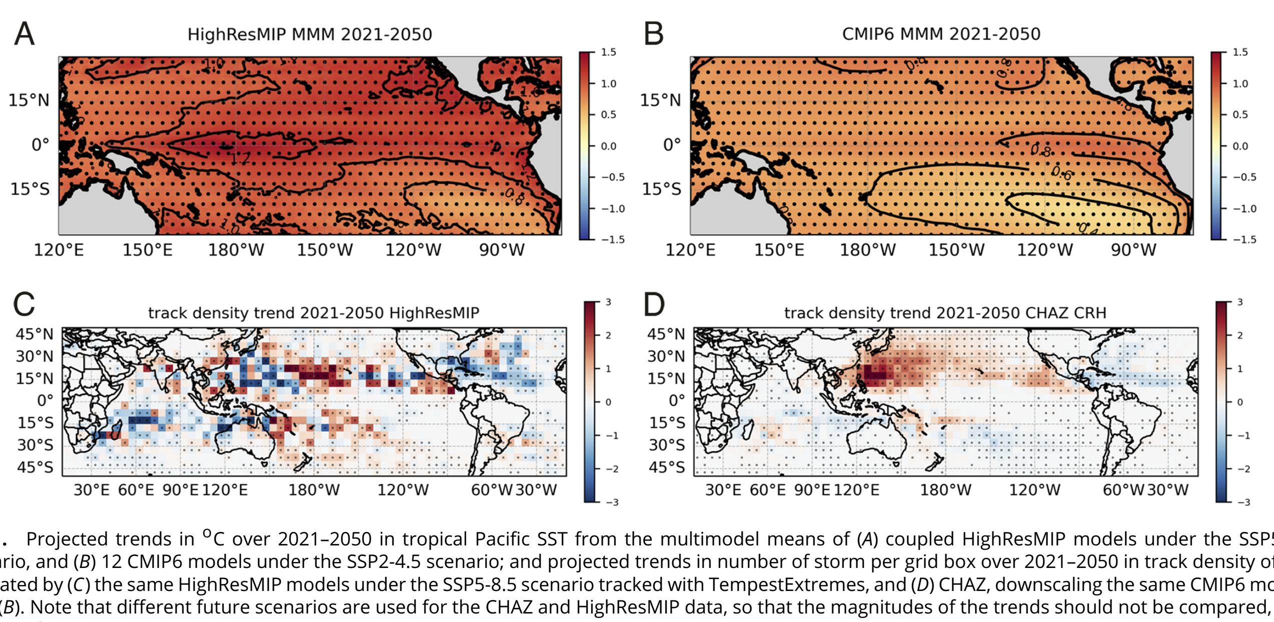

Fig. 1. Projected trends in °C over 2021–2050 in tropical Pacific SST from the multimodel means of (*A*) coupled HighResMIP models under the SSP5-8.5 scenario, and (*B*) 12 CMIP6 models under the SSP2-4.5 scenario; and projected trends in number of storm per grid box over 2021–2050 in track density of TCs simulated by (*C*) the same HighResMIP models under the SSP5-8.5 scenario tracked with TempestExtremes, and (*D*) CHAZ, downscaling the same CMIP6 models as in (*B*). Note that different future scenarios are used for the CHAZ and HighResMIP data, so that the magnitudes of the trends should not be compared, only the spatial patterns.

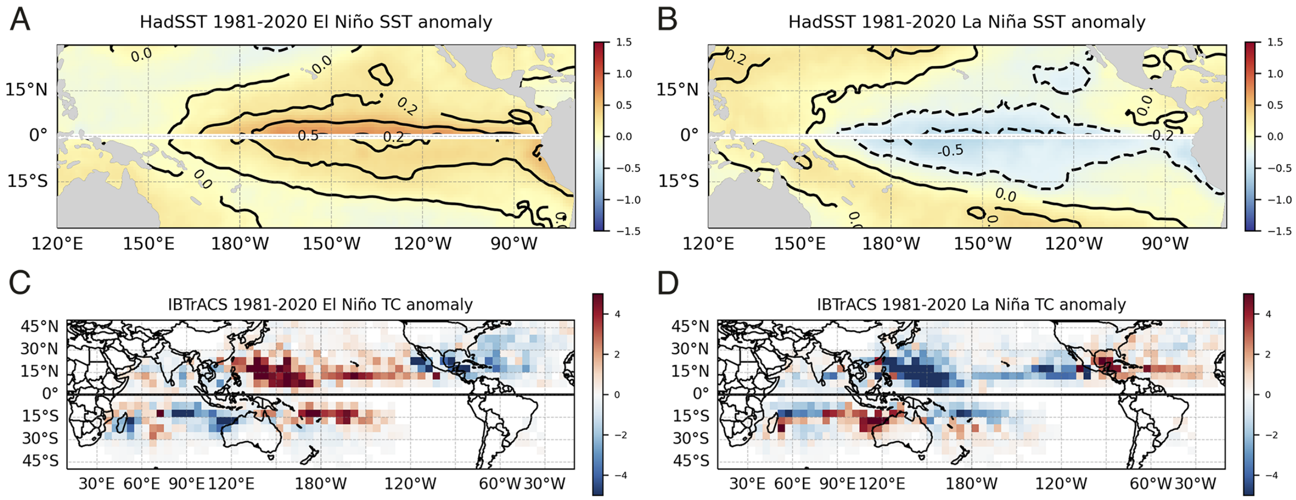

Fig. 2. Composite anomalies in historical observations (1981–2020) from (*A* and *C*) El Niño and (*B* and *D*) La Niña events in (*A* and *B*) tropical Pacific SST and (*C* and *D*) global tropical cyclone track density. In the Northern Hemisphere, the ENSO status is defined by the average ONI over August, September, and October and the anomalies in track density and SST are then constructed from data from January to December in the same year. In the Southern Hemisphere, the average ONI over January, February, and March are used to composite TCs and SST from July to December the year before and from January to June in the same year.

in response to historical ENSO anomalies (22, 23). To make concrete the degree to which the patterns of projected trends shown in Fig. 1 resemble those associated with ENSO, Fig. 2 shows composite El Niño (*A* and *C*) and La Niña (*B* and *D*) anomalies in both SST (*A* and *B*) and TC track density (*C* and *D*) from historical observations for comparison. Comparing the projected SST trends in Fig. 1 to the SST anomaly composites in Fig. 2, we see that while the CMIP6 and HighResMIP trends are different in detail, with peak warming considerably further west in HighResMIP, both sets of models project that the tropical Pacific will evolve under greenhouse gas–induced warming to a more El Niño-like state over the next several decades, with a reduced zonal SST gradient and weakened atmospheric Walker circulation (11, 13, 24). Accordingly, all else equal—e.g., neglecting possible rectified interactions between an altered mean state and ENSO variability which could itself also be altered—one might expect a future in which patterns of extreme weather events would also resemble those that have historically occurred during El Niño events.

Indeed, both the CMIP6/CHAZ and HighResMIP TC track density trends have features in common with historical El Niño composites: increases over the central and northwest Pacific, either a decrease (HighResMIP) or a lesser increase or no change (CHAZ) over the Atlantic and Gulf of Mexico, and increases in the southwest Pacific and decreases over the south Indian Ocean. There are also some features in the modeled trends, such as the CHAZ increase off the US East Coast or the HighResMIP decrease in the Philippine region, that are not present in the historical El Niño composite. These differences may reflect ways in which global warming affects TC activity differently from how ENSO does; differences between the spatial patterns of the SST trend projections and those of historical El Niños; biases in the CHAZ and HighResMIP models' simulations of TCs; differences in seasonality between the typical ENSO event and longer-term warming trends; or all of these factors. But both simulated track density trend patterns resemble those in the El Niño composites more than they do the La Niña composites.

To the extent that the model-projected future trends in Fig. 1 resemble the El Niño anomalies in Fig. 2, it is reasonable to expect that the projected TC activity trends are, at least in part, a consequence of the projected trends in the state of the tropical Pacific. Thus, if the projected Pacific climate trends are wrong, the TC trends will also be wrong, perhaps even in the sign of the trend. Of course, other aspects of climate change also affect TCs, including the global mean response; we might think of the change in TC activity as resulting from the sum of a global mean component that would occur in response to uniform warming, and a "pattern effect" (25) due to the spatial structure of the warming. Some models (and some genesis indices) project large global decreases in TC frequency under uniform warming, for example. Other models, however, predict little change, or even an increase in global TC frequency under global warming. The total change—the sum of the global mean change and the pattern effect—is therefore hard to project. Even so, it is important to understand the component that is due to the Pacific SST pattern, as it may have a substantial, perhaps even dominant effect on regional scales.

Do models represent the tropical Pacific climate system's response to greenhouse gas forcing correctly? A starting point for answering that question is to assess how well the same models have simulated observed changes in the tropical Pacific over the historical period, particularly the last several decades when greenhouse gas forcing has been greatest and the observations are of the highest quality. To the extent that the models are correct, and the greenhouse gas-forced signal is responsible for the observed trends in the historical period, we might expect to see a trend towards El Niño-like conditions, with a decreased zonal SST gradient. In TCs, we might expect to see increased activity in the Pacific and decreased activity in the Atlantic. These expectations are not met. Observations over the last 50 y show the opposite trend to that simulated, instead toward a

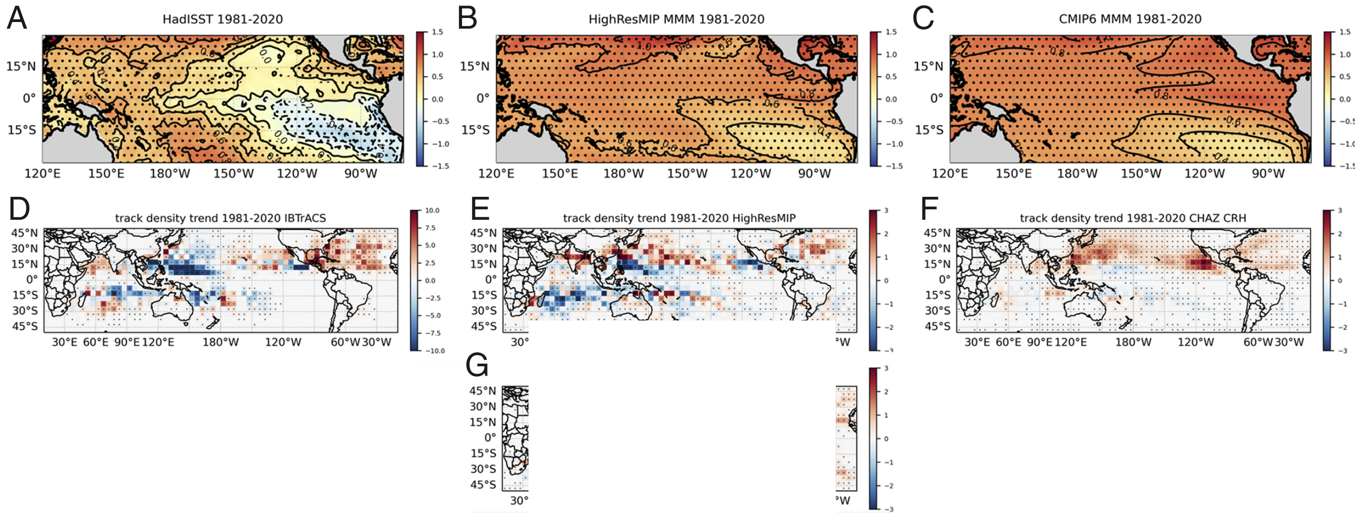

Fig. 3. Historical trends (1981 to 2020) in SST from (*A*) obser , and (*C*) CMIP6 historical simulations; and in tropical cyclone track density from (*D*) observations, (*E*) HighResMIP coupled historical simulations, (*F*) CHAZ, downscaling the same CMIP6 models as in (*C*), and (*G*) HighResMIP atmosphere-only simulations using observed SST up to 2014 and observed SST blended with CMIP5 RCP8.5 SST from 2015 to 2020. The units are similar to Fig. 1 but over 40 y.

more La Niña-like state, with an increased zonal SST gradient (9, 10, 26, 27). This is illustrated in Fig. 3, which shows maps of the historical (1981 to 2020) trends in SST from (*A*) one observational dataset, (*B*) HighResMIP, and (*C*) the CMIP6 multimodel mean. The La Niña-like strengthening of the zonal SST gradient is apparent in the observations. In the coupled models, the SST trend structure is closer to El Niño than La Niña, with greater warming in the east than west on the equator particularly in CMIP6; in HighResMIP, the southeast Pacific cooling edges closer to the equator, yielding a pattern somewhere between those in the observations and CMIP6. Also shown in Fig. 3 are TC track density trends for 1981 to 2020 from (*D*) historical observations, (*E*) the same coupled HighResMIP models as shown above, using historical runs from 1981 to 2014 and the SSP5-8.5 runs from 2015 to 2020; (*F*) CHAZ, downscaling historical CMIP6 simulations from 1981 to 2014 and then the SSP2-4.5 runs from 2015 to 2020; and (*G*) uncoupled, atmosphere-only HighResMIP runs forced with observed SST from 1981 to 2014 and with observed SST variability blended with the climate change signal from CMIP5 RCP8.5 models from 2015 to 2020.

Evidence for the importance of getting the SST right comes from uncoupled experiments, where the actual observed SST is prescribed. Fig. 3*G* shows that the pattern of more Atlantic and less Pacific TC activity (as in observations) can be broadly reproduced given the SST. This leads us to interpret differences in track density between the coupled HighResMIP simulations and observations as due primarily to the differences in SST and associated large-scale climate, rather than to biases in the models' simulations of TCs for a given climate. That said, there are areas of agreement between the coupled and uncoupled HighResMIP simulations (Fig. 3 *E* and *G*), such as North Atlantic increases and decreases east of the Philippines, both of which are in agreement with observations. Further analysis will be needed to determine to what extent these are explainable in terms of SST changes (which for this purpose may not be adequately represented by the degree to which they resemble El Niño or La Niña events, e.g., off-equatorial anomalies are particularly important for TCs). Simulations with CHAZ forced by historical reanalysis datasets show that the model produces ENSO composites that compare reasonably well to observations, but trends for this period that are highly sensitive to which reanalysis dataset is used, as well as the exact period used to calculate the trend. Nonetheless, the impression we obtain from these figures is that our models overall do not successfully simulate the SST trends of the last 40 y well, that this is likely to cause substantial errors in TC trends produced by any TC model that responds to the tropical Pacific state in a way consistent with historical observations, and that the presence of similar biases in future SST projections should cast doubt on future TC projections.

Potential Causes of the Projected SST Trends

While it is possible that the observed trend in equatorial Pacific SST is largely "noise" resulting from internal ocean-atmosphere dynamics, observational errors, or both, recent research provides compelling evidence that it is, in fact, radiatively forced, meaning that the ESMs are wrong in this respect. If it were entirely internal variability—and assuming that variability as well as mean state trends were realistically captured by the models—we would expect that some realizations from the large multimodel ensemble would resemble the observations. Following ref. 9, Fig. 4 addresses this in detail. Fig. 4 *A* and *B* show observed and modeled SST trends over a longer historical period than in Fig. 3, providing a sense of the sensitivity of the trend to the period chosen. The La Niña-like trend is still present in observations (but not models), though the relative cooling is much more confined about the equator. Fig. 4 *C* and *D* quantify the degree of resemblance using two indices of the tropical Pacific state, one that measures the east–west SST gradient and one that measures the north–south gradient,

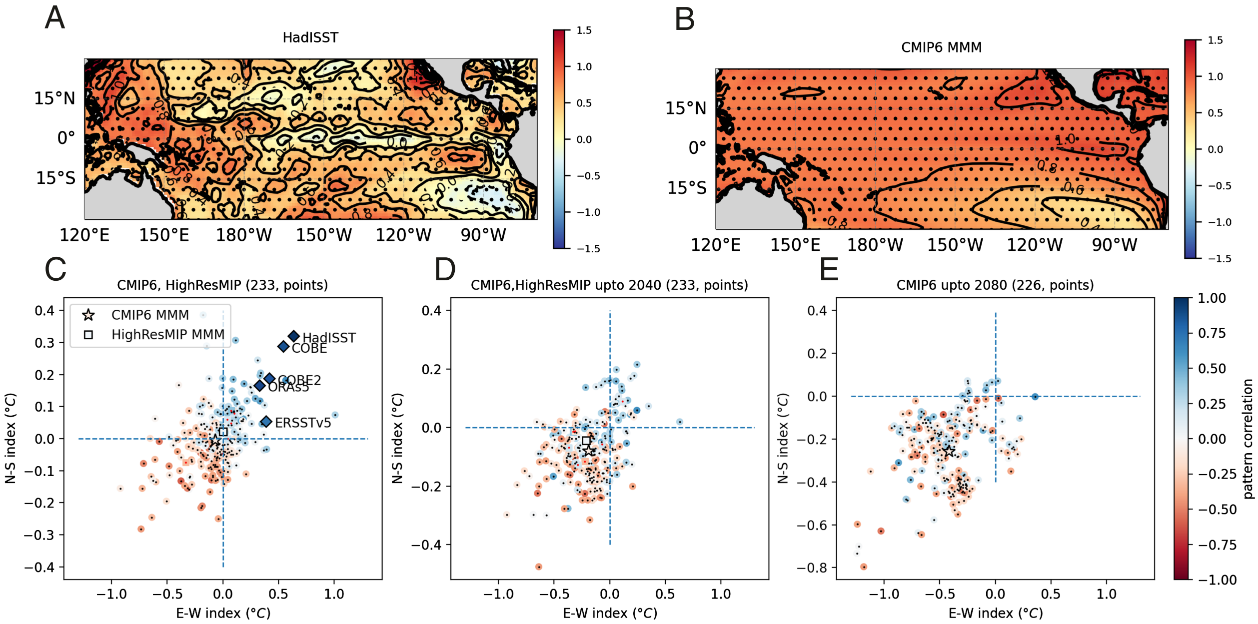

Fig. 4. (*A*) SST trend from HadISST observational data; (*B*) SST trend from CMIP6 models; (*C*) trends in CMIP6 (in circles and star) and HighResMIP (in squares) model simulations of the east–west SST trend index and north–south SST trend index for the historical period (1958 to 2020); observational datasets are represented by diamonds, colors indicate the pattern correlation (PC) of equatorial Pacific between model and HadISST trend during historical period; (*D*) as in (*C*) but the trends are for the period 1958 to 2040; (*E*), as (*C*) but for 1958 to 2080.

and a spatial pattern correlation. The north–south index measures the ability of models to reproduce the observed, equatorially confined, lack of warming, or even cooling in the upwelling region of the central to eastern equatorial Pacific. Models which enhance the zonal SST gradient but do so via a meridionally broad SST anomaly akin to that occurring during Pacific decadal variability Zhang et al. (28) would not have as high a value of the north–south metric as the observed trend does. The indices are plotted for (*C*) the historical period (1958 to 2020), and (*D*) the period 1958 to 2050, using the SSP2-4.5 scenario for the future periods (except for the HighResMIP models which use SSP5-8.5). A trend toward an El Niño-like state lies in the lower left, toward a La Niña-like state in the upper right. There is some diversity in the magnitudes of the trends in the observational datasets, with the HadISST [whose trend map is shown in (*A*)] having the strongest La Niña-like trend. The overlap between models and observations in (*C*) is not zero, but it is small, while (*D*) and (*E*) show that the simulated future trends are even more strongly toward an El Niño-like state than those in the historical period.

Multiple explanations for the mismatch in trends shown in Fig. 4 have been proposed, including ones involving geographic changes in aerosol forcing (29, 30), Antarctic ozone depletion (31), or sea ice melt (32). Seager et al. (33) argue, on the other hand, that it is a consequence of the well-known cold tongue-double Intertropical Convergence Zone (ITCZ) bias that is common to virtually all past and present ESMs (34, 35). A model's cold tongue-double ITCZ bias is manifest in a simulated equatorial cold tongue in the eastern equatorial Pacific that is colder than observed during the historical period, and a southern hemisphere tropical rain belt, or ITCZ, that extends eastward, parallel to the equator, further than in observations. Seager et al. present evidence that by inducing a specific set of errors in the air–sea fluxes of water, heat, and momentum over the equatorial eastern Pacific, this bias is responsible for the models' tendencies to produce the trends toward an El Niño-like mean state in response to greenhouse gas forcing and that the correct response—and one consistent with observations over the last five decades—is opposite in sign, toward an increased SST gradient and a La Niña-like state. In this view, the relative cooling in the east is a consequence of the ocean dynamical thermostat (36), an oceanic mechanism. The models, on the other hand, appear to be responding more strongly to the weakened Walker circulation, a consequence of atmospheric dynamics (37); increased thermal damping of the zonal SST gradient with warming (38, 39) also acts in the same direction. These mechanisms are all present in models (and, presumably, in nature), and compete, along with other possible mechanisms, to determine the Pacific response (40, 41); the argument here is that the ocean dynamical thermostat wins, at least for now and the next few decades, in nature, while the weakened Walker circulation and/or increased thermal damping wins during this period, erroneously, in the models. Atmosphere and surface ocean mechanisms for changes in the zonal gradient and sources of bias in models are discussed by Lee et al. (27) and Coats and Karnauskas (42) argue for a role for model biases in upper ocean circulation.

Coupled ocean–atmosphere models broadly similar to those used in CMIP are also used in seasonal climate prediction, where they are initialized with the observed climate state and run for relatively short times. Though these forecast integrations are not designed to examine long-term trends, such trends can be evaluated from long (over three decades) hindcast runs. Analyses of these simulations show that as forecast lead time increases, the long-term trends in the eastern equatorial Pacific become increasingly different from those observed, in the sense we would expect from the CMIP results. The short-lead forecasts, which remain relatively close to the observations with which they are initialized, show a cooling trend; while the long-lead forecasts, in which model dynamics and biases increasingly take over as the runs progress, show a warming trend that increases with lead time (43, 44). Most of the models include realistic greenhouse gas concentrations over the period, so it is plausible to see this error in the simulated trends as resulting from the same model biases as do those in the CMIP5 and CMIP6 results.

Implications for Present and Future Tropical Cyclone Risk

To the extent that trends in the pattern of equatorial Pacific SST simulated by ESMs may be wrong as described above, it implies a specific pattern of error in the forced component of TC activity simulated by those models, whether directly or through downscaling. This possibility should be taken into account in views of both present and future TC risk. Below, we discuss the implications for specific basins.

Our focus here is on changes in the tropical Pacific mean state, which can create more or less favorable conditions for TC genesis or intensification. To the extent that the mean state changes resemble those we observe during El Niño or La Niña events, we assume that changes in TC activity will have corresponding changes familiar from those events historically. It is also possible that changes in the tropical Pacific mean state could change the amplitude of ENSO variability or could modulate the nature of ENSO teleconnections (even if the ENSO variability amplitude does not change), either of which could affect TC activity in ways that could be different from the effects directly induced by mean state changes. We do not attempt to determine the extent to which these latter possibilities occur, but only point out that projected changes in ENSO variability are highly uncertain and differ across multimodel ensembles, perhaps even more so than mean state changes (45).

Implications for the North Atlantic. TC activity in the North Atlantic is historically affected by the state of the equatorial Pacific, which varies interannually due to ENSO and also by SSTs in the North Atlantic (46–48). The latter vary on multidecadal time scales, due to some combination of internal atmosphere–ocean dynamics and radiative forcing. It has been argued that the North Atlantic climate and TC variations in the late 20th century, in particular, are in large part radiatively forced (49, 50), with decreases in aerosol forcing playing a particularly large role in the North Atlantic warming, and associated increase in TC activity, from the 1970s and 1980s to the more recent period. It is also possible that the trend to more La Niña-like conditions in the Pacific during the late 20th and early 21st centuries could have played a role, however, since we would expect that trend to be associated with increased Atlantic TC activity, all else equal.

If the future forced trends in the tropical Pacific SST pattern resemble the trends observed over the last 50 y, rather than those simulated by ESMs—that is, if the forced trend is toward a La Niña-like rather than an El Niño-like state—then the future Atlantic may be very different from that the model projections indicate. The projections portray a future with decreased Atlantic TC activity (Fig. 1), whereas a future in which present trends toward a La Niña-like Pacific continue can be expected to see increased Atlantic TC activity.

Implications for the North Pacific. In El Niño years, TC activity in the eastern and central North Pacific increases. Over the western North Pacific, the typical genesis region for typhoons shifts eastward and equatorward, compared to where it is in normal or La Niña years. As these storms follow their typical tracks westward, they have longer lifetimes during which to intensify, and typically obtain greater intensities (51). Although the total number of western North Pacific storms forming each year does not vary systematically with ENSO, the number of the most intense storms does increase with El Niño and decrease with La Niña, and integrated measures of storm activity do as well.

Projections of trends in future Pacific TC activity have much in common with the patterns observed historically during El Niño events. Relative to the global mean trend, they show increased activity across the North Pacific, though the precise distribution of change varies between models (and between HighResMIP and CHAZ overall, in Fig. 1). These responses are presumably consequences of the projected SST pattern change, at least in part, and are likely to be overestimates if that pattern change is erroneous.

Implications for the North Indian. Variations in TC activity over the north Indian Ocean are affected both by the state of the tropical Pacific and by local climate variations, both of which are subject to similar biases when simulated in models. The Arabian Sea in particular has seen a substantial increase in TC activity in recent years (e.g., ref. 52 or see Fig. 3). Storms occur infrequently in this region, so their statistics are noisy. It has nonetheless been argued that the increase in the postmonsoon season (one of two TC seasons in the region, the pre- and post-monsoons, as TCs are suppressed during the monsoon season itself) is attributable to anthropogenic forcings, including greenhouse gas forcing (53). In models, greenhouse gas forcing leads to a warming of the Arabian Sea which exceeds that of the Bay of Bengal, favoring cyclones in the former, potentially explaining the recent trend in observations. While this relative Arabian Sea warming is robust across models (54–56), it has been argued that it is in fact a spurious consequence of model bias (57), though again this conclusion has been disputed (58).

There is no question that, in the simulated mean state of the atmosphere and upper Indian Ocean, the SST is too warm in the west and too cold in the east of the equatorial Indian Ocean, accompanied by surface winds that are too easterly (e.g., ref. 59), all somewhat reminiscent of Pacific model biases. In terms of the dominant mode of interannual variability, the so-called "Indian Ocean Dipole" (60), or IOD, tends to reside in a more positive state in the models than in observations. In the recent historical period, the Indian Ocean has also warmed more, both in the absolute sense and relative to the entire tropics, in observations than models (10). The question is whether, and if so how, the mean state bias affects simulated trends in the response to radiative forcing. This debate is analogous to that we describe above regarding the Pacific. Could the simulated

Indian Ocean trends be in part forced by the Pacific trends? It seems plausible, since on an interannual basis the IOD is known to be influenced by ENSO (e.g., refs. 61 and 62); an increasingly El Niño-like Pacific in the models with warming (right or wrong) would be expected to induce a more positive IOD state, with greater warming of the Arabian Sea. This is speculation, but it is in any case reasonable to conclude that projections of north Indian Ocean TCs are subject to as much question as those in other basins, because of the possibility that biases, both those in the Indian Ocean basin's own dynamics and in the Pacific, may be determining the structure and sign of the forced trends.

Implications for the Southern Hemisphere. Studies from over a decade ago (20, 63) showed TC activity in the Southern Hemisphere shifting northward during El Niño years and southward during La Niña years, consistent with changes in the environment for tropical cyclogenesis; zonal expansions of the region of TC activity to the east over the Southwest Pacific and to the west over the Southern Indian Ocean are also apparent in El Niño years, with corresponding contractions in La Niña years, in these studies. (There is almost no TC activity over the South Atlantic or Southeast Pacific, in any years, so the Southwest Pacific and South Indian basins account for approximately all Southern Hemisphere TC activity.) Fig. 2, with more data than the earlier studies cited above, is broadly consistent with this picture but shows more of a decrease over the South Indian Ocean in El Niño years. Overall, TC activity is reduced in the Southern Hemisphere during El Niño years and increased during La Niña years.

HighResMIP projections of Southern Hemisphere TC activity are broadly consistent with the El Niño pattern, showing an eastward shift over the Pacific and a net decrease over the Indian Ocean. The CHAZ trends are broadly consistent over the Indian Ocean, but the Pacific increase extends less far to the east. Recent observation-based studies have generally found an absence of statistically significant TC activity trends in Southern Hemisphere basins (63–65). However, Klotzbach et al. (66) find a decreasing trend in Southern Hemisphere TC activity, which they attribute to the trend toward La Niña conditions in the Pacific.

The Time Frame

The ocean dynamical thermostat mechanism (36), hypothesized to be responsible for the recent historical trends in the tropical Pacific, may be transient. It results from the greater near-term greenhouse gas-forced warming in the uppermost ocean than in the subsurface ocean within and below the thermocline, in the equatorial eastern Pacific. Because of the resulting increase in vertical temperature gradient, the cooling effect of upwelling in the equatorial eastern Pacific is enhanced. The subthermocline water reaches the equator via subduction from the surface in the subtropics as part of the upper ocean's meridional overturning circulation. This water is warmed by greenhouse gas forcing as well, since the subtropical surface ocean is also exposed to that forcing. Because it takes decades for this water to reach the equatorial subsurface, however, its warming lags that of surface waters, resulting in relative surface cooling (i.e., a lesser degree of warming) in the equatorial cold tongue, compared to elsewhere, as this water upwells and mixes to the surface. It is possible, then, that the disagreement of ESMs with observed trends will continue for several decades, but eventually diminish, if and when Earth's climate reaches a new equilibrium under stabilized greenhouse gas concentrations, such that the difference in warming between the equatorial Pacific surface and subsurface disappears. This is by no means certain, however; a number of uncertainties about the equilibrium solution remain, including how much the SST warms in regions of subduction and whether locations of subduction and interior pathways shift along with wind systems. But if true, it implies that the greatest disagreement between models and observations may occur in coming decades and diminish by the end of the century.

Even if the ESMs' response to warming in the tropical Pacific is correct as an equilibrium response, the hypothesized transient errors are likely to be greatest during the historical period and the next few decades and will be important during that period. For many practical purposes, several decades is a long time. In the sixth assessment report of the IPCC, however, the concerns about Pacific biases raised here are addressed only briefly. Some possible reasons for the disagreement between models and observations are discussed (67, figure 3.16), and it is noted that the thermostat mechanism and the associated pattern of warming "may not persist to equilibrium" due to eventual subsurface warming (68). While this is a scientifically defensible statement (e.g., ref. 69), it glosses over the importance of the issue to climate adaptation projects, many of which have time frames of decades or less. To the extent that planning of such projects is informed by near-term climate prediction or projection, it is the errors in the simulated transient response of the tropical Pacific that are the most relevant, not the equilibrium response.

The possible model errors discussed here will be consequential not only for future projections but for estimates of present risk. Because of large internal variability on interannual and longer time scales, it is not straightforward to ascertain from observations alone how present risk may differ from that in the recent historical past—as defined, say, by an average over the last 50 or 100 y. For some purposes it is desirable to quantify the contribution of anthropogenic radiative forcings to this difference.

In this regard, it is likely that recent trends in TC activity have been influenced by recent trends in tropical Pacific climate. Over the last couple of decades, the North Atlantic has been relatively active, for example, while the western North Pacific has been relatively quiet, on average (70). The active Atlantic is likely a consequence of relative North Atlantic warming (71, 72) for which the relative roles of anthropogenic forcing (49, 50, 73) and internal ocean dynamics (74) are a topic of active debate. These TC signals are also broadly consistent, however, with the trend toward a more La Niña-like Pacific. The observed Pacific trend also surely is a consequence of a combination of internal, unforced Pacific decadal variability and anthropogenic forcing, with the relative importance of the two components being the question at issue. If as we suggest here, the anthropogenic signal explains the sign of the trend over the last several decades, it implies that the recent La Niña-like state, and associated TC activity signals, are likely to persist, and thus can be taken as representative of longer-term risk. On the other hand, if the recent Pacific trend is predominantly due to internal variability (as ESMs might lead one to believe, since they simulate the opposite trend in response to GHG warming), it implies instead that this trend is misleading as a guide to current and near-future risk and instead is likely to reverse. Of course, it need not be entirely one or the other; both internal variability and errors in the forced response may well have contributed to the discrepancy between models and observations. Overall, it is our assessment that multiple future possibilities—a continuing La Niña-like trend, a reversal of that trend such as ESMs predict, and the range of possibilities in between—need to be considered, until future research can reject one in favor of the other.

Other Perils

While we have focused on TC activity, the same issue affects most other climate-related perils. Drought, extreme precipitation, severe convective storms, and other kinds of extreme events, occurring in many parts of the world, are strongly influenced by the state of the tropical Pacific. If the ESMs' responses to greenhouse gas forcing in the tropical Pacific have the wrong sign, that will introduce systematic and possibly large errors into any assessment of the climate change signal, present or future, in those perils, as with TCs.

A salient example is drought in southwest North America. On interannual to decadal timescales it has been well established that when the central to eastern equatorial Pacific is cooler than normal, the associated reduced convective precipitation drives Rossby wave trains that place an anomalous high over the North Pacific Ocean. This displaces the extratropical westerlies and storm track poleward bringing dry conditions to southwest North America (75–77). The equatorial Pacific SST pattern also affects the intraseasonal to interannual variability in this region, and thus seasonal predictability there (78, 79). Until recently, the southwest was in serious drought, to which an extended multiyear La Niña was certainly at least a substantial contributing factor; and drought has prevailed generally since the 1997/98 El Niño because of the cool-tropics phases of the Pacific Decadal Oscillation (80, 81), while models project increases in this region in the future (82). A strengthened zonal SST gradient is also implicated in reduced precipitation during the short rains during northern hemisphere fall in the Horn of Africa. As in the case of southwest North America, the Horn of Africa has been experiencing drier conditions this century than in the end of the 20th century, despite climate models projecting a wetter future for the region (83, 84). Similarly, an enhanced tropical Pacific SST gradient favors drought in extratropical Central America, both in the Mediterranean-type climate of Chile and the wet summer climate east of the Andes (e.g., ref. 85, and references therein). A stronger tropical Pacific zonal SST gradient response to rising GHGs would enhance drought risk for the American southwest, where water resources for agriculture and people are seriously stressed and fire hazard is intensifying; for the Horn of Africa, which already struggles with food security; and for southern South America, which is a major player in global commodity crop markets. Consequently, CMIP6 models with enhanced Pacific cold tongue warming and a reduced zonal SST gradient might be underestimating drought risk in these three important regions with knock-on effects on ecosystems and local and global food security.

ENSO also modulates the frequency of US severe thunderstorms (ones that produce tornadoes, large hail, or damaging straight-line winds), particularly in the southeast in winter and early spring (86–88). Overall, increased US severe thunderstorm activity is expected during La Niña conditions, though the opposite signal is seen in Florida, where increased tornado activity is typically expected during El Niño episodes. Quantifying the ENSO signal in US severe thunderstorm activity is challenging because the signal is modest and thunderstorm activity is highly variable and does not have a long robust observational record. A clearer picture emerges by considering vertical wind shear and convective available potential energy (CAPE), meteorological factors that are favorable for thunderstorms and which are both enhanced during La Niña conditions. Examination of the same quantities in climate change projections finds upward trends in CAPE and little or downward trends in vertical wind shear, which together combine for an upward projected trend in severe thunderstorm activity in the United States and most of the world (89, 90). A Pacific bias toward an El Niño-like mean state would suggest that the projected US climate change signal in severe thunderstorm activity has been underestimated. Interestingly, observational studies that have detected trends in US thunderstorm report data have also found trends in wind shear, not CAPE, to be the dominant factor, perhaps reflecting the observed trend to more La Niña-like conditions in the Pacific (91–93).

Solutions

Ongoing scientific debate notwithstanding, the evidence that current ESMs' simulations of the response of the tropical Pacific to greenhouse gas forcing are wrong is compelling enough that this hypothesis needs to be fully fleshed out. Given the importance of trends in extreme events, and the sensitivity of those trends to the state of tropical Pacific, there is a critical need to develop alternative projections in which the forced Pacific trends are consistent with the trends observed in recent history. These could be used to test what the implications are for extreme events of a forced trend toward a La Niña-like state, as well as for necessary adaptation strategies in the near term. At a minimum, this is necessary if we are to characterize the current state of scientific uncertainty adequately for applications.

The ideal solution, of course, would be to develop ESMs that do not have any systematic biases that could cause errors in the forced Pacific trends, whether that be the Pacific cold tongue-double ITCZ bias or others. If such models were to exist and could simulate recent historical trends in the tropical Pacific similar to those observed, we would consider their future projections much more reliable than those we have today. If this were straightforward to do, however, it would have been done already; instead, the cold-tongue-double ITCZ bias, in particular, has proved resistant to many generations of model development effort. In the near term, then, some form of bias correction is probably necessary. Flux adjustment (94), though long unpopular in climate studies, is justified in cases where prediction is the goal and where skill is demonstrably improved by it. In seasonal TC forecasting, for example, it has recently been used (95). We argue that it is justified in longer-term climate prediction and projection as well, given the importance of the tropical Pacific. Any other bias correction approaches (e.g., nudging of the model state to that observed) that exist or can be developed should also be tried.

At present, in any case, those using ESMs for risk assessment of extreme events (including via downscaling) should be aware of the possibility that their simulated tropical Pacific response to greenhouse gas forcing may be wrong, and that this may strongly influence their simulated trends in extreme events. This applies to estimates of historical, present, and future risk, and to extreme events either simulated directly by the ESMs or generated offline by downscaling methods. In the case of TCs, this means, all else equal, that the risk is likely being underpredicted in the Atlantic and overpredicted in the Pacific, for example.

More generally, those using ESM-derived assessments of climate risk for applied purposes should understand the nature of the scientific uncertainties inherent in those assessments. While multimodel ensembles may be able to characterize some aspects of the uncertainty, they will fail to do so if and to the extent that there is reason to suspect that most or all models share a common error. Here, we argue for considering the hypothesis that the entire ensemble is simulating the trend in the pattern of Pacific warming qualitatively incorrectly, as a consequence of a common model bias. There is now substantial evidence that this bias may be causing erroneous trends in a highly consequential aspect of the tropical climate, and through that, in TCs and other extreme events. If true, this conclusion implies a need for substantial changes in how various regions of the globe prepare for future societal impacts from climate-related shifts in extreme weather events. While there are no easy resolutions of this difficulty, we hope greater awareness of the issue sparks both more urgent research to address it, and greater appreciation of the nature of the uncertainty in the meantime.

Data, Materials, and Software Availability. Some study data available [Tropical cyclone tracks downscaled from CMIP6 using the CHAZ model can be shared for research purposes but cannot be shared with some commercial companies due to restrictions from the research sponsor, Aon. Thus, we will provide these data upon request. All other data, including the data shown in the figures from the CHAZ tracks (which are summary statistics) can be freely shared. The CMIP6 and observation-based SST data as well as the HighResMIP tropical cyclone track data are available at the links given in the supplemental information. Analysis codes and the data shown in the figures are available at https://github.com/cl3225/Sobel-et-al-2023-PNAS (96)].

ACKNOWLEDGMENTS. A.H.S., C.-Y.L., S.G.B., S.J.C., B.F., and M.K.T. acknowledge support from Aon/Impact Forecasting for this work. A.H.S. and S.J.C. also received support for this work from the Volkswagen Foundation. A.H.S., C.-Y.L., S.J.C., K.A.R., and R.S. also acknowledge the support of the NSF (AGS2217620) and US Department of Energy (DOE) (DE-SC0023333). A.C. received support from NOAA Climate Program Office Grant NA20OAR4310400. Analyses shown in several figures were made using scripts adapted from ones originally written for previous studies by Naomi Henderson.

1. T. Fiedler *et al*., Business risk and the emergence of climate analytics. *Nat. Clim. Change* **11**, 87–94 (2021).
2. J. Yoshimura, M. Sugi, A. Noda, Influence of greenhouse warming on tropical cyclone frequency. *J. Meteorol. Soc. Japan* **84**, 405–428 (2006).
3. M. Zhao, I. M. Held, S. J. Lin, G. A. Vecchi, Simulations of global hurricane climatology, interannual variability, and response to global warming using a 50-km resolution GCM. *J. Clim.* **22**, 6653–6678 (2009).
4. Y. Yamada, K. Oouchi, M. Satoh, H. Tomita, W. Yanase, Projection of changes in tropical cyclone activity and cloud height due to greenhouse warming: Global cloud-system-resolving approach. *Geophys. Res. Lett.* **37** (2010), https://doi.org/10.1029/2010GL042518.
5. M. F. Wehner, K. A. Reed, B. Loring, D. Stone, H. Krishnan, Changes in tropical cyclones under stabilized 1.5 and 2.0 °C global warming scenarios as simulated by the Community Atmospheric Model under the HAPPI protocols. *Earth Syst. Dyn.* **9**, 187–195 (2018).
6. K. A. Emanuel, Climate and tropical cyclone activity: A new model downscaling approach. *J. Clim.* **19**, 4797–4802 (2006).
7. C. Y. Lee, M. K. Tippett, A. H. Sobel, S. J. Camargo, An environmentally forced tropical cyclone hazard model. *J. Adv. Model Earth Syst.* **10** (2018).
8. R. Jing, N. Lin, An environment-dependent probabilistic tropical cyclone model. *Clim. Dyn.* **12**, e2019MS001975 (2020).
9. R. Seager, N. Henderson, M. Cane, Persistent discrepancies between observed and modeled trends in the Tropical Pacific Ocean. *J. Clim.* **35**, 4571–4584 (2022).
10. R. C. J. Wills, Y. Dong, C. Proistosecu, K. C. Armour, D. S. Battisti, Systematic climate model biases in the large-scale patterns of recent sea-surface temperature and sea-level pressure change. *Geophys. Res. Lett.* **49**, e2022GL100011 (2022).
11. T. Andrews, J. M. Gregory, M. J. Webb, The dependence of radiative forcing and feedback on evolving patterns of surface temperature change in climate models. *J. Clim.* **28**, 1630–1648 (2015).
12. T. Andrews, M. J. Webb, The dependence of global cloud and lapse rate feedbacks on the spatial structure of tropical Pacific warming. *J. Clim.* **31**, 641–654 (2018).
13. P. Ceppi, J. M. Gregory, Relationship of tropospheric stability to climate sensitivity and Earth's observed radiation budget. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 13126–13131 (2017).
14. Y. Dong *et al*., Biased estimates of equilibrium climate sensitivity and transient climate response derived from historical CMIP6 simulations. *Geophys. Res. Lett.* **48**, e2021GL095778 (2021).
15. G. V. Cesana, A. D. Del Genio, Observational constraint on cloud feedbacks suggests moderate climate sensitivity. *Nat. Clim. Change* **11**, 213–218 (2021).
16. C. Y. Lee, A. H. Sobel, S. J. Camargo, M. K. Tippett, Statistical–dynamical downscaling projections of tropical cyclone activity in a warming climate: Two diverging genesis scenarios. *J. Clim.* **33**, 4815–4834 (2020).
17. R. J. Haarsma *et al*., High resolution model intercomparison project (HighResMIP v1.0) for CMIP6. *Geosci. Model Dev.* **9**, 4185–4208 (2016).
18. S. J. Camargo, A. H. Sobel, A. G. Barnston, P. J. Klotzbach, "The influence of natural climate variability on tropical cyclones and seasonal forecasts of tropical cyclone activity" in *Global Perspectives on Tropical Cyclones, from Science to Mitigation, Series on Earth System Science in Asia*, J. C. L. Chan, J. D. Kepert, Eds. (World Scientific, ed. 2, 2010), vol. 4, pp. 325–360.
19. I. I. Lin *et al*., "ENSO and Tropical Cyclones" in *El Niño Southern Oscillation in a Changing Climate, Geophysical Monograph Series* (American Geophysical Union, 2020), pp. 377–408.
20. S. J. Camargo, K. A. Emanuel, A. H. Sobel, Use of a genesis potential index to diagnose ENSO effects on tropical cyclone genesis. *J. Clim.* **20**, 4819–4834 (2007).
21. S. J. Camargo, A. H. Sobel, A. G. Barnston, P. J. Klotzbach, "The influence of natural climate variability on tropical cyclones and seasonal forecasts of tropical cyclone activity" in *Global Perspectives on Tropical Cyclones, from Science to Mitigation, Series on Earth System Science in Asia*, J. C. L. Chan, J. D. Kepert, Eds. (World Scientific, ed. 2, 2010), pp. 325–360.
22. S. S. Chand, K. J. Tory, H. Ye, K. J. E. Walsh, Projected increase in El Niño-driven tropical cyclone frequency in the Pacific. *Nat. Clim. Change* **7**, 123–127 (2017).
23. A. C. T. Sena, C. M. Patricola, B. Loring, Future changes in active and inactive Atlantic hurricane seasons in the energy exascale Earth system model. *Geophys. Res. Lett.* **49**, e2022GL100267 (2022).
24. Y. Dong *et al*., Intermodel spread in the pattern effect and its contribution to climate sensitivity in CMIP5 and CMIP6 models. *J. Clim.* **33**, 7755–7775 (2020).
25. T. Andrews *et al*., Accounting for changing temperature patterns increases historical estimates of climate sensitivity. *Geophys. Res. Lett.* **45**, 8490–8499 (2018).
26. S. Coats, K. B. Karnauskas, Are simulated and observed twentieth century tropical Pacific sea surface temperature trends significant relative to internal variability? *Geophys. Res. Lett.* **44**, 9928–9937 (2017).
27. S. Lee *et al*., On the future zonal contrasts of equatorial pacific climate: Perspectives from observations, simulations, and theories. *npj Clim. Atmos. Sci.* **5**, 82 (2022).
28. Y. Zhang, J. M. Wallace, D. S. Battisti, ENSO-like interdecadal variability. *J. Clim.* **10**, 1004–1020 (1997).
29. C. Deser *et al*., Isolating the evolving contributions of anthropogenic aerosols and greenhouse gases: A new CESM1 large ensemble community resource. *J. Clim.* **33**, 7835–7858 (2020).
30. S. M. Kang, S. P. Xie, C. Deser, B. Xiang, Zonal mean and shift modes of historical climate response to evolving aerosol distribution. *Sci. Bull.* **66**, 2405–2411 (2021).
31. D. L. Hartmann, The Antarctic ozone hole and the pattern effect on climate sensitivity. *Proc. Natl. Acad. Sci. U.S.A.* **119**, e2207889119 (2022).
32. Y. Dong, K. C. Armour, D. S. Battisti, E. Blanchard-Wigglesworth, Two-way teleconnections between the Southern Ocean and the tropical Pacific via a dynamic feedback. *J. Clim.* **35**, 2667–2682 (2022).
33. R. Seager *et al*., Strengthening tropical Pacific zonal sea surface temperature gradient consistent with rising greenhouse gases. *Nat. Clim. Change* **9**, 517–522 (2019).
34. O. Adam, T. Schneider, F. Brient, Regional and seasonal variations of the double-ITCZ bias in CMIP5 models. *Clim. Dyn.* **51**, 101–117 (2018).
35. B. Tian, X. Dong, The double-ITCZ bias in CMIP3, CMIP5, and CMIP6 models based on annual mean precipitation. *Geophys. Res. Lett.* **47**, e2020GL087232 (2020).

36. A. C. Clement, R. Seager, M. A. Cane, S. E. Zebiak, An ocean dynamical thermostat. *J. Clim.* **9**, 2190–2196 (1996).
37. G. A. Vecchi *et al*., Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. *Nature* **441**, 73–76 (2006).
38. T. R. Knutson, S. Manabe, Time–mean response over the Tropical Pacific to increased CO_2 in a coupled ocean–atmosphere model. *J. Clim.* **8**, 2181–2199 (1995).
39. S. P. Xie *et al*., Global warming pattern formation: Sea surface temperature and rainfall. *J. Clim.* **23**, 966–986 (1995).
40. P. DiNezio *et al*., Climate response of the equatorial pacific to global warming. *J. Clim.* **22**, 4873–4892 (2009).
41. U. K. Heede, A. V. Federov, N. J. Burls, Time scales and mechanisms for the Tropical Pacific response to global warming: A tug of war between the ocean thermostat and weaker walker. *J. Clim.* **33**, 6101–6118 (2020).
42. S. Coats, K. Karnauskas, A role for the equatorial undercurrent in the ocean dynamical thermostat. *J. Clim.* **31**, 6245–6261 (2018).
43. C. S. Shin, B. Huang, A spurious warming trend in the NMME equatorial Pacific SST hindcasts. *Clim. Dyn.* **53**, 7287–7303 (2019).
44. M. L. L'Heureux, M. K. Tippett, W. Wang, Prediction challenges from errors in tropical Pacific sea surface temperature trends. *Front. Clim.* **4**, 837483 (2022).
45. N. Maher *et al*., The future of the El Niño-Southern Oscillation: Using large ensembles to illuminate time-varying responses and inter-model differences. *Earth Syst. Dyn.* **14**, 413–431 (2023).
46. J. P. Kossin, D. J. Vimont, A more general framework for understanding Atlantic hurricane variability and trends. *Bull. Am. Meteor. Soc.* **88**, 1767–1782 (2007).
47. C. M. Patricola, R. Saravanan, P. Chang, The impact of the El Niño-Southern Oscillation and Atlantic meridional mode on seasonal Atlantic tropical cyclone activity. *J. Clim.* **27**, 5311–5328 (2014).
48. S. B. Goldenberg, C. W. Landsea, A. M. Mestas-Nuñez, W. M. Gray, The recent increase in Atlantic hurricane activity: Causes and implications. *Science* **293**, 474–479 (2001).
49. M. E. Mann, K. A. Emanuel, Atlantic hurricane trends linked to climate change. *EOS* **71**, 233–241 (2006).
50. L. N. Murphy, K. Bellomo, M. A. Cane, A. Clement, The role of historical forcings in simulating the observed Atlantic multidecadal oscillation. *Geophys. Res. Lett.* **44**, 2472–2480 (2017).
51. S. J. Camargo, A. H. Sobel, Western North Pacific tropical cyclone intensity and ENSO. *J. Clim.* **18**, 2996–3006 (2005).
52. M. Deshpande *et al*., Changing status of tropical cyclones over the north Indian Ocean. *Clim. Dyn.* **57**, 3545–3567 (2021).
53. H. Murakami, G. A. Vecchi, S. Underwood, Increasing frequency of extremely severe cyclonic storms over the Arabian Sea. *Nat. Clim. Change* **7**, 885–889 (2017).
54. X. T. Zheng *et al*., Indian Ocean dipole response to global warming in the CMIP5 multimodel ensemble. *J. Clim.* **26**, 6067–6080 (2013).
55. W. Liu, J. Lu, S. P. Xie, Understanding the Indian Ocean response to double CO_2 forcing in a coupled model. *Ocean Dyn.* **65**, 1037–1046 (2015).
56. S. L. Yao, G. Huang, R. G. Wu, Inhomogeneous warming of the tropical Indian Ocean in the CMIP5 model simulations during 1900–2005 and associated mechanisms. *Clim. Dyn.* **46**, 619–636 (2016).
57. G. Li, S. P. Xie, Y. Du, A robust but spurious pattern of climate change in model projections over the tropical Indian Ocean. *J. Clim.* **29**, 5589–5608 (2016).
58. G. Wang, W. Cai, A. Santoso, Assessing the impact of model biases on the projected increase in frequency of extreme positive Indian Ocean dipole events. *J. Clim.* **30**, 2757–2767 (2017).
59. B. Lyon, Biases in sea surface temperature and the annual cycle of Greater Horn of Africa rainfall in CMIP6. *Int. J. Climatol.* **42**, 4179–4186 (2022).
60. N. H. Saji, B. N. Goswami, P. N. Vinayachandran, T. Yamagatai, A dipole mode in the tropical Indian Ocean. *Nature* **401**, 360–363 (1999).
61. V. Krishnamurthy, B. P. Kirtman, Variability of the Indian Ocean: Relation to monsoon and ENSO. *Q. J. R. Meteorol. Soc.* **129**, 1623–1646 (2003).
62. M. F. Stuecker *et al*., Revisiting ENSO/Indian Ocean dipole phase relationships. *Geophys. Res. Lett.* **44**, 2481–2492 (2017).
63. Y. Kuleshov, L. Qi, R. Fawcett, D. Jones, On tropical cyclone activity in the Southern Hemisphere: Trends and the ENSO connection. *Geophys. Res. Lett.* **35**, L14S08 (2008).
64. S. S. Chand *et al*., Review of tropical cyclones in the Australian region: Climatology, variability, predictability, and trends. *WIREs Clim. Change* **10**, e602 (2019).
65. S. S. Chand, A. Dowdy, S. Bell, K. Tory, *A Review of South Pacific Tropical Cyclones: Impacts of Natural Climate Variability and Climate Change*, L. Kumar, Ed. (Springer International Publishing, Cham, Switzerland, 2020), pp. 251–273.
66. P. J. Klotzbach *et al*., Trends in global tropical cyclone activity: 1990–2021. *Geophys. Res. Lett.* **49**, e2021GL095774 (2022).
67. V. Eyring *et al*., "Human influence on the climate system" in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, V. Masson-Delmotte *et al*., Eds. (Cambridge University Press, 2021), pp. 423–552.
68. P. Forster *et al*., "The Earth's energy budget, climate feedbacks, and climate sensitivity" in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, V. Masson-Delmotte *et al*., Eds. (Cambridge University Press, 2021).
69. U. K. Heede, A. V. Fedorov, Colder eastern equatorial pacific and stronger walker circulation in the early 21st century: Separating the forced response to global warming from natural variability. *Geophys. Res. Lett.* **50**, e2022GL101020 (2023).
70. H. Murakami *et al*., Detected climatic change in global distribution of tropical cyclones. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 10706–10714 (2020).
71. G. A. Vecchi, B. J. Soden, Effect of remote sea surface temperature change on tropical cyclone potential intensity. *Nature* **450**, 1066–1070 (2007).
72. G. A. Vecchi, K. L. Swanson, B. J. Soden, Whither hurricane activity? *Science* **322**, 687–689 (2008).
73. A. Clement *et al*., The Atlantic multidecadal oscillation without a role for ocean circulation. *Science* **350**, 320–324 (2015).
74. R. Zhang *et al*., A review of the role of the Atlantic meridional overturning circulation in Atlantic multidecadal variability and associated climate impacts. *Rev. Geophys.* **57**, 316–375 (2019).
75. R. Seager *et al*., Mechanisms of ENSO-forcing of hemispherically symmetric precipitation variability. *Q. J. R. Meteor. Soc.* **131**, 1501–1527 (2005).
76. R. Seager, Y. Kushnir, C. Herweijer, N. Naik, J. Velez, Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856–2000. *J. Clim.* **18**, 4068–4091 (2005).
77. H. Huang, R. Seager, Y. Kushnir, The 1976/77 transition in precipitation over the Americas and the influence of tropical SST. *Clim. Dyn.* **24**, 721–740 (2005).
78. Z. Q. Zhou, S. P. Xie, X. T. Zheng, Q. Liu, H. Wang, Global warming-induced changes in El Nino teleconnections over the North Pacific and North America. *J. Clim.* **27**, 9050–9064 (2014).
79. D. L. Swain, B. Langenbrunner, J. Neelin, A. Hall, Increasing precipitation volatility in twenty-first-century California. *Nat. Clim. Change* **8**, 427–433 (2018).
80. T. Delworth, F. Zeng, A. Rosati, G. A. Vecchi, A. T. Wittenberg, A link between the hiatus in global warming and North American drought. *J. Clim.* **28**, 3834–3845 (2015).
81. R. Seager *et al*., Mechanisms of a meteorological drought onset: Summer 2020 to spring 2021 in southwestern North America. *J. Clim.* **35**, 7367–7385 (2022).
82. M. Almazroui *et al*., Projected changes in temperature and precipitation over the United States, Central America, and the Caribbean in CMIP6 GCMs. *Earth Syst. Environ.* **5**, 1–24 (2021).
83. B. Lyon, Reconciling past and future rainfall trends over East Africa. *J. Clim.* **28**, 9768–9788 (2015).
84. D. P. Rowell, Reconciling past and future rainfall trends over East Africa. *J. Clim.* **28**, 9768–9788 (2015).
85. W. Cai *et al*., Climate impacts of the El Niño-Southern Oscillation on South America. *Nat. Rev. Earth Environ.* **1**, 215–231 (2020).
86. A. R. Cook, J. T. Schaefer, The relation of El Niño-Southern Oscillation (ENSO) to winter tornado outbreaks. *Mon. Weather Rev.* **136**, 3121–3137 (2008).
87. J. T. Allen, M. K. Tippett, A. H. Sobel, Influence of the El Niño/Southern Oscillation on tornado and hail frequency in the United States. *Nat. Geosci.* **8**, 278–283 (2015).
88. T. W. Moore, Seasonal frequency and spatial distribution of tornadoes in the United States and their relationship to the El Niño/Southern Oscillation. *Ann. Am. Assoc. Geogr.* **109**, 1033–1051 (2019).
89. N. S. Diffenbaugh, M. Scherer, R. J. Trapp, Robust increases in severe thunderstorm environments in response to greenhouse forcing. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 16361–16366 (2013).
90. C. Lepore, R. Abernathey, N. Henderson, J. T. Allen, M. K. Tippett, Future global convective environments in CMIP6 models. *Earth's Future* **9**, e2021EF002277 (2021).
91. M. Lu, M. Tippett, U. Lall, Changes in the seasonality of tornado and favorable genesis conditions in the Central United States. *Geophys. Res. Lett.* **42**, 4224–423 (2015).
92. M. K. Tippett, Changing volatility of U.S. annual tornado reports. *Geophys. Res. Lett.* **41**, 6956–6961 (2014).
93. M. K. Tippett, C. Lepore, J. E. Cohen, More tornadoes in the most extreme U.S. tornado outbreaks. *Science* **354**, 1419–1423 (2016).
94. S. J. Lambert, G. J. Boer, CMIP1 evaluation and intercomparison of coupled climate models. *Clim. Dyn.* **17**, 83–106 (2001).
95. G. A. Vecchi *et al*., On the seasonal forecasting of regional tropical cyclone activity. *J. Clim.* **27**, 7994–8016 (2014).
96. C.-Y. Lee, Sobel-et-al-2023-PNAS. *Github*. https://github.com/cl3225/Sobel-et-al-2023-PNAS. Deposited 10 July 2023.