



Twentieth century tropical sea surface temperature trends revisited

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[1] This study compares the global distribution of 20th century SST and marine air temperature trends from a wide variety of data sets including un-interpolated archives as well as globally-complete reconstructions. Apart from the eastern equatorial Pacific, all datasets show consistency in their statistically significant trends, with warming everywhere except the far northwestern Atlantic; the largest warming trends are found in the middle latitudes of both hemispheres. Two of the SST reconstructions exhibit statistically significant cooling trends over the eastern equatorial Pacific, in disagreement with the un-interpolated SST and marine air temperature datasets which show statistically significant warming in this region. Twentieth century trends in tropical marine cloudiness, precipitation and SLP from independent data sets provide physically consistent evidence for a reduction in the strength of the atmospheric Walker Circulation accompanied by an eastward shift of deep convection from the western to the central equatorial Pacific. **Citation:** Deser, C., A. S. Phillips, and M. A. Alexander (2010), Twentieth century tropical sea surface temperature trends revisited, *Geophys. Res. Lett.*, 37, L10701, doi:10.1029/2010GL043321.

1. Introduction

[2] Sea surface temperature (SST), a fundamental physical parameter of the climate system, is well suited for monitoring climate change due to the oceans' large thermal inertia compared with that of the atmosphere and land. Accurate determination of long-term SST trends is hampered, however, by poor spatial and temporal sampling and inhomogeneous measurement practices [Hurrell and Trenberth, 1999; Rayner et al., 2009]. As a result, 20th century SST trends are subject to considerable uncertainty, limiting their physical interpretation and utility as verification for climate model simulations. This uncertainty is especially evident in the tropical Pacific where even the sign of the centennial trend is in question [Vecchi et al., 2008]. Given the influence of tropical Pacific SST anomalies on climate worldwide, resolving these discrepancies remains an important task.

[3] Previous studies have focused largely on SST trends from reconstructed data sets. The purpose of this study is to provide a broad assessment of 20th century global SST trends by considering a wide variety of gridded data sources

including un-interpolated archives as well as globally complete reconstructions. The SST trends are compared with independently measured night-time marine air temperature (NMAT) trends for evidence of physical consistency. The SST/NMAT trends over the tropical Pacific are further evaluated in the context of trends in tropical cloudiness, precipitation, and sea level pressure.

2. Data and Methods

[4] Global SST trends since 1900 are computed for 5 different datasets: Hadley Centre SST version 2 (HadSST2) [Rayner et al., 2006; Minobe and Maeda, 2005]; Hadley Centre sea ice and SST version 1 (HadISST1) [Rayner et al., 2003]; National Oceanic and Atmospheric Administration Extended Reconstructed SST version 3 (ERSSTv3b) [Smith et al., 2008]; and Kaplan Extended SST version 2 (Kaplanv2) [Kaplan et al., 1998]. HadSST2 and Minobe/Maeda (both on a $2^\circ \times 2^\circ$ latitude/longitude grid) are based on the International Comprehensive Atmosphere-Ocean Data Set (ICOADS) and employ different quality-control and bias correction procedures; no "analysis" of the data is performed (e.g., no spatial or temporal smoothing or interpolation) and missing grid boxes are not filled in. HadISST1 ($1^\circ \times 1^\circ$), ERSSTv3b ($2^\circ \times 2^\circ$), and Kaplanv2 ($5^\circ \times 5^\circ$) are analysis products which use different optimal statistical procedures to smooth the data and fill in missing values; further information is given in the cited references.

[5] In addition to SST, we compute trends in night-time marine air temperatures (NMAT) from Meteorological Office Historical Marine Air Temperature version 4 (MOHMAT4) [Rayner et al., 2003] and terrestrial air temperatures from Hadley Centre/Climate Research Unit Temperature version 3 variance-adjusted (HadCRUT3v) [Brohan et al., 2006]. Both datasets are on a $5^\circ \times 5^\circ$ grid, and like HadSST2 missing grid boxes are not filled in and no "analysis" of the data is performed. It should be noted that MOHMAT4, HadCRUT3v and HadSST2 are independent in that they consist of measurements from different observational platforms or instruments (N. Rayner, personal communication, 2010). Over the tropics, we also compute trends in land station precipitation from Hulme et al. [1998], total cloud amount and sea level pressure (SLP) from ICOADS version 2.4 [Woodruff et al., 2008], and SLP from Hadley Centre SLP version 2 [Allan and Ansell, 2006]. The Hulme ($2.5^\circ \times 3.75^\circ$) and ICOADS ($2^\circ \times 2^\circ$) data are neither smoothed nor interpolated, while HadSLP2 ($5^\circ \times 5^\circ$) is a globally complete optimal reconstruction based on terrestrial station records and marine observations from ICOADS.

[6] We calculate linear trends from monthly anomalies using the method of least-squares, and assess their statistical significance using a Student's-t test and taking into account

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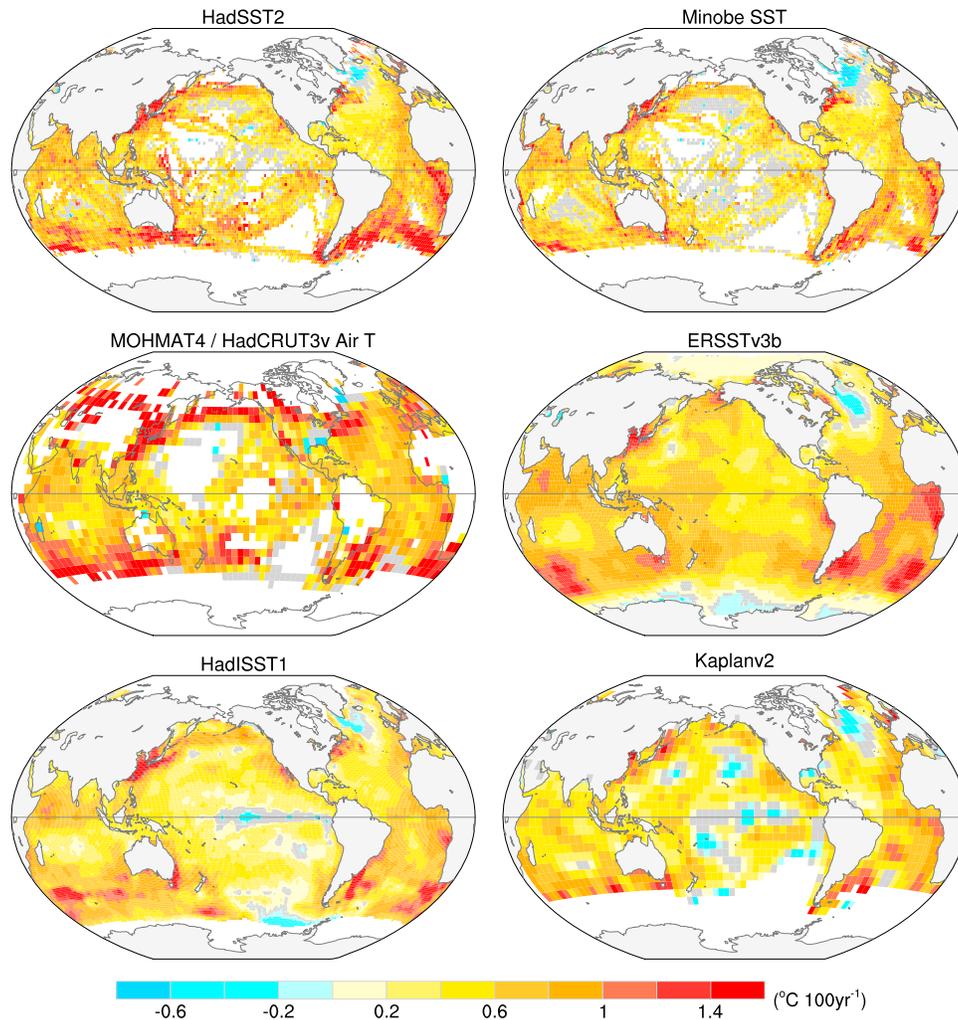


Figure 1. Twentieth century SST trends ($^{\circ}\text{C}$ per century) computed from monthly anomalies since 1900 for various data sets as indicated. White grid boxes denote insufficient data, and gray boxes indicate trends that are not statistically significant at the 95% confidence level. See text for additional information.

serial autocorrelation based on the method of *Zwiers and von Storch* [1995].

3. Results

3.1. Data Coverage

[7] In order to discriminate between secular climate change and naturally-occurring multi-decadal variability, it is important to consider as long a period of record as possible. Seeking a balance between adequate data coverage (see Figure S1 in the auxiliary material) and length of record, we have examined SST trends using a variety of start dates (1900, 1910 and 1920) and data sampling thresholds; all of the results discussed below are robust to the different choices.¹ In the figures that follow, we show trend maps based on the period 1900–2008 using a 3 month per decade threshold; trends based on 1920–2008 using a 24 month per decade threshold are shown in Figure S2 of the auxiliary material. We emphasize that although our sampling crite-

riion is lenient, we rely on additional factors such as regional coherency (note that no additional spatial smoothing has been applied to any of the data sets) and consistency with independently measured marine air temperatures to assess the reality of the SST trends.

3.2. Global SST Trends

[8] The 20th century SST trend distributions from the 5 different data sets are compared in Figure 1 for the period 1900 to 2008 (2002 for Minobe/Maeda, the latest year available), along with air temperature trends based on HadCRUTv3 over land and MOHMAT4 over the oceans for the period 1900 to 2005 (the latest year available). The SST trends from the un-interpolated HadSST2 and Minobe/Maeda archives are similar, exhibiting positive values everywhere except the western portion of the northern North Atlantic. The largest warming trends (approximately $1.2\text{--}1.6^{\circ}\text{C}$ per century) occur directly east of the continents in the northern hemisphere, in the Southern Ocean and the eastern tropical Atlantic. The eastern tropical Pacific warms by approximately $0.8\text{--}1.0^{\circ}\text{C}$ per century, similar in magnitude to the tropical Indian Ocean and the central tropical Atlantic. Trends in NMAT from the un-interpolated MOHMAT4

¹Auxiliary materials are available in the HTML. doi:10.1029/2010GL043321.

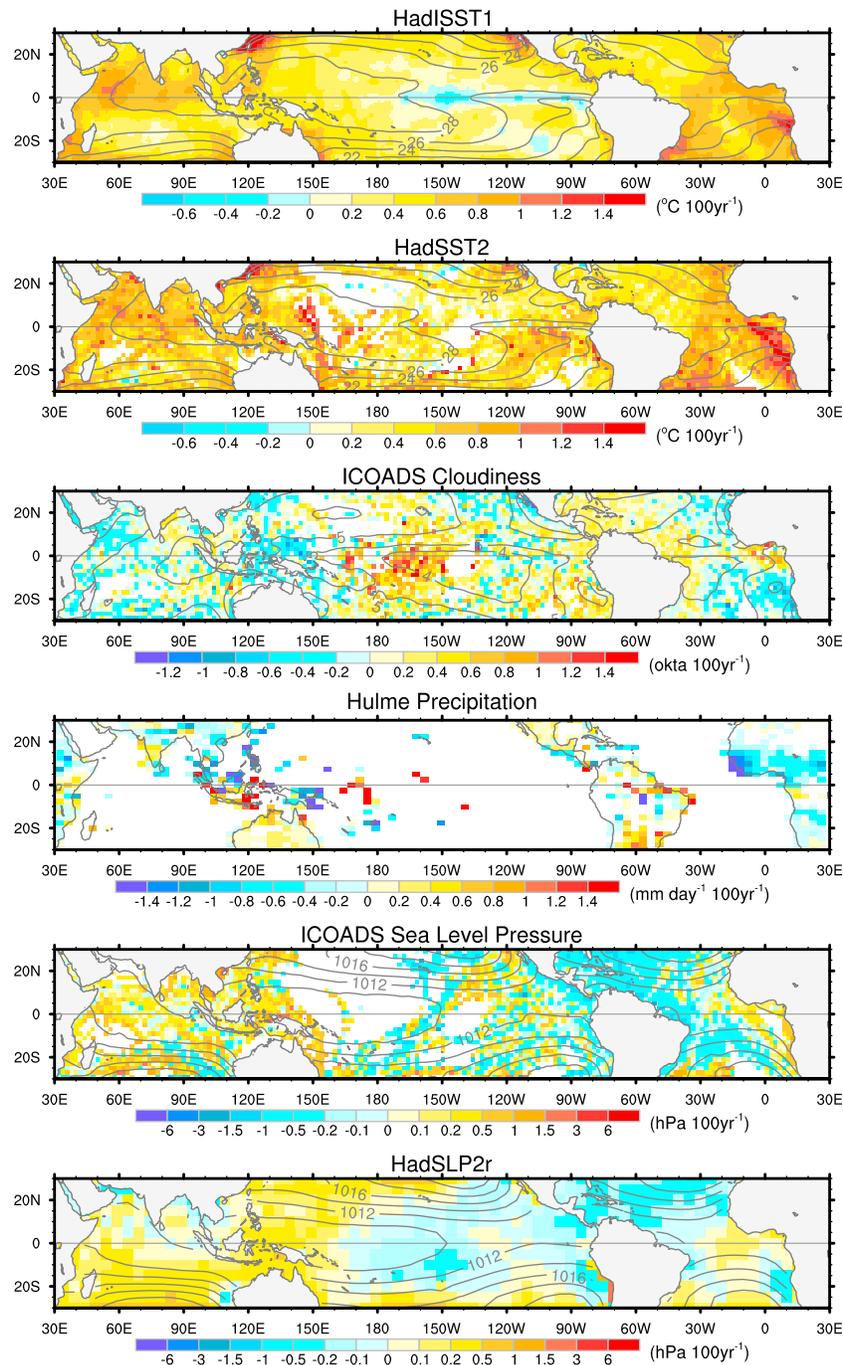


Figure 2. Twentieth century tropical climate trends from a variety of data sources as indicated. White grid boxes denote insufficient data. See text for additional information.

dataset corroborate those in SST from HadSST2 and Minobe/Maeda, with generally similar large-scale patterns and amplitudes. The agreement between NMAT and SST, physically related quantities from independent data sets, provides strong support for the reality of their trends. Another important confirmation of the marine NMAT trends is their coherence with independent air temperature trends over nearby land areas from HadCRUT3v. For example, the terrestrial warming over the islands of Indonesia and coastal regions of Australia, South America, South Africa, North America, Europe, and eastern Asia is remarkably similar in

amplitude to the air temperature increases over the adjacent oceanic regions (even the cooling at the southern tip of Greenland agrees with the cooling over the far north Atlantic). There are a few isolated areas where the air temperature trends over land do not match those over nearby maritime areas, for example Madagascar, the southeastern United States, and northern Chile.

[9] The 3 reconstructed SST data sets (ERSSTv3b, HadISST1, and Kaplanv2) exhibit broad similarity in their trend patterns and amplitudes, as well as overall agreement with the un-interpolated SST data sets, with the notable

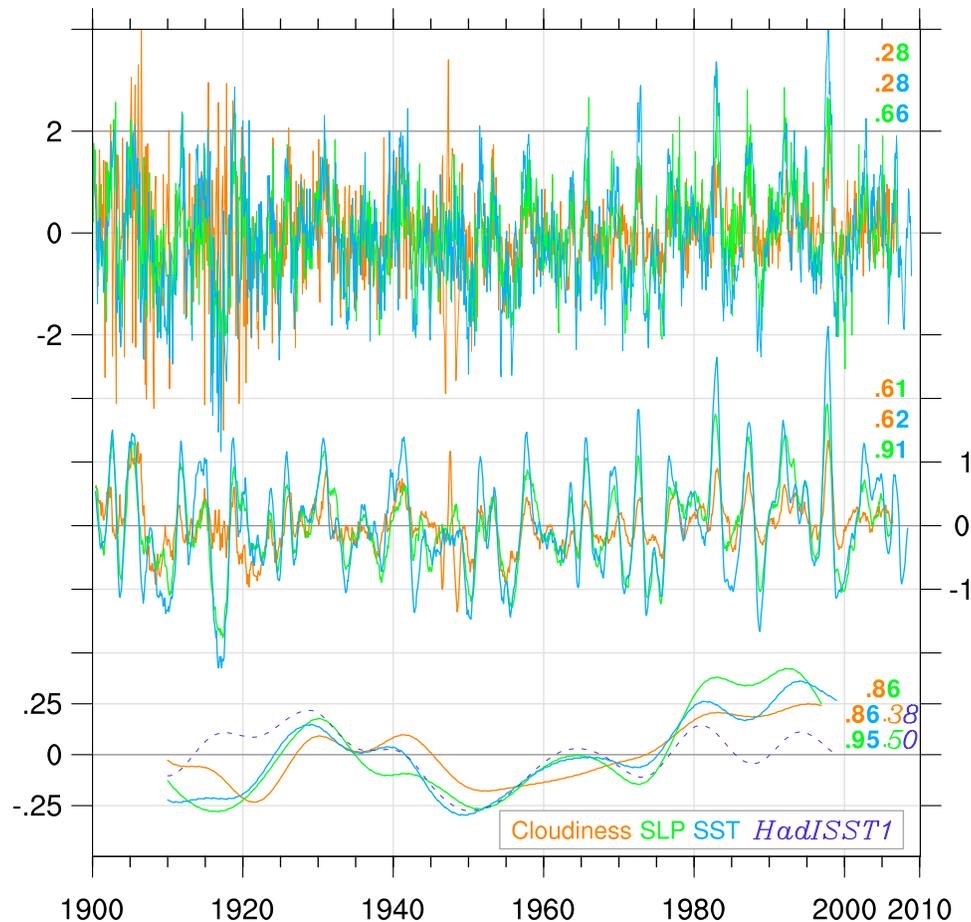


Figure 3. Monthly anomaly time series for selected regional tropical climate indices (see text for definitions). Blue and purple denote SST ($^{\circ}\text{C}$) from HadSST2 and HadISST1, respectively; orange denotes cloudiness (oktas); and green denotes SLP (hPa). The top, middle and bottom sets of curves show the raw, 12-month running mean, and 20-year low-pass filtered monthly anomaly time series, respectively. Color coded numbers to the right of each set of curves denote correlation coefficients between each pair of indices (e.g., an orange and blue numeral gives the correlation between cloudiness and SST).

exception of the central and eastern equatorial Pacific. In this region, HadISST1 and Kaplanv2 exhibit weak but significant cooling while ERSSTv3b shows significant warming, the latter in agreement with HadSST2, Minobe/Maeda, and MOHMA4. The discrepancy between HadISST1 and ERSST was highlighted by Vecchi *et al.* [2008] [see also Hurrell and Trenberth, 1999].

3.3. Tropical Climate Trends

[10] Trends in tropical marine cloudiness from ICOADS, land station precipitation from Hulme, and SLP from ICOADS and HadSLP2r are shown in Figure 2; SST trends from HadISST1 and HadSST2 are also shown for reference. All trends are computed based on monthly anomalies beginning in 1900 and ending in 2008 (2006 for ICOADS) except for precipitation which uses a start date of 1920 due to insufficient data coverage before that time and an end date of 1996, the last year of data available. As in Figure 1, no spatial smoothing has been applied to any of the trend maps. Changes in observing practice may have caused spurious increases in ICOADS cloudiness [Norris, 1999]. Following Deser and Phillips [2006], we account for these

artificial trends by removing the tropical (30°N – 30°S) mean cloudiness trend from each oceanic grid box. The resemblance of the spatial patterns of land station precipitation and residual cloudiness trends provides strong evidence for the spurious nature of the tropical mean cloudiness trend (Figure 2).

[11] The distribution of residual cloudiness trends exhibits positive values (0.8 – 1.4 oktas per century) over the central equatorial Pacific accompanied by negative values over the western equatorial Pacific (-0.4 – -0.8 oktas per century). This pattern is reminiscent of the cloudiness (and precipitation) changes that occur in association with El Niño events [Deser *et al.*, 2004] and the 1976/77 climate regime “shift” [Deser and Phillips, 2006]. Negative cloudiness trends are also found over the western Indian Ocean, the Pacific Inter-Tropical Convergence Zone (ITCZ) east of 135°W and the subtropical eastern Pacific and Atlantic. Precipitation trends are generally consistent with residual cloudiness trends in regions where the two data sets overlap: in particular, positive precipitation trends are found at island stations in the central equatorial Pacific between 160°E and 140°W , and negative trends to the west between 130°E and 160°E . SLP

trends from ICOADS are generally positive over the tropical Indian Ocean and western Pacific, and a mixture of negative and positive values over the eastern Tropical Pacific. The smoother HadSLP2r trends corroborate the large-scale pattern evident in ICOADS, and are indicative of a weakening of the SLP gradient between the eastern Pacific and the Indian Ocean/West Pacific. Collectively, the independent trends in marine cloudiness, precipitation and SLP provide physically consistent evidence for a reduction in the strength of the atmospheric Walker Circulation accompanied by an eastward shift in convection from the western to the central equatorial Pacific.

[12] Based on the maps shown in Figure 2, we formed the following regional time series: eastern equatorial Pacific SST (1°N – 1°S , 170°W – 90°W) from HadSST2 (a narrow equatorial box is used for later comparison with HadISST1, but similar results are obtained for 5°N – 5°S); central equatorial Pacific cloudiness (6°N – 12°S , 165°E – 150°W) minus central north Pacific cloudiness (18°N – 6°N , 165°E – 150°W) from ICOADS; and Indian Ocean/West Pacific SLP (20°N – 20°S , 30°E – 150°E) minus eastern Pacific SLP (20°N – 20°S , 180° – 70°W) from ICOADS. These indices are not sensitive to the precise definitions of the regions except for cloudiness, which exhibits some differences in the first few decades of the 20th century (not shown); similar regions were used for characterizing Pacific multi-decadal variability by *Deser et al.* [2004]. These indices are displayed in Figure 3 using various degrees of temporal smoothing to emphasize different aspects of the variability.

[13] Although the raw monthly anomaly time series exhibit considerable high frequency noise, they are coherent on interannual and longer time scales and exhibit prominent ENSO variability throughout the record. The main periods of disagreement occur in association with high levels of noise due to paucity of data especially during the first two decades and World War II. The correlation coefficients between each pair of indices (marked directly on Figure 3) are all significant at the 99% level: the 0.66 correlation between the SST and SLP records is particularly noteworthy given the large number of data points and lack of temporal smoothing. There is also strong correspondence among the 12-month running mean records, with 95% significant correlations of 0.61–0.91. The 20-year low-pass filtered records also exhibit high correlations (0.86–0.95) reflecting consistency in their multi-decadal fluctuations as well as in their overall upward trends. Note that the trends constitute only a small fraction of the total variability of the raw monthly anomaly time series and less than half of the variability on time scales longer than 20 years. Strong correspondence between two canonical SLP and SST records of ENSO dating back to 1877 was shown by *Bunge and Clarke* [2009] using more sophisticated analysis techniques.

[14] The disagreement in sign between the trends in HadSST2 and HadISST1 in the eastern equatorial Pacific is readily apparent by comparing their 20-year low-pass filtered records (Figure 3). Note that the two SST indices agree well on inter-annual and multi-decadal timescales (correlation coefficients of 0.95 for detrended 12-month running means and 0.90 for detrended 20yr lowpass filtered data): only their long term trends differ. The correlations between the 20-yr lowpass filtered equatorial Pacific SST index based on HadISST1 and the cloudiness and SLP records shown in Figure 3 (0.38 and 0.50, respectively) are sub-

stantially lower than those based on HadSST2 (0.86 and 0.95, respectively).

4. Summary and Discussion

[15] We have evaluated 20th century (1900 to approximately 2008) SST trends from a variety of data sources including un-interpolated archives as well as globally complete reconstructions. Statistically significant SST trends from the two un-interpolated datasets (HadSST2 and Minobe/Maeda) are positive everywhere except the northern North Atlantic, with magnitudes approximately 0.4 – 1.0°C per century in the tropics and subtropics and 1.2 – 1.6°C per century at higher latitudes. These SST trends are corroborated by independently measured NMAT trends from the un-interpolated MOHMA4 dataset and by terrestrial air temperature trends at coastal locations from the un-interpolated HadCRUT3v archive. SST trends from the reconstructed datasets (ERSSTv3b, HadISST1 and Kaplanv2) are generally similar to those from the un-interpolated archives with the notable exception of the tropical Pacific which exhibits cooling in HadISST1 and Kaplanv2.

[16] The intensified warming trends off the east coasts of China and northern North America and over the northern North Pacific may be related to the relatively shallow bathymetry and associated ocean mixed layer depths as suggested by *Xie et al.* [2002]. In addition, advection of continental air temperature trends by the prevailing westerlies and a reduction in cloud cover (not shown) may play a role. The cooling trend directly south of Greenland may be related to the century-long upward trend in the North Atlantic Oscillation via the associated increase in wind speed and resulting heat loss from the ocean surface. Enhanced warming over the Southern Ocean may be due in part to a decrease in cloud cover (not shown). Alternatively, the pattern of cooling in the far north Atlantic coupled with warming in the Southern Ocean may be a signature of a weakened oceanic thermohaline circulation in response to global warming. Further work is needed to assess the mechanisms responsible for the spatial distribution of the 20th century SST trends.

[17] The HadISST1 and Kaplanv2 reconstructions disagree with ERSSTv3b and the un-interpolated datasets on the sign of the SST trend in the eastern equatorial Pacific. Independent NMAT measurements show a warming trend in this region that is very close in magnitude to that from HadSST2 (0.36°C compared to 0.35°C per century). Given that marine air temperature and SST anomalies are physically constrained by surface energy exchange, the agreement between NMAT and HadSST2 provides strong support for the reality of the warming trend in the eastern equatorial Pacific. Though the trends in HadISST1 and Kaplanv2 over the eastern equatorial Pacific appear to be erroneous, their interannual to decadal variations are in agreement with those in HadSST2 and NMAT (correlation coefficients of 0.95 and 0.92, respectively, based on detrended 12-month running mean anomalies for the region 1°N – 1°S , 170°W – 90°W). Our results have implications for the design of atmospheric model experiments forced with observed SST trends. In particular, specifying the 20th century trend component from HadISST1 or Kaplanv2 in the eastern tropical Pacific may lead to an unrealistic atmospheric circulation response.

[18] Centennial trends in tropical marine cloudiness, precipitation, and SLP from independent data sources were also

evaluated. These additional climate parameters were shown to exhibit physically consistent trends consisting of a weakening of the zonal SLP gradient between the eastern Pacific and the Indian Ocean/western Pacific accompanied by an eastward shift of cloudiness and precipitation from the western to the central equatorial Pacific. The causal relationship between the tropical Pacific SST and atmospheric circulation trends is open to interpretation. On the one hand, a weakening of the atmospheric Walker Circulation is expected to occur in response to increasing GHG concentrations, even with a zonally uniform warming of the tropical oceans, as discussed by *Vecchi and Soden* [2007]. In this view, the role of tropical ocean dynamics is to reduce the amplitude of both the Walker Circulation change and the warming in the eastern equatorial Pacific. Alternatively, the physical paradigm for ENSO holds that a weakening of the zonal SLP gradient (e.g., the Walker Circulation) is accompanied by a weakening of the zonal SST gradient (more warming in the eastern compared to the western equatorial Pacific) due to the Bjerknes feedback mechanism. Both mechanisms could contribute to the observed centennial trends documented in this study.

[19] Recently, *Karnauskas et al.* [2009] reported that the HadISST1, Kaplanv2 and ERSSTv3b reconstructions all exhibit a strengthening of the east-to-west SST gradient across the equatorial Pacific during the 20th century, despite disagreeing on the sign of the SST trend in east. However, only the month of September showed a statistically significant strengthening for ERSSTv3b, compared to June–January (July–January) for HadISST1 (Kaplanv2). Using data from all months of the year, we find no evidence for a statistically significant strengthening of the zonal gradient in ERSSTv3b, HadSST2, Minobe/Maeda, or MOHMAT4. Further, we emphasize that data coverage constraints make it difficult to accurately determine the 20th century trend in the zonal SST gradient across the equatorial Pacific (Figure S1 of the auxiliary material), and indeed no such determination is possible when a 20% threshold (24 months per decade) is used for computing the trends since 1920 (Figure S2 of the auxiliary material).

[20] Characterizing the pattern and amplitude of SST trends over the past century remains a challenge due to observational uncertainties associated with limited data sampling, changing measurement techniques and analysis procedures. Thus, there is a continuing need for refining and improving the development of homogeneous gridded SST data sets and associated globally-complete reconstructions for climate change research following the recommendations of *Rayner et al.* [2009].

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