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Forced and unforced ocean temperature changes in Atlantic and Pacific tropical cyclogenesis regions


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Previous research has identified links between changes in sea surface temperature (SST) and hurricane intensity. We use climate models to study the possible causes of SST changes in Atlantic and Pacific tropical cyclogenesis regions. The observed SST increases in these regions range from 0.32°C to 0.67°C over the 20th century. The 22 climate models examined here suggest that century-time-scale SST changes of this magnitude cannot be explained solely by unforced variability of the climate system. We employ model simulations of natural internal variability to make probabilistic estimates of the contribution of external forcing to observed SST changes. For the period 1906–2005, we find an 84% chance that external forcing explains at least 67% of observed SST increases in the two tropical cyclogenesis regions. Model “20th-century” simulations, with external forcing by combined anthropogenic and natural factors, are generally capable of replicating observed SST increases. In experiments in which forcing factors are varied individually rather than jointly, human-caused changes in greenhouse gases are the main driver of the 20th-century SST increases in both tropical cyclogenesis regions.

Hurricane activity is influenced by a variety of physical factors, such as sea surface temperatures (SSTs), wind shear, moisture availability, and atmospheric stability (1). Theory, observations, and modeling provide evidence of a direct link between changes in SSTs and hurricane intensity (2–6). One recent investigation found that secular SST changes in the Atlantic and Pacific tropical cyclogenesis regions (ACR and PCR) were highly correlated with a measure of hurricane intensity based on maximum wind speeds (6). This research raises an important question: What are the causes of past SST changes in areas where hurricanes develop?

This question is timely in view of the unprecedented level of activity during the 2005 Atlantic hurricane season (7) and evidence that a recent increase in the number of category 4 and 5 hurricanes is largely SST-driven (8, 9). There are, however, conflicting estimates of the relative contributions of internal climate variability and external forcing to observed SST changes. Some analyses suggest that 20th century SST changes in the ACR can be fully explained by internal variability of the climate system (10). In contrast, detection and attribution studies find a substantial anthropogenic component in observed increases in upper ocean heat content (11–13). Such work has examined the behavior of ocean heat content averaged over large ocean basins, while our investigation focuses on elucidating the causes of SST changes in the much smaller ACR and PCR.1

Previous research has relied on observational data to assess the relative contributions of internal noise and external forcing to SST changes in tropical cyclogenesis regions (7, 14). Partitioning of signal and noise components is difficult to achieve with observations alone. In the real world, human-induced changes in external climate forcings are superimposed on (and may even modulate) natural internal climate variability. We do not have a control experiment without anthropogenic forcings, which could be used to isolate and quantify climate noise. Such systematic experimentation can be performed only with numerical models of the climate system.

Model and Observational Data

Here, we use 22 different climate models to estimate the magnitude of SST changes arising from internally generated variability and external forcing. Our focus is on SST changes in the ACR and PCR on timescales of the last 20–100 years. We analyze both control simulations with no forcing changes and 20th-century (20CEN) experiments with estimated historical changes in external forcings (15). 20CEN forcings were not standardized across different modeling groups (see Supporting Text, which is published as supporting information on the PNAS web site). The 20CEN results therefore reflect differences and uncertainties in the applied forcings and in the physics and parameterizations of the models themselves. The most comprehensive experiments include changes in combined natural external forcings (solar irradiance and volcanic dust loadings in the atmosphere) and in a wide variety of anthropogenic influences (such as well mixed greenhouse gases, ozone, sulfate and black carbon aerosols, and land surface properties). All simulations were performed with coupled atmosphere–ocean General Circulation Models, in which SST changes are predicted.

Model SSTs are compared with the Extended Reconstructed SST data set (ERSST) of the National Oceanic and Atmospheric Administration (NOAA) (16) and the Hadley Centre Sea Ice and SST data set (HadISST) (17). The aim of these comparisons is to determine whether observed SST changes in the ACR and PCR can be explained by internally generated variability estimated from control simulations, and to evaluate how successfully the 20CEN runs capture important features of the observed SST behavior in these two tropical cyclogenesis regions. Use of both ERSST and HadISST data provides information on the sensitivity of our results to structural uncertainties in the observations (15, 18).

Observed and Modeled SST Time Series

We consider the observations first. In the smoothed ERSST and HadISST data (19), SSTs in the ACR were at record levels during
For visual display, the modeled and observed SST data in Figs. 1 and 6 were smoothed by using a digital filter (19) with a window width W = 21 months, corresponding to a half-power point of 25 months. This smoothing damps variability on interannual and El Niño/Southern Oscillation timescales, while information on the SST response to volcanic forcing is largely preserved. The overall linear trend was subtracted before filtering and was reinserted after filtering. Data loss was avoided by “reflecting” (W − 1)/2 points at the beginning and end of the time series. To estimate modeled and observed variability on decadal and longer timescales (Fig. 4C), we applied the same digital filter to the detrended SST anomaly data and set W = 145 months, yielding a half-power point at 119 months. The response functions for both choices of W are shown in Fig. 7.

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Fig. 1. Modeled and observed SST changes in tropical cyclogenesis regions and observed changes in stratospheric aerosol optical depth (SAOD). Time series of monthly mean, spatially averaged SST anomalies are for the ACR (A) and PCR (B). Observational results are from the NOAA ERSSST data set (16). Results for a second observational data set (17) are very similar (see Fig. 6). Model data from simulations of 20CEC climate change are partitioned into two groups, with and without volcanic forcing (V and No-V). All model data were low-pass filtered (with window width W = 21 months; see Fig. 7, which is published as supporting information on the PNAS web site) before formation of V and No-V averages (19). ERSSST data were smoothed with the same filter. The yellow and gray envelopes are the ±1σ confidence intervals for the V averages, calculated with the smoothed data at each time t. Because most 20CEC experiments end in December 1999, and No-V averages are calculated only until that month, ERSSST data are shown through December 2005. All SST anomalies were defined relative to climatological monthly means over 1900 through 1909. This reference period was chosen for visual display purposes only, and it has no impact on subsequent trend analyses or variability estimates. The amplitudes of the observed and simulated SST variability are not directly comparable, because the latter was damped by averaging over different realizations and models. (C) Estimate of the SAOD (21). Dotted vertical lines denote the times of maximum SAOD during major volcanic eruptions.

Fig. 2. Comparison between observed and simulated SST changes in the ACR (A, C, E, and G) and PCR (B, D, F, and H). Results are expressed as the total linear change, b × n, where b is the slope parameter of the least-squares linear trend (in °C/month) and n is the total number of months. Trend comparisons are made on four different timescales: 100 years (A and B), 50 years (C and D), 30 years (E and F), and 20 years (G and H). Observed ACR and PCR SST trends from HadISST and ERSSST were calculated over the periods 1906–2005, 1956–2005, 1976–2005, and 1986–2005. Sampling distributions of unforced SST trends on 100-, 50-, 30-, and 20-year timescales were computed as described in the main text. For visual display purposes, unforced SST trends were fitted to segments of the ACR and PCR anomaly time series that overlapped by all but 10 years. For the century-timescale results, this procedure yields 698 unforced SST trends for each tropical cyclogenesis region. Unforced trends are plotted in the form of histograms. Very similar (but less smooth) histograms are obtained if trends are fitted to nonoverlapping segments of control run SST data. Red and blue vertical lines indicate observed SST trends in the HadISST and ERSSST data, respectively.

between observational data sets primarily reflect the different procedures used by the NOAA and Hadley Centre groups to infill missing SST data (16, 17). Variability on sub- to multidecadal timescales is superimposed on these overall increases in observed SSTs (Fig. 1). Commonly discussed sources of this variability are the El Niño/Southern Oscillation and the Atlantic Multidecadal Oscillation (7, 20). In the ERSSST and HadISST data, part of this variability is in phase with fluctuations in the optical depth of stratospheric aerosols produced by massive volcanic eruptions (21) (Figs. 1 and 6). This result is consistent with the identification of volcanic effects (albeit at much larger spatial scales) in many different climate variables (22–24). The relationship between SST variability and stratospheric aerosol optical depth is clearer in the PCR than in the ACR, particularly for the eruption of Mt. Pinatubo in June
Table 1. Statistics for observed and simulated SST trends in the ACR and PCR

<table>
<thead>
<tr>
<th>Region</th>
<th>Dataset</th>
<th>Length, yr</th>
<th>Period</th>
<th>$b_{OBS}$</th>
<th>$b_{CTL}$</th>
<th>$b_{OBS}/b_{CTL}$</th>
<th>$p_1$</th>
<th>$p_2$</th>
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<tr>
<td>ACR</td>
<td>HadISST</td>
<td>100</td>
<td>1906–2005</td>
<td>0.046</td>
<td>0.015</td>
<td>3.158</td>
<td>0.000***</td>
<td>0.024**</td>
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<td>1956–2005</td>
<td>0.042</td>
<td>0.035</td>
<td>1.204</td>
<td>0.074*</td>
<td>0.177</td>
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<td>1976–2005</td>
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<td>0.064</td>
<td>2.838</td>
<td>0.010***</td>
<td>0.014**</td>
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<td>0.000***</td>
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<td>0.029***</td>
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<td>0.193</td>
<td>0.064</td>
<td>3.014</td>
<td>0.007***</td>
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<td>0.318</td>
<td>0.117</td>
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<td>0.014**</td>
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<tr>
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<td>0.036</td>
<td>0.012</td>
<td>3.061</td>
<td>0.000***</td>
<td>0.012**</td>
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<tr>
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<td>0.063</td>
<td>0.030</td>
<td>2.124</td>
<td>0.011**</td>
<td>0.034**</td>
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<td>0.065</td>
<td>2.243</td>
<td>0.010***</td>
<td>0.028**</td>
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<td>0.010</td>
<td>0.987</td>
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<tr>
<td>PCR</td>
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<tr>
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<td>0.010***</td>
<td>0.028**</td>
</tr>
<tr>
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<td>ERSST</td>
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<td>1986–2005</td>
<td>0.195</td>
<td>0.105</td>
<td>1.855</td>
<td>0.038***</td>
<td>0.063*</td>
</tr>
</tbody>
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The observed SST trends in the ACR and PCR ($b_{OBS}$; °C/decade) are given for the last 100, 50, 30, and 20 years of the HadISST and ERSST data sets. The standard deviation of the model-based sampling distribution of unforced SST trends ($b_{OBS}/b_{CTL}$; °C/decade) was calculated from nonoverlapping segments of the control run SST time series (see Fig. 2 and main text). The ratio $b_{OBS}/b_{CTL}$ is a simple measure of signal to noise. The $p$ values are estimates of the probability that $b_{OBS}$ could be caused by (model-simulated) natural internal variability alone. Probabilities are based on tests against actual and absolute values of unforced SST trends ($p_1$ and $p_2$, respectively). All trends were calculated with monthly mean, spatially averaged anomaly data. Trend significance at the 10%, 5%, and 1% levels is indicated by one, two, or three asterisks, respectively.

1991 (Figs. 1 and 6). Regional differences in the observed SST changes after volcanic eruptions are expected, partly because of spatial differences in climate noise (25).

Eleven of the 22 historical forcing experiments included some representation of volcanic effects on climate (see Supporting Text and Tables 2 and 3, which are published as supporting information on the PNAS web site). We therefore partitioned the 20CEN results in Fig. 1 into two sets, with and without volcanic forcing (V and No-V, respectively). The pronounced differences between the V and No-V averages during major eruptions support the observational evidence of volcanically induced cooling of SSTs in both tropical cyclogenesis regions.

Comparison of Observed and Unforced SST Trends

To assess whether observed ACR and PCR trends could be due to climate noise alone, we used information from 22 model control runs to generate sampling distributions of the unforced SST trends in these regions (Fig. 2). For each control run, least-squares linear trends were fitted to successive nonoverlapping segments of the ACR and PCR anomaly time series (Figs. 8 and 9, which are published as supporting information on the PNAS web site). Results from the 22 models were combined to obtain “multimodel” sampling distributions of unforced SST trends. This was done for timescales of 100, 50, 30, and 20 years, yielding trend sample sizes of $N_i = 84, 175, 287$, and 444, respectively (see Supporting Text). Observed SST trends in both tropical cyclogenesis regions were calculated with the last 100, 50, 30, and 20 years of the HadISST and ERSST data sets.

We then estimated $p$ values by comparing the observed SST trend, $b_{OBS}$, with both actual and absolute values of $b_{CTL}(i)$, $i = 1, \ldots, N_r$, the unforced SST trends from the multimodel sampling distributions. In 29 of 32 cases (2 cyclogenesis regions × 2 observational data sets × 4 trend lengths × 2 different methods of estimating $p$ values), the null hypothesis that observed SST trends could be explained by natural internal variability (as simulated in current climate models) is rejected at the 10% level or better (Table 1). Our finding that observed SST trends in the ACR and PCR are significantly larger than model-based estimates of unforced SST variability is therefore relatively insensitive to observational uncertainty, the timescale over which trends are calculated, and the details of our significance testing strategy.

The $p$ values partly obscure the expected relationship between the timescale of SST changes and the relative sizes of observed and unforced trends (Fig. 2). Because the amplitude of unforced variability decreases with an increase in the temporal averaging period, a slowly evolving greenhouse-gas-induced warming signal should be more easily discernible at longer than at shorter timescales (26). Such relationships are more clearly revealed by using the signal-to-noise ratio $b_{OBS}/b_{CTL}$, where $b_{CTL}$ is the standard deviation of the sampling distribution of unforced SST trends (Table 1). While $b_{OBS}$ trends over the past 100 years are at least 3.2–5.1 times larger than $b_{CTL}$, observed SST changes over the past 20 to 30 years typically have smaller ratios of $b_{OBS}/b_{CTL}$, particularly in the PCR, where they vary from 1.0 to 2.3. In the ACR, however, partly because of the unusual warmth of 2005 in the observational record (Fig. 1), even $b_{OBS}$ trends over the past 20–30 years are 2.7–3.3 times larger than values of $b_{CTL}$.

Contribution of External Forcing to Observed SST Trends

The results from Figs. 1 and 2 can be used to estimate the contribution of external forcing to observed SST trends in the ACR and PCR. We do this in two different ways: (i) by comparing observed trends with model-based estimates of unforced trends, and (ii) by comparing the forced SST changes in the 20CEN experiments with observations. The first approach has the advantage that the “spread” of model-based noise estimates arises solely from structural differences in the models (e.g., in terms of physics, parameterizations, resolution, and spin-up procedures), whereas the second approach uses experiments that convolve differences in model structure and the applied external forcings.
In the first approach, we assume that an observed SST trend, $b_{OBS}$, can be decomposed into $b_{EXT}$, the true (but unknown) slope of the SST trend in response to external forcing, and $b_{INT}$, the slope of the SST trend arising from a (random) realization of natural internal variability. The percentage contribution of external forcing to the observed trend can be estimated by $F_1 = \frac{100(\hat{b}_{OBS} - \hat{b}_{INT})}{\hat{b}_{OBS}}$. In the real world, $b_{INT}$ may be either positive (contribution to the observed warming) or negative (offsetting some portion of externally forced warming). Assuming that the model-based estimates of internal variability are reasonable estimates of the true amplitude of internal noise, and that the sampling distribution of this unforced trend component (derived from control run data) is Gaussian with zero mean and standard deviation $s_{CTL}$, the 68% confidence interval for $b_{INT}$ is $(s_{CTL} - s_{CTL})$, which can be easily transformed into a corresponding confidence interval for $F_1$. This procedure yields $F_1$ values in the range 100 – $D$ to 100 + $D$, where $D = 100 (s_{CTL}/\hat{b}_{OBS})$. There is therefore a 16% chance that the signal percentage is less than 100 – $D$, and a 16% chance that the signal percentage exceeds 100 + $D$.

In the second approach, we assume that the 20CEN runs provide reliable estimates of $b_{INT}$. As in the case of $b_{INT}$, a 68% confidence interval can be specified for $b_{INT}$, i.e., $(\hat{b}_V - s_V, \hat{b}_V + s_V)$, where $\hat{b}_V$ is the model-average SST trend in the subset of 20CEN runs with volcanic forcing, and $s_V$ is the intermodel standard deviation of SST trends in the V models. Under this assumption, the percentage contribution of external forcing to $b_{OBS}$ is estimated by $F_2 = 100 (\hat{b}_V/\hat{b}_{OBS})$, and the ±1σ range of $\hat{b}_V$ yields the error bars on the $F_2$ results in Fig. 3.

Consider the results for the century-timescale observed trends. Values of $F_1$ are symmetrical around 100% (Fig. 3). Based on the multimodel sampling distributions of unforced SST trends (and on one-tailed tests), there is an 84% chance that the externally forced component of observed SST increases in the ACR and PCR is at least 67%, and an 84% chance that this component is not greater than 133%. For central values of $\hat{b}_V$, $F_2$ yields a larger range (55–184%) for this externally forced component. The $F_2$ error bars overlap with the $F_1$ ranges, demonstrating consistency in the signal-to-noise partitioning obtained with the two methods. This implies that our finding of $\hat{b}_V > b_{OBS}$ in the PCR is not inconsistent with an “offsetting” of an externally forced warming by a century-timescale natural cooling trend. Clearly, model error (in both the applied 20CEN forcings and the model responses) may also be important in explaining why $\hat{b}_V > b_{OBS}$.

**Model Performance in Simulating Means, Variability, and Trends**

The $p$ values and $F_1$ results in the previous sections are only as reliable as the model-based estimates of climate noise on which they are based. The $p$ values in Table 1 could be spuriously low (and the $F_1$ values in Fig. 3 spuriously high) if there were a systematic underestimate of internally generated variability in the models used here. We tried to guard against this possibility by using a large number of models to estimate $s_{CTL}$.

Although we lack sufficiently long observational records to evaluate model estimates of century-timescale variability, the data are of adequate length for assessing simulated SST variability on subdecadal to decadal timescales. We use the 20CEN simulations to compare modeled and observed means, variability and trends. A discussion of model performance in simulating the climatological seasonal cycles of ACR and PCR SSTS is given in the Supporting Text (see Fig. 10, which is published as supporting information on the PNAS Web site).

Most models systematically underestimate the climatological annual-mean SST in the ACR and PCR (Fig. 4A). There is no evidence of such a systematic underestimate in the temporal standard deviation of unfiltered SST anomalies, which is dominated by variability on interannual and El Niño/Southern Oscillation timescales (Fig. 4B). In the ACR (PCR), roughly one-third (two-thirds) of the 60 20CEN realizations overestimate observed SST variability. These variance differences are not statistically significant.

The model results in Fig. 4A and B show apparent relationships between SST behavior in the ACR and PCR. SST biases in one tropical cyclogenesis region tend to be correlated with biases in the other region (Fig. 4A). There is an even stronger linear relationship (across models) between the amplitude of the high-frequency variability in the ACR and PCR (Fig. 4B). The apparent correlation of biases in geographically disparate regions may reflect common underlying causes, such as model errors in the large-scale mean state and in the amplitude of tropically coherent modes of variability.

Model performance in simulating variability on decadal and longer timescales is of most interest here, because this constitutes the background noise against which any slowly evolving forced signal must be detected (Fig. 4C). SST data were low-pass filtered to isolate variability on these timescales (see Supporting Text). In the

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*Fig. 3. Estimates of the percentage contribution of external forcing to observed SST changes in the ACR (A) and PCR (B). Results are for $F_1$ (solid bars) and $F_2$ (circles and thin error bars). For definitions of $F_1$ and $F_2$, refer to main text. In computing $F_2$, model estimates of $s_{INT}$ were obtained from histograms similar to those shown in Fig. 2, but based on trends fitted to nonoverlapping rather than overlapping segments of SST time series.*

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*Values of $F_1$ is calculated with observed trends over 1906–2005, 1956–2005, etc., whereas $F_2$ is based on $b_{OBS}$ and $\hat{b}_V$ trends over 1900–1999 only. This is because most of the 20CEN experiments end in 1999, thus hampering direct comparisons with the full observational record.*
ACR, the standard deviations of the filtered SST data are systematically lower in models than in observations, pointing to possible biases in model low-frequency variability. Only 5 of the 22 models have 20CEN realizations with standard deviations close to or exceeding observed values. In the PCR, 21 of 22 models produce 20CEN realizations with greater than observed low-frequency SST variability. The implications of these results are discussed below.

Compared with Fig. 4A and B, Fig. 4C displays much larger differences between the individual realizations of any given model’s results. For example, the Parallel Climate Model (PCM) of the National Center for Atmospheric Research (27) has one 20CEN realization with low-frequency SST variability that is very similar to observed values (in both the ACR and PCR), whereas two other realizations have substantially lower ACR variability than either HadISST or ERSST. This difference illustrates that a large ensemble size (or long control run) is necessary to obtain reliable model estimates of low-frequency SST variability. It also suggests that it may be difficult to obtain a reliable observational estimate of internally generated low-frequency SST variability from the relatively short data records available.

These large differences between the temporal variance of individual realizations are also relevant to comparisons of modeled and observed trends (Fig. 4D). In the ACR and PCR, 20 and 13 (respectively) of the 22 models have at least one realization of the 20th century SST trend that lies within the statistical confidence intervals of the observed results. There is no evidence of a systematic model deficiency in simulating the magnitude of 20CEN SST trends in the ACR. In the PCR, nearly half of the simulated SST trends exceed the 2σ confidence interval for the observed trends.

**Single-Forcing Experiments**

Although our work points toward a pronounced influence of external forcing on SST changes in ACR and PCR, it does not separate and quantify the relative contributions of anthropogenic factors and natural external forcing. Separation is difficult without “single-forcing” experiments, in which key climate forcings are varied individually (rather than jointly, as in the 20CEN experiments).

Single-forcing experiments performed with PCM (27) indicate that increases in well mixed greenhouse gases are the main driver of century-timescale increases in ACR and PCR SSTs (Fig. 5). PCM’s greenhouse-gas induced warming is partly offset by the cooling effects of anthropogenic sulfate aerosol particles, thus supporting observational findings in ref. 14, while solar, volcanic, and ozone forcing make much smaller contributions to the simulated SST changes over the 20th century.

**Conclusions**

Current model estimates of internal climate variability cannot explain observed SST increases in either the ACR or the PCR. This conclusion is insensitive to existing uncertainties in model physics and parameterizations, to observational uncertainty, and to the details of the procedure used to compare SST trends in observations and model control runs. It is also reasonably robust to the choice of time period used to estimate historical SST trends.

Our confidence in this conclusion would be undermined if models substantially underestimated the amplitude of natural internal climate variability. On decadal timescales, most current models underestimate SST variability in the ACR and overestimate variability in the PCR. It is possible that biases of similar magnitude may also apply on the multidecadal and century timescales consid-

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\(^{6}\)Missing or incorrectly specified forcings also influence the model-versus-observed variability differences shown in Fig. 4C. For example, the observed decadal variability in ACR and PCR SSTs receives a contribution from volcanic forcing (see Figs. 1 and 6), which is neglected in the No-V group of models. This missing forcing must contribute to the No-V models’ underestimate of observed SST variability in the ACR.
In the PCR, the evidence against an internal variability explanation is even stronger. The model overestimate of the PCR low-frequency SST variability implies that the observed PCR trends (which are already highly significant over 1906–2005) are even less likely to be due to internal variability.

These results, together with other observational and modeling studies (7, 14, 28) contradict claims that internal climate noise accounts for all of the observed variability in tropical Atlantic SSTs (10). We find a large externally forced component of SST change in the ACR and PCR. On the basis of our $F_2$ results for the period 1906–2005, there is a 54% chance that external forcing explains at least 67% of the observed SST increases in the ACR and PCR. In both regions, model simulations with external forcings by combined natural and anthropogenic effects are broadly consistent with observed SST increases. The PCR experiments suggest that forcing by well mixed greenhouse gases has been the dominant influence on century-timescale SST increases. We also find clear evidence of a volcanic influence on observed SST variability in the ACR and PCR.

Hurricanes are complex phenomena. Although changes in ocean surface temperatures may be a key influence on hurricane intensity (6, 8, 9), SSTs are only one of a variety of factors that control hurricane formation and evolution (1, 9, 29). Detailed analyses of changes in other large-scale conditions that affect tropical cyclogenesis (such as wind shear and vertical stability) are required to obtain a more complete understanding of how hurricane activity has changed and may continue to change in a warming world. Our research illustrates that models can be of considerable benefit in understanding the causes of such changes.

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Fig. 5. Contribution of different external forcings to SST changes in tropical cyclogenesis regions. (A and B) Results are for the ACR (A) and PCR (B) and are from a 20CEN run and single-forcing experiments performed with the PCM (27). Each result is the low-pass filtered average of a four-member ensemble, with window width $W = 145$ months. For anomaly definition, refer to Fig. 1. Stratospheric aerosol optical depth (21) is also shown (C).

The temporal standard deviation of the observed low-pass filtered ACR SST data, $s_{\text{OBS}}$, is $\sim 0.18^\circ$C for both the HadISST and ERSST data (see Fig. 4C). Model-average values of this quantity, $s_{\text{MODS}}$, are 0.12$^\circ$C and 0.13$^\circ$C for the V and No-V 20CEN runs.