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Attribution of cyclogenesis region sea surface temperature change to anthropogenic influence

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[1] Previous research has identified links between tropical cyclone activity and sea surface temperatures in the tropical cyclogenesis regions of the North Atlantic and Western North Pacific. Other work has demonstrated that warming in these regions is inconsistent with simulated internal variability. After evaluating the variability of a suite of climate models on a range of timescales, we use detection and attribution methods and a suite of 20th century simulations including anthropogenic and natural forcing to identify a significant response to external forcing in both regions during the June–November hurricane season over the 20th century. We then use separate simulations of the response to natural and anthropogenic forcing to identify anthropogenic influence independently of natural influence in both the Atlantic and Pacific Cyclogenesis Regions. **Citation:** Gillett, N. P., P. A. Stott, and B. D. Santer (2008), Attribution of cyclogenesis region sea surface temperature change to anthropogenic influence, *Geophys. Res. Lett.*, *35*, L09707, doi:10.1029/2008GL033670.

1. Introduction

[2] Over recent decades there has been an increase in the frequency of the most intense category four and five tropical cyclones according to *Webster et al.* [2005] and an increase in the Potential Destructiveness Index (PDI), in the Western North Pacific and North Atlantic, indicating increased duration and intensity of tropical cyclones [*Emanuel*, 2005, 2007; *Trenberth et al.*, 2007]. Tropical cylcone activity is strongly correlated with sea surface temperatures (SSTs) in the Atlantic Cyclogenesis Region (ACR) [*Emanuel*, 2005; *Elsner et al.*, 2006; *Holland and Webster*, 2007; *Emanuel*, 2007; *Saunders and Lea*, 2008] and more weakly correlated in the Pacific Cyclogenesis Region (PCR) [*Chan and Liu*, 2004; *Emanuel*, 2005, 2007]. Future changes in wind shear and atmospheric stability may act to decrease tropical cyclone intensity [*Vecchi and Soden*, 2007; *Trenberth et al.*, 2007, Box 3.5], but high resolution models tend to show that the effect of warming SSTs dominates, giving an increase in tropical cyclone intensity in the future [*Meehl et al.*, 2007, section 10.3.6.3].

[3] SSTs in both the tropical North Atlantic and tropical Western North Pacific have warmed over recent decades [*Emanuel*, 2005; *Trenberth et al.*, 2007]. Warming in the tropical North Atlantic has been associated with the Atlantic Multidecadal Oscillation (AMO) [*Goldenberg et al.*, 2001], a mode of climate variability associated with variations in the strength of the thermohaline circulation [*Trenberth et al.*, 2007, section 3.6.6]. However the contribution of the AMO to the North Atlantic warming trend is subject to debate, and *Trenberth and Shea* [2006] suggest an alternate definition of the AMO in which the global mean temperature is subtracted from Atlantic SSTs. Warming of the ACR is thus interpreted as being associated with global warming [*Trenberth and Shea*, 2006; *Mann and Emanuel*, 2006]. Such analyses led *Hegerl et al.* [2007] to conclude that "increasing greenhouse gas concentrations have likely contributed to a warming of SSTs" in this region.

[4] Nonetheless, even if warming in the ACR is consistent with larger-scale global warming, the question remains of whether it is robustly distinguishable from internal variability in this region, and if so, whether anthropogenic influence is identifiable independently of natural climate influences. *Santer et al.* [2006] address the first of these questions by comparing annual mean observed SST data over the ACR and PCR with simulated internal variability in 22 CMIP3 coupled climate models. They conclude that observed trends over the 20th century are inconsistent with simulated internal variability over both regions. However, while interannual variability was found to be realistic in both the PCR and ACR, most models were found to exhibit lower decadal variability in the ACR compared to observations, which *Santer et al.* [2006] suggest may be partly explainable by missing volcanic forcing in some of the models. *Randall et al.* [2007] point out that coupled climate models are able to simulate the AMO, but they do not comment on whether its amplitude or timescale is generally realistic. *Santer et al.* [2006] go on to demonstrate that observed warming is consistent in magnitude with the simulated response to external forcings in 20th century simulations from the CMIP3 models including both natural and anthropogenic forcings. However, while this result is suggestive of an anthropogenic influence on SSTs in these regions, it does not conclusively demonstrate the presence of an anthropogenic response. We build on this work by separating anthropogenic and natural influences, by focusing on the hurricane season alone, and by considering the temporal evolution of cyclogenesis region SSTs.

2. Observational and Model Data

[5] We use three globally-complete gridded observational SST data sets, the Hadley Centre Sea Ice and SST data set [*Rayner et al.*, 2003] (HadISST), the National Oceanic and Atmospheric Administration Extended Reconstructed SST

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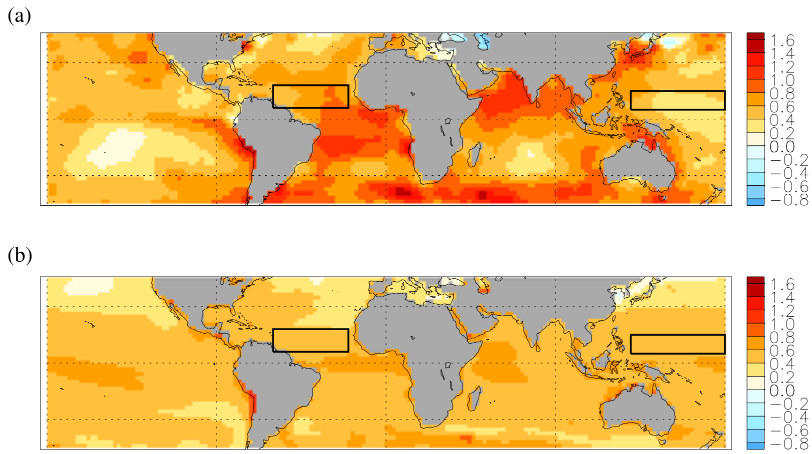

Figure 1. Linear trends in June–November 1900–1999 SST from (a) ERSST observations and (b) 72 twentieth century all-forcings simulations from 22 CMIP3 coupled climate models in K/century. Black boxes in the Atlantic and Pacific mark the ACR and PCR, respectively.

data set [*Smith and Reynolds*, 2004] (ERSST), and Kaplan SST V2 [*Kaplan et al.*, 1998] (Kaplan). We also use the non-interpolated HadSST2 data [*Rayner et al.*, 2006] in detection and attribution analyses. Following *Santer et al.* [2006] we compare observed SSTs with simulated SSTs from 22 coupled ocean-atmosphere models with data available on the PCMDI CMIP3 archive. We use control simulations with constant external forcing and 20th century simulations which at a minimum contain specified greenhouse gas and sulphate aerosol changes, and in some cases other forcings including stratospheric ozone depletion, volcanic aerosol and solar irradiance changes. We divide the simulations into those including volcanic forcing (V) and those excluding volcanic forcing (No-V), since a response to volcanic forcing is evident in observations of ACR and PCR SST [*Santer et al.*, 2006]. In all cases, we average SSTs over the June–November hurricane season, and take spatial means over the ACR (6°N–18°N, 20°W–60°W) and PCR (5°N–15°N, 130°E–180°E) (Figure 1) [*Emanuel*, 2005]. Since many simulations finish in 1999 and start in 1900, we base our analysis on the 1900–1999 period, although observations over the period 1870–2007 are shown in Figure 2 for comparison.

3. Results

[6] Figures 2a and 2b show time series of the simulated and observed ACR and PCR 5-yr smoothed mean temperature anomalies, along with approximations of the 5th and 95th percentiles of the simulated variability. A warming trend is clearly visible over the 20th century in both regions, and differences between the three data sets are small compared to the variability. While the PCR shows a relatively smooth warming trend, the ACR shows a strong warming in the 1920–1940 period and again in the 1990s. Both periods of warming have been associated in part with the AMO [*Trenberth et al.*, 2007, section 3.6.6]. In both regions the V and No-V models appear to simulate the warming trend reasonably well: The response to volcanoes, as simulated by the V models, is apparent in the observations, particularly for Pinatubo (1991) and El Chichón (1982) [*Santer et al.*, 2006]. Figure 1a shows that the ACR has warmed more than the zonal mean over the twentieth century, and the PCR has warmed less. Such a pattern is not seen in the mean response of the CMIP3 models (Figure 1b), although observed grid box temperature trends in the ACR and PCR are within the 5th–95th percentile range of trends simulated across the 72-member CMIP3 ensemble, indicating that the enhanced warming of the ACR and reduced warming of the PCR are likely due to internal variability [*Vecchi and Soden*, 2007].

[7] Power spectra of simulated and observed ACR and PCR SSTs, based on annual June–November averages over the period 1900–1999 and using a Tukey-Hanning window with a width of 30 years are shown in Figures 2c and 2d. On average the 20th century CMIP3 simulations tend to overestimate variability in the PCR on all the timescales considered [*Santer et al.*, 2006], and this difference in variability is significant compared with the ERSST and HadISST data sets. In the ACR interannual variability is significantly less in the V models than in ERSST, but differences between the V models and other observational data sets or between ERSST and the No-V models are not significant. There are no significant differences in decadal variability between models and observations in the ACR.

[8] To test for the presence of an externally-forced signal in the cyclogenesis region SSTs, we use a detection and attribution analysis. After taking five-year means of simulated and observed 1900–1999 temperature averaged over the ACR and PCR and sampling the simulated 5-yr means where observations are present, we use a total least squares optimal fingerprinting method [*Allen and Stott*, 2003; *Hegerl et al.*, 2007, section 9.A.1] to regress the observed SST changes onto the multi-model mean simulated 20th century response. We denote this response ALL here, although the forcings included in each simulation varied. Simulated and observed SST time series were projected onto the 15 leading common EOFs of the first halves of the CMIP3 control simulations, and uncertainties in the regression coefficients were estimated using the latter halves of the controls, following the approach of *Gillett et al.* [2002]. Figure 3a shows the estimated regression coefficients for the ALL response in the ACR and PCR, and using HadSST2, ERSST and Kaplan SSTs. The presence of

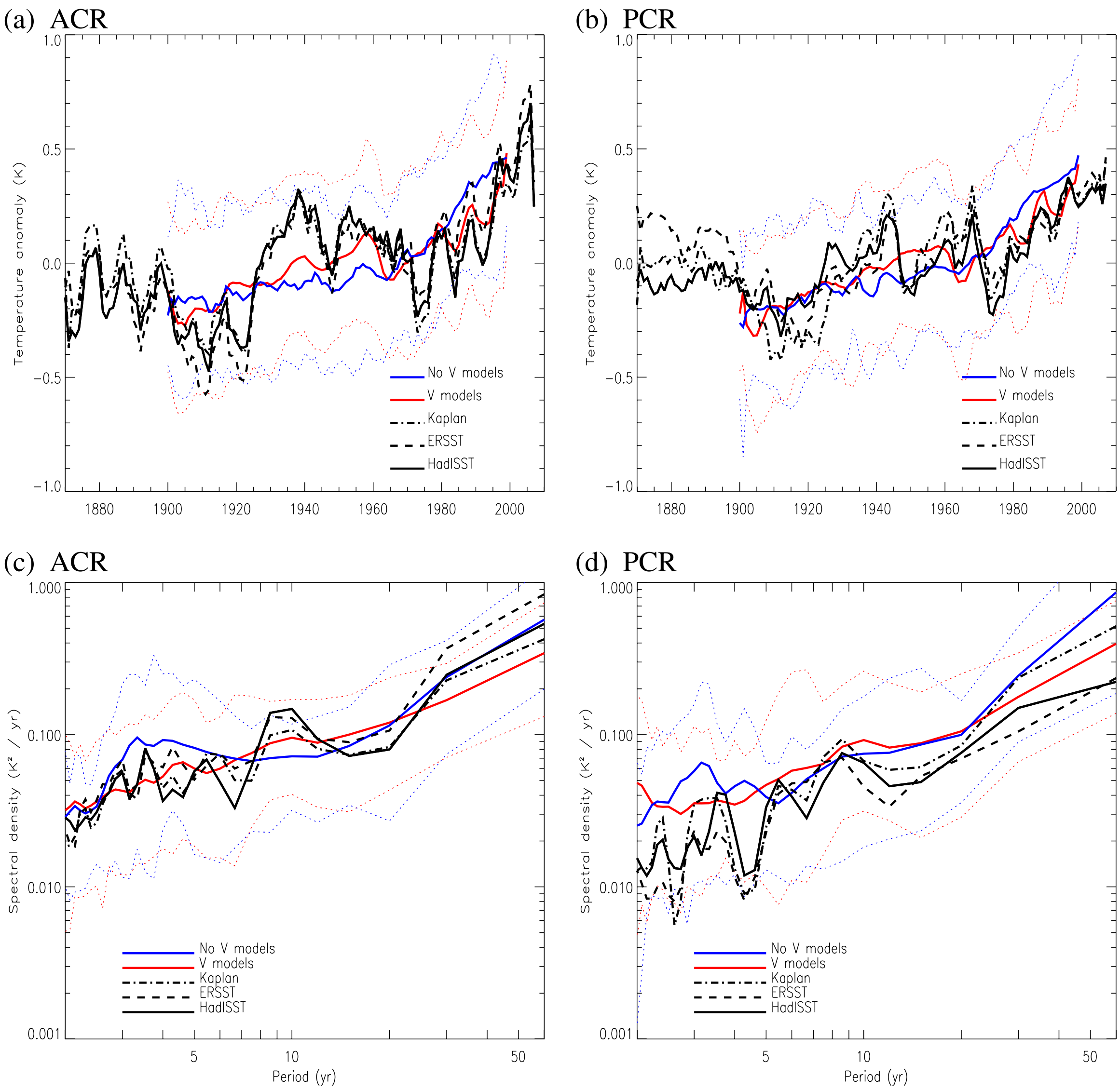

Figure 2. Time series of observed and simulated June-November SSTs averaged over the (a) ACR (6°N–18°N, 20°W–60°W) and (b) PCR (5°N–15°N, 130°E–180°E) smoothed with a running 5-yr mean and expressed as anomalies relative to 1900–1999. Black lines show observed SSTs from HadISST, ERSST and Kaplan data sets. Solid blue lines show the ensemble mean of 50 20th century simulations including volcanic forcing (from CCSM3, GFDL-CM2.0, GFDL-CM2.1, GISS-EH, GISS-ER, MIROC3.2(hires), MIRCO3.2(medres), MIUB/ECHO-G, MRI-CGCM2.3.2, PCM, UKMO-HadCM3, and UKMO-HadGEM1), and solid red lines show the ensemble mean of 22 20th century simulations without volcanic forcing (from BCCR-BCM2.0, CGCM3.1(T47), ECHAM5/MPI-OM, CGCM3.1(T63), CNRM-CM3, CSIRO-Mk3.0, FGOALS-g1.0, GISS-AOM, INM-CM3.0, and IPSL-CM4). For each year dotted red lines show the 3rd and 48th warmest V simulation, and dotted blue lines the 2nd and 21st warmest No-V simulation, approximately representing the 5th and 95th percentiles. Both sets of simulations also include greenhouse gas and direct sulphate aerosol forcing, and other forcings such as the indirect sulphate aerosol effect and solar forcing in some cases. The corresponding power spectra of (c) ACR and (d) PCR SSTs are shown below, based on annual June-November means, calculated with a Tukey-Hanning window with a width of 30 years.

external forcing is detected in both regions using all three data sets: None of the 5–95% uncertainty ranges overlap with zero. All the uncertainty ranges are consistent with one, except for HadSST2 and ERSST in the PCR. The large difference between the HadSST2 regression coefficient and those based on ERSST and Kaplan in this region likely relates to limited spatial sampling at the beginning of the record. A residual consistency test [*Allen and Tett*, 1999] indicated that residuals in the regression were not significantly different from those expected based on control variability for the Kaplan data set, but were inconsistent for the ERSST data set over the ACR, and for the HadSST2 data set over both regions. This may in part relate to incomplete spatial sampling in the HadSST2 data set. When the standard deviation of the control was inflated by 50% the response to external forcing was still detected and residuals were consistent with control variability in all cases. When the analysis was repeated over the period 1870–1999 using a subset of 16 models with simulations starting at or before 1870, external influence was detected over the ACR with all three data sets, and over the PCR with HadSST2 and Kaplan SSTs.

[9] To separate the effects of natural and anthropogenic forcing we use two sets of ensembles of simulations from the Parallel Climate Model (PCM) and third Hadley Centre Coupled Model (HadCM3), one with natural forcing only (solar irradiance changes and volcanic aerosol, denoted NAT) and one with anthropogenic forcings only (greenhouse gas, sulphate aerosol, and stratospheric ozone changes, denoted ANT). Figures 3b and 3c show regression coefficients from two-way regressions of ACR and PCR SSTs onto two-model-mean ANT and NAT responses, using each of the three data sets HadSST2, ERSST and Kaplan, and the same 5-yr mean diagnostic and 15 EOF truncation as for the single pattern analysis. In all cases an anthropogenic response is separately detectable, and in all cases the residual test [*Allen and Tett*, 1999] indicated residual variability consistent with simulated internal variability. In the ACR a natural response is also detected, although NAT regression coefficients are larger than one, suggesting that the NAT response is underestimated by these models. The detectable natural response is likely dominated by volcanic aerosol, with the anthropogenic response dominated by greenhouse gas-induced warming, partly compensated by sulphate-induced cooling [*Santer et al.*, 2006]. An attributable warming calculation using ERSST [*Tett et al.*, 2002] indicates that 0.53 K (5–95% uncertainty range of 0.21–0.93 K) of the observed 0.69 K warming over the ACR and 0.32 K (0.09–0.56 K) of the observed 0.41 K warming over the PCR is attributable to anthropogenic influence. The best estimates therefore indicate that warming over both regions is mainly anthropogenic, although the uncertainty ranges are relatively large. We could not extend the multi-model analysis back to 1870 because the PCM simulations started in 1900. A single-model analysis with HadCM3 over the period 1870–1999 did not yield robust separate detection of anthropogenic influence over either region, likely because of a reduced signal-to-noise ratio due to our use of a single model.

4. Conclusions

[10] Sea surface temperature changes in the Atlantic and Pacific cyclogenesis regions are of particular interest

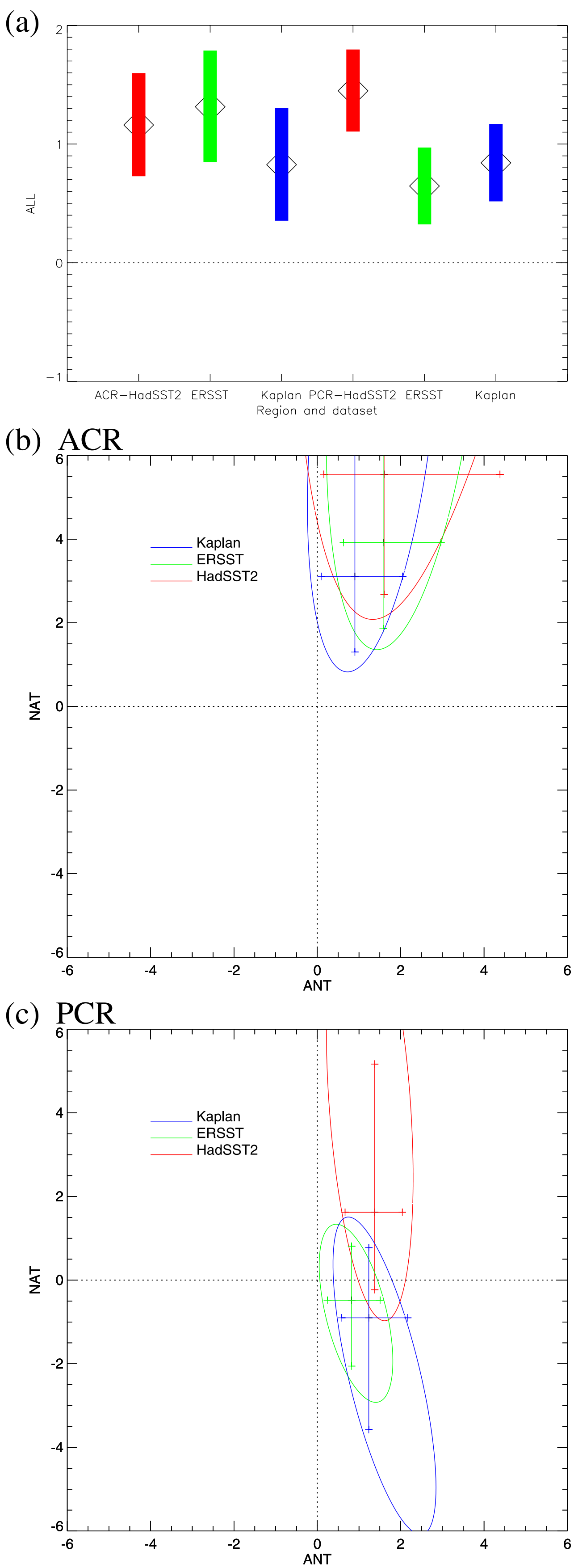

Figure 3. (a) Dimensionless regression coefficients from a single-pattern optimal detection analysis of observed ACR and PCR temperatures against the ensemble mean temperature simulated in 72 20th century simulations from 22 CMIP3 models. Dimensionless regression coefficients from two-pattern optimal detection analyses of observed (b) ACR and (c) PCR temperatures against the mean response to natural (NAT) and anthropogenic (ANT) forcings simulated by HadCM3 and PCM. All calculations are based on 5-yr June–November mean SSTs over each region. Observed SSTs are from HadSST2 (red), ERSST (green), and Kaplan (blue). Uncertainty bars show 5–95% uncertainty ranges derived from control variability. In Figures 3b and 3c, curves enclose 90% of the estimated joint distribution of the regression coefficients for each dataset.

because of their links to tropical cyclone intensity and duration [*Emanuel*, 2005; *Elsner et al.*, 2006; *Saunders and Lea*, 2008]. *Santer et al.* [2006] demonstrate that annual mean SST trends in these regions are inconsistent with internal variability as simulated by a suite of 22 CMIP3 coupled climate models. We build on this work by considering SSTs during the June–November hurricane season alone, by considering temporal evolution of 5-yr means of SSTs rather than just trends, and by separately identifying natural and anthropogenic influence. Using the 22 CMIP3 models, we find a detectable response to external forcing in both the ACR and PCR. The attribution analysis is dependent on simulated internal variability: A residual consistency test indicates that model variability may be underestimated over both regions compared to HadSST2 data, but is consistent with Kaplan data. When model variability was inflated by 50%, external influence was still detected over both cyclogenesis regions, and residuals were consistent with model variability in all cases. We find that over both the ACR and PCR, anthropogenic influence is detectable independently of natural climate influences. Since *Santer et al.* [2006] show that greenhouse gases are the only forcing which gives rise to a strong simulated warming over this period, our results indicate that greenhouse gas increases are indeed likely the dominant cause of the ACR warming, consistent with the suggestion of *Hegerl et al.* [2007]. Moreover these results disagree with the suggestion that warming in the Atlantic Cyclogenesis Region is driven primarily by internal multidecadal variability [*Goldenberg et al.*, 2001].

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