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Possible artifacts of data biases in the recent global surface warming hiatus

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Much study has been devoted to the possible causes of an apparent decrease in the upward trend of global surface temperatures since 1998, a phenomenon that has been dubbed the global warming "hiatus." Here we present an updated global surface temperature analysis that reveals that global trends are higher than reported by the IPCC, especially in recent decades, and that the central estimate for the rate of warming during the first 15 years of the 21st century is at least as great as the last half of the 20th century. These results do not support the notion of a "slowdown" in the increase of global surface temperature.

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (*1*) concluded that the global surface temperature "has shown a much smaller increasing linear trend over the past 15 years [1998-2012] than over the past 30 to 60 years." The more recent trend was "estimated to be around one-third to one-half of the trend over 1951-2012." The apparent slowdown was termed a "hiatus," and inspired a suite of physical explanations for its cause, including changes in radiative forcing, deep ocean heat uptake, and atmospheric circulation changes (*2*–*12*). While these analyses and theories have considerable merit in helping to understand the global climate system, other important aspects of the "hiatus" related to observational biases in global surface temperature data have not received similar attention. In particular, residual data biases in the modern era could well have muted recent warming, and as stated by IPCC, the trend period itself was short and commenced with a strong El Niño in 1998. Given recent improvements in the observed record (*13*, *14*) and additional years of global data (including a record-warm 2014), we reexamine the observational evidence related to a "hiatus" in recent global surface warming.

The data used in our long-term global temperature analysis primarily involve surface air temperature observations taken at thousands of weather observing stations over land, and for coverage across oceans, the data are sea surface temperature (SST) observations taken primarily by thousands of commercial ships and drifting surface buoys. These networks of observations are always undergoing change. Changes of particular importance include: (i) an increasing amount of ocean data from buoys, which are slightly different than data from ships; (ii) an increasing amount of ship data from engine intake thermometers, which are slightly different than data from bucket sea-water temperatures; and (iii) a large increase in land-station data that enables better analysis of key regions that may be warming faster or slower than the global average. We address all three of these, none of which were included in our previous analysis used in the IPCC report (*1*).

First, several studies have examined the differences between buoy- and ship-based data, noting that the ship data are systematically warmer than the buoy data (*15*–*17*). This is particularly important, as much of the sea surface is now sampled by both observing systems, and surface-drifting and moored buoys have increased the overall global coverage by up to 15% (see supplemental material for details). These changes have resulted in a time-dependent bias in the global SST record, and various corrections have been developed to account for the bias (*18*). Recently, a new correction (*13*) was developed and applied in the Extended Reconstructed Sea Surface Temperature dataset version 4, which we use in our analysis. In essence, the bias correction involved calculating the average difference between collocated buoy and ship SSTs. The average difference globally was −0.12°C, a correction which is applied to the buoy SSTs at every grid cell in ERSST version 4. [Notably, IPCC (*1*) used a global analysis from the UK Met Office that found the same average ship-buoy difference globally, although the corrections in that analysis were constrained by differences observed within each ocean basin (*18*).] More generally, buoy data have been proven to be more accurate and reliable than ship data, with better known instrument characteristics and automated sampling (*16*). Therefore, ERSST version 4 also considers this smaller buoy uncertainty in the reconstruction (*13*).

Second, there was a large change in ship observations (i.e., from buckets to engine intake thermometers) that peaked immediately prior to World War II. The previous version of ERSST assumed that no ship corrections were necessary after this time, but recently improved metadata (*18*) reveal that some ships continued to take bucket observations even up to the present day. Therefore, one of the improvements to ERSST version 4 is extending the ship-bias correction to the present, based on information derived from comparisons with night marine air temperatures. Of the 11 improvements in ERSST version 4 (*13*), the continuation of the ship correction had the largest impact on trends for the 2000-2014 time period, accounting for 0.030°C of the 0.064°C trend difference with version 3b. (The buoy offset correction contributed 0.014°C dec^{-1} to the difference, and the additional weight given to the buoys because of their greater accuracy contributed 0.012°C dec^{-1}. See supplementary materials for details.)

Third, there have also been advancements in the calculation of land surface air temperatures (LSTs). The most important is the release of the International Surface Temperature Initiative (ISTI) databank (*14*, *19*), which forms the basis of the LST component of our new analysis. The ISTI databank integrates the Global Historical Climatology Network (GHCN)–Daily dataset (*20*) with over 40 other historical data sources, more than doubling the number of stations available. The resulting integration improves spatial coverage over many areas, including the Arctic, where temperatures have increased rapidly in recent decades (*1*). We applied the same methods used in our old analysis for quality control, time-dependent bias corrections, and other data processing steps (*21*) to the ISTI databank to address artificial shifts in the data caused by changes in station location, temperature instrumentation, observing practice, urbanization, siting conditions, etc. These corrections are essentially the same as those used in the GHCN–Monthly version 3 dataset (*22*, *23*), which is updated operationally by NOAA's NCEI. To obtain our new global analysis, the corrected ISTI land data (*14*) were systematically merged with ERSST version 4 (*13*), as described in the supplemental materials.

In addition to the three improvements just discussed, since the IPCC report (*1*), new analyses (*24*) have revealed that incomplete coverage over the Arctic has led to an underestimate of recent (since 1997) warming in the Hadley Centre/Climate Research Unit data used in the IPCC report (*1*). These analyses have surmised that incomplete Arctic coverage also affects the trends from our analysis as reported by IPCC (*1*). We address this issue as well.

Figure 1 depicts temperature trends in our old analysis, our new analysis, and our new analysis supplemented with polar interpolation. (In this discussion, "old" refers to the analysis based on ERSST version 3b for ocean areas and GHCN–Monthly version 3 for land areas). For the most recent IPCC period (1998–2012), the new analysis exhibits more than twice as much warming as the old analysis at the global scale (0.086 vs. 0.039°C dec^{-1}; see Table S1 in the supplementary material). This is clearly attributable to the new SST analysis, which itself has much higher trends (0.075 vs. 0.014°C dec^{-1}). In contrast, trends in the new LST analysis are only slightly higher (0.117 vs. 0. 112°C dec^{-1}).

IPCC (*1*) acknowledged that trends since 1998 were tenuous because the period was short and commenced with a strong El Niño. Two additional years of data are now available to revisit this point, including a record-warm 2014, and trends computed through 2014 confirm the IPCC supposition. Specifically, the central trend estimate in our new analysis for 1998–2014 is 0.020°C dec^{-1} higher compared to 1998–2012. Likewise, global trends for 2000–2014 are 0.030°C dec^{-1} higher than for 1998–2012. In other words, changing the start and end date by two years does in fact have a notable impact on the assessment of the rate of warming, but less compared to the impact of new time-dependent bias corrections.

Our analysis also suggests that short- and long-term warming rates are far more similar than previously estimated in IPCC (*1*). The difference between the trends in two periods used in IPCC (*1*) (1998-2012 and 1951-2012) is an illustrative metric: the trends for these two periods in the new analysis differ by 0.043°C dec^{-1} compared to 0.078°C dec^{-1} in the old analysis reported by IPCC (*1*). The smaller difference results from more warming in the new ocean analysis since 1998, reflecting the improved bias corrections in ERSST version 4. The new corrections show that the 90% confidence interval for 1998–2012 encompasses the best estimate of the trend for 1951–2012.

It is also noteworthy that the new global trends are statistically significant and positive at the 0.10 significance level for 1998–2012 (Fig. 1 and table S1) using the approach described in (*25*) for determining trend uncertainty. In contrast, IPCC (1), which also utilized the approach in (*25*), reported no statistically significant trends for 1998-2012 in any of the three primary global surface temperature datasets. Moreover, for 1998–2014, our new global trend is 0.106± 0.058°C dec^{-1}, and for 2000–2014 it is 0.116± 0.067°C dec^{-1} (see table S1 for details). This is similar to the warming of the last half of the 20th century (Fig. 1). A more comprehensive approach for determining the 0.10 significance level (see supplement) that also accounts for the impact of annual errors of estimate on the trend, also shows that the 1998–2014 and 2000–2014 trends (but not 1998–2012) were positive at the 0.10 significance level.

For the full period of record (1880–present) (Fig. 2), the new global analysis has essentially the same rate of warming as the previous analysis (0.068°C dec^{-1} and 0.065°C dec^{-1} respectively; Table S1), reinforcing the point that the new corrections mainly have an impact in recent decades. However, it is also clear that the long-term trend would be significantly higher (by 0.085°C dec^{-1}; Fig. 2B) without corrections for other historical biases as described in (*26*).

Figure 3 shows that there are important differences between the latitudinal structure of trends for the second half of the 20th century and for the 21st century (2000–2014). For example, the Arctic latitudes have shown strong warming trends both over the land and ocean since 2000, but during the latter half of the 20th century, the ocean trends in this area are near zero. The longer term 50-year trend has more consistency in the rates of warming across all latitudes, and this is even more evident over the full period of record back to 1880 (fig. S1). There is a distinct Northern Hemisphere mid-latitude cooling in LST during the 21st century, which is also showing up in cooling of the cold extremes as reported for the extreme minimum temperatures in this zone in (*27*). Atmospheric teleconnections and regional forcings could be relevant in understanding these short time-scale zonal trends. It is evident that in most latitude bands, the global trends in the past 15 years are comparable to trends in the preceding 50 years.

Finally, we consider the impact of larger warming rates in high latitudes (*24*) on the overall global trend. To estimate the magnitude of the additional warming, we applied large-area interpolation over the poles using the limited observational data available. Results (Fig. 1) indicate that, indeed, additional global warming of a few hundredths of a degree Celsius per decade over the 21st century is evident, providing further evidence against the notion of a recent warming "hiatus." See supplemental materials for details.

In summary, newly corrected and updated global surface temperature data from NOAA's NCEI do not support the notion of a global warming "hiatus." As shown in Fig. 1, there is no discernable (statistical or otherwise) decrease in the rate of warming between the second half of the 20th century and the first 15 years of the 21st century. Our new analysis now shows the trend over the period 1950-1999, a time widely agreed as having significant anthropogenic global warming (*1*), is 0.113°C dec^{-1}, which is virtually indistinguishable with the trend over the period 2000-2014 (0.116°C dec^{-1}). Even starting a trend calculation with 1998, the extremely warm El Niño year that is often used as the beginning of the "hiatus", our global temperature trend (1998-2014) is 0.106°C dec^{-1} – and we know that is an underestimate due to incomplete coverage over the Arctic. Indeed, based on our new analysis, the IPCC's (*1*) statement of two years ago – that the global surface temperature "has shown a much smaller increasing linear trend over the past 15 years than over the past 30 to 60 years" – is no longer valid.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Fig. S1
Table S1
References (*28*–*38*)

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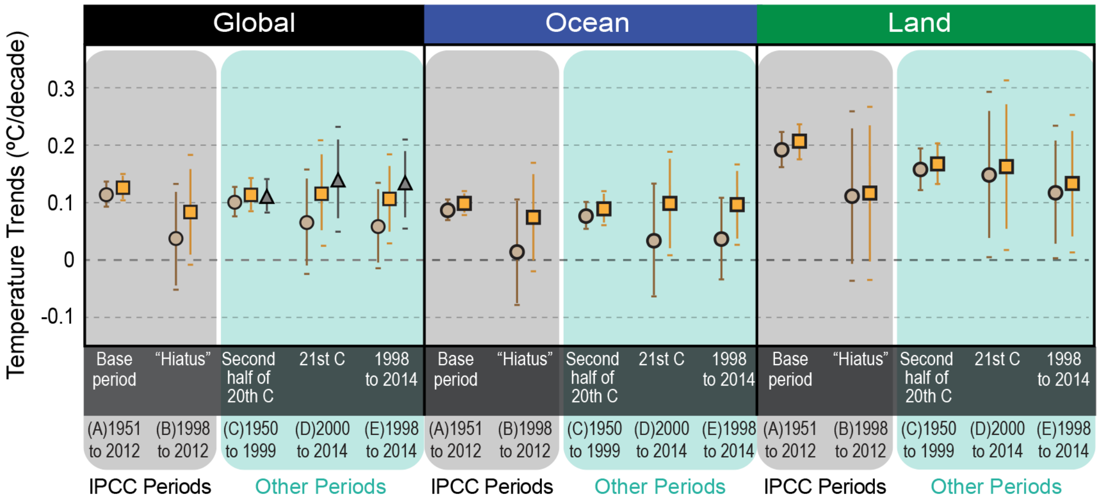

Fig. 1. Effect of new analysis on global surface temperature trends for several periods. Temperature trends are shown for data with the "new" analysis (squares) and "old" analysis (circles) for several periods of interest. Also indicated are global values calculated with the new corrections and the polar interpolation method (triangles). Consistent with IPCC (*1*), the error bars represent the 90% confidence intervals (CIs). The additional error associated with uncertainty of our corrections extends the 90% CI and is depicted with a horizontal dash. (**A**) and (**B**) show the base period (1951–2012) and "hiatus" period used in IPCC (*1*). (**C**) An alternate base period—the second half of the 20th century. (**D**) The 21st century through 2014. (**E**) 1998 (a strong El Niño year) through the 21st century. See Table S1 for source data.

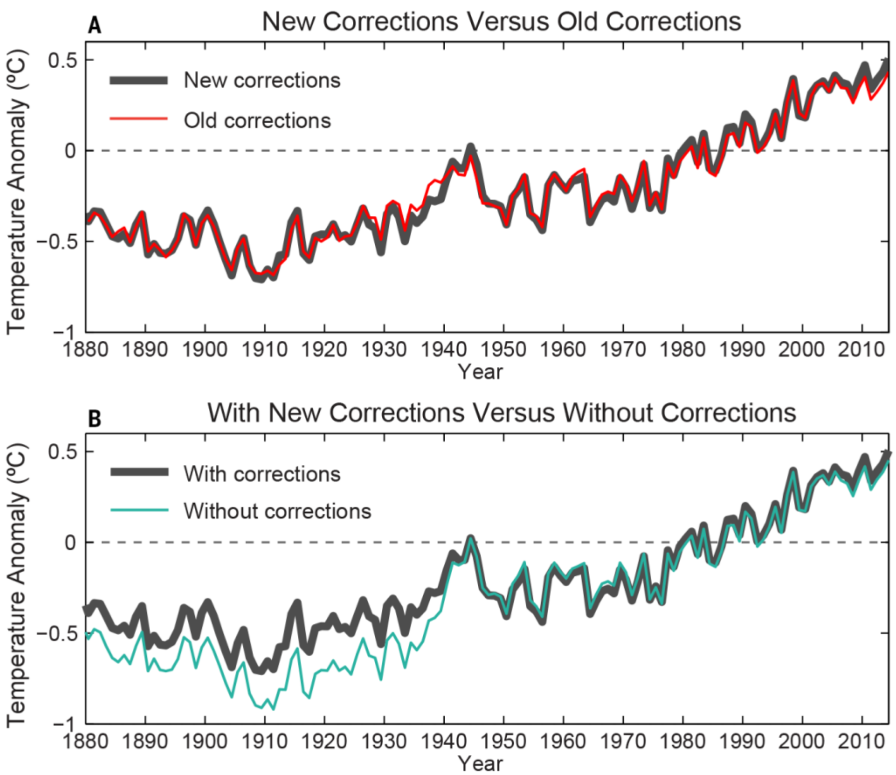

Fig. 2. Global (land and ocean) surface temperature anomaly time series with new analysis, old analysis, and with and without time-dependent bias corrections. (**A**) The new analysis (solid black) compared to the old analysis (red). (**B**) The new analysis (solid black) versus no corrections for time-dependent biases (cyan).

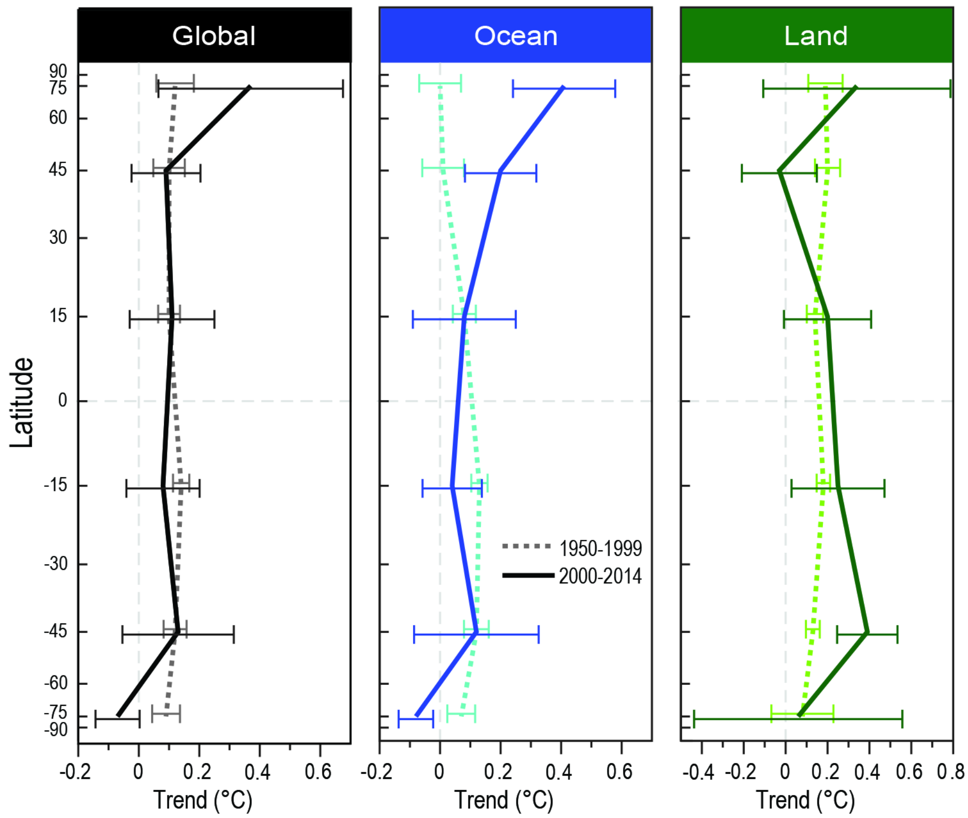

Fig. 3. Latitudinal profiles of surface temperature trends. Zonal mean trends and statistical uncertainty of the trend estimates for global, ocean, and land surface temperature, averaged in 30-degree latitudinal belts, for the second half of the 20th century (dashed) compared to the past 15 years (solid). Trends are cosine-weighted within latitude belts, and the vertical axis is on a sine scale to reflect the proportional surface area of the latitude bands. Note that only the uncertainty related to the trend estimates is provided because zonal standard errors of estimate are not available in contrast to the global averages.