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Supplementary Material for

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

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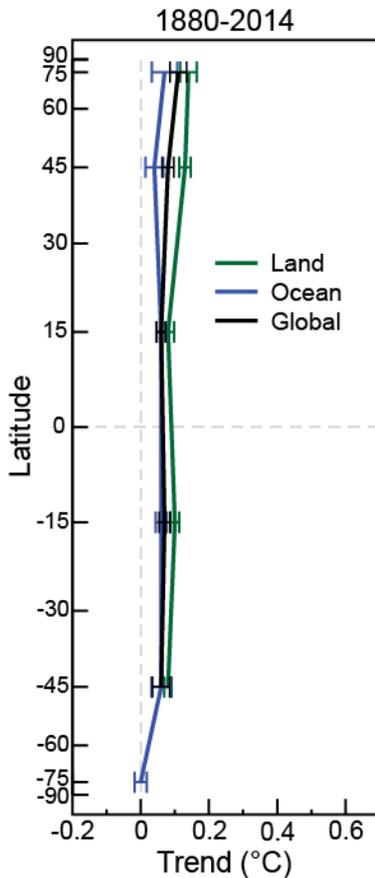
Materials and Methods
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1 **Title: The recent global surface warming hiatus: Fact or artifact of data**
 2 **biases?**

3

4 **Supplementary Materials:**

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6

7 **Fig. S1. Latitudinal profile of surface temperature trends.** Zonal mean trends (°C per decade) of global, ocean,
 8 and land surface temperature, averaged in 30-degree latitudinal belts, for the entire observational period of record,
 9 1880-2014. Trends are cosine-weighted in latitude bands, and the vertical axis is on a sine scale to reflect the
 10 proportional surface area of the latitude bands. The IPCC (*I*) methodology is used to show the 90% confidence
 11 interval for the statistical uncertainty of the trend, indicated by horizontal bars.

12 ***Data and Analysis Method:***

13 The new analyses presented here are based on foundational datasets and processing
14 procedures for land surface air temperature and sea surface temperature. The data sets are the
15 publically available ERSST v4 data set of sea surface temperature anomalies (13)
16 (<ftp://ftp.ncdc.noaa.gov/pub/data/cmb/ersst/v4>), and the ISTI Databank v1.0.0 of land surface air
17 temperature (14) (<http://www.surface temperatures.org/databank>). A global grid of land and
18 ocean anomalies are produced from the two independent data sets using the procedures described
19 below.

20 *Land Surface Air Temperature:* Bias corrections are applied to stations in the ISTI v1.0.0
21 databank as described by Menne and Williams (21). This is followed by computation of
22 temperature anomalies for the stations in the databank. The anomalies are then averaged within
23 5°x5° boxes. From the gridded anomalies a global analysis is performed for each year-month
24 using Empirical Orthogonal Teleconnections as described by Smith et al. (28). The resulting in-
25 filled 5°x5° grid of monthly anomalies is then area-averaged using cosine weighting to produce
26 globally averaged land surface air temperature anomalies for each month from 1880 to present.
27

28 *Sea Surface Temperature:* ERSST v4 provides monthly sea surface temperature
29 anomalies with respect to the 1971-2000 base period for a global 2°x2° grid. The gridded field is
30 produced from ship and buoy sea surface temperatures in the ICOADS release 2.5 data set (29)
31 using bias correction and Empirical Orthogonal Teleconnection methodologies as described in
32 (13). The addition of buoy data in recent decades has been particularly important as the spatial
33 coverage from ship observations has decreased since the 1990's (cf. Fig. 1(a) in (13)). As stated
34 in this article, three of the 11 major improvements incorporated into ERSST version 4 had by far
35 the largest impact on the trend during the recent "hiatus" period (2000-2014). To make the buoy
36 data equivalent to ship data on average requires a straightforward addition of 0.12°C to each
37 buoy observation. This impacts the trend only because the number of buoys and percentage of
38 coverage by buoys has increased over this period.
39

40 In addition, because buoy data were determined to have less noise than ship data (greater
41 precision), another improvement was to give buoy data more weight when using Empirical
42 Orthogonal Teleconnections to reconstruct SST (see equation 3 in (13)). With this correction,
43 the buoy data have now been homogeneously integrated with the ship data. This resulted in
44 additional warming.
45

46 The factor that contributed the largest change in SST trends over this period was
47 continuing to make corrections to ship data after 1941. These corrections are based on
48 information derived from night marine air temperature. This correction cools the ship data a bit
49 more in 1998-2000 than it does in the later years, which thereby adds to the warming trend. To
50 evaluate the robustness of this correction, trends of the corrected and uncorrected ship data were
51 compared to co-located buoy data without the offset added. As the buoy data did not include the
52 offset the buoy data are independent of the ship data. The trend of uncorrected ship minus buoy
53 data was $-0.066^{\circ}\text{C dec}^{-1}$ over the period 2000-2014, while the trend in corrected ship minus buoy

54 data was $-0.002^{\circ}\text{C dec}^{-1}$. This close agreement in the trend of the corrected ship data indicates
55 that these time dependent ship adjustments did indeed correct an artifact in ship data impacting
56 the trend over this hiatus period.

57

58 In our current analyses we do not include Argo buoys because of the relatively small
59 additional spatial coverage (the floats are submerged for much of their lifetimes). As an example
60 for December 2014, the number of Argo floats that measured SSTs are only about 1% of those
61 from buoys and about 14% of those from ship observations. Note that most Argo floats shut
62 down at 5 m or deeper depths to protect against bio-fouling. Although little impact is expected
63 on the global trends by including the Argo float observed SSTs, their contribution may become
64 larger in some localized regions in the Southern Ocean and other places where measurements
65 from surface drifters, moored buoys and ships are limited. In the next version of ERSST, we will
66 analyze Argo floats' regional impacts, and if merited, we will include these data in future
67 version. In order to include the Argo float SSTs, we will need to carefully calibrate the Argo
68 float SSTs against ship and surface drifter/moored buoy SSTs, just as we did for the buoy-ship
69 SST inter-calibrations in the current version of ERSST that is used in this paper.

70

71 Previous versions of our SST analysis included satellite data, but it was dis-included in a
72 later release because the satellite SSTs were not found to add appreciable value to a monthly
73 analysis on a 2° grid, and they actually introduced a small but abrupt cool bias at the global scale
74 starting in 1985 (30). Other observing systems, including satellites, and model simulations could
75 provide important insights that would enable the quantification of interpolation uncertainties in
76 data-sparse regions, but haven't been used in this study.

77

78 Land+Ocean Temperature: The SST dataset is combined with the gridded land surface air
79 temperature anomalies to generate a merged Land+Ocean $5^{\circ}\times 5^{\circ}$ gridded surface temperature data
80 set. The methodology is the same as is used in NCEI's current operational version of its global
81 merged data set (NOAAGlobalTemp/MLOST v3.5, [http://www.ncdc.noaa.gov/data-
82 access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst-v3b/mlost](http://www.ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst-v3b/mlost)) (31).
83 That version was used in the IPCC AR5 assessment. Standard errors of estimate for selected
84 latitudinal bands are available for each year of record using the methods described in (32).

85

86 Subsequent to the merging procedure, globally averaged annual mean temperature time
87 series are produced for three domains: 1) Land-Only; 2) Ocean-Only; and 3) Land+Ocean
88 (global). The IPCC AR5 Working Group 1 (33) procedure is used to produce the global time
89 series and to compute the ordinary least squares (OLS) linear trend slope with a confidence
90 interval of 90% for error estimates, where the confidence intervals were computed according to
91 the IPCC modification of the procedure outlined in (25). This process reduces the number of
92 degrees of freedom ("effective sample size") when data residuals with regard to the OLS trend
93 line are positively auto-correlated at lag-1. In the IPCC AR5 Supplementary Material (Section
94 2SM), the panel members had examined different methods of calculating linear trends and their
95 uncertainties, and concluded that for the annual mean time used, the trend line slope and its

96 uncertainty limits are very similar for most of the methods that take into account dependency in
 97 the data sets in the form of the first-order autoregressive model AR(1). They further concluded
 98 that these results are similar to those obtained by the Restricted Maximum Likelihood (REML)
 99 method used in AR4.

100
 101 For our large-region interpolation assessment, monthly surface temperature anomalies
 102 from available land stations were used to estimate anomalies over data sparse, high latitude
 103 regions where estimates are not currently provided by the operational NOAA Temp/MLOST v3.5
 104 process (31). Specifically, the corrected ISTI databank v1.0.1 station temperatures were
 105 expressed as anomalies relative to the 1971–2000 base period, then the anomalies were
 106 interpolated to the same $5^\circ \times 5^\circ$ latitude–longitude grid produced by NOAA Temp/MLOST v3.5.
 107 Interpolation was done using the inverse-distance-weighting method described by (34). This
 108 method, known as “SPHEREMAP” (software version 99.8a) performs interpolation in spherical
 109 coordinates to increase gridding accuracy, accounts for angular relationships between stations
 110 and grid points, and corrects for the directional isolation of stations. The approach is
 111 conservative in that it only allows for only a limited amount of linear extrapolation beyond the
 112 range of the original data values. Consequently, using the annual estimates of temperature
 113 anomalies for various interpolation methods as calculated in (35) we were able to calculate the
 114 differences in the trend over the period 1998 to 2011 using data provided by the authors of (35).
 115 Using the data provided in their Figure 4 (left panel) we found that linear interpolation methods
 116 are 10-15% lower over the Arctic since 1998 compared to nonlinear methods such as kriging
 117 (32). Therefore, our estimate of the additional warming over recent decades in the arctic, not
 118 included in our primary global analysis, is likely to be an underestimate of the actual warming.
 119 However, because our data date back to 1880, further investigation (beyond the scope of this
 120 analysis) is required to demonstrate the optimum interpolation approach for both short and long
 121 periods in data-sparse, high-latitude regions.

122
 123 ***Combined IPCC Trend Uncertainty and Uncertainty Attributed to Annual Mean Values:***

124 A number of studies including (36) and (37) have defined the standard error of the trend,
 125 s_{tr} , for autocorrelated time series. Consider a time series, $x(t)$, where t varies from 1 to N . An
 126 ordinary least squares regression line fit through $x(t)$ takes the form $y(t)=bt+a$ and the residuals
 127 are $e(t)=x(t)-y(t)$. The error variance, s_e^2 , of the residuals is defined as follows:

128

$$s_e^2 = \frac{1}{N-2} \sum_{t=1}^N e^2(t) \quad [1]$$

129
 130 The error variance of the trend, s_{tr}^2 , is

131

$$s_{tr}^2 = \frac{s_e^2}{\sum_{t=1}^N (t - \bar{t})^2} \quad [2]$$

133 where \bar{t} is the arithmetic mean of t . To account for serial autocorrelation, N is replaced with N_e ,
 134 the effective sample size, in the denominator of [1]. A simple approximation for N_e is $N(1-$
 135 $\rho)/(1+\rho)$ where ρ is the lag-1 autocorrelation of $e(t)$. Rearranging and incorporating this
 136 approximation, the formula for the standard trend error, s_{tr} , is as follows:
 137

$$s_{tr} = \left[\frac{\sum_{t=1}^N e^2(t)}{\left[N \frac{(1-\rho)}{(1+\rho)} - 2 \right] [\sum_{t=1}^N (t - \bar{t})^2]} \right]^{\frac{1}{2}} \quad [3]$$

138
 139 The approach in [3] is the standard method used to characterize trend uncertainty in
 140 comprehensive assessments such as IPCC (1). However, another source of trend error is the
 141 statistical uncertainty of the global annual mean temperature time series as described in (38), s_{ts} ,
 142 attributed to many factors, such as the time-dependent bias corrections and non-polar
 143 interpolation errors. We estimate this additional source of trend error using an analogous
 144 approach to the analyses in (37) and (38). One thousand Monte Carlo simulations of NOAA's
 145 NCEI annual global temperature time series are produced by randomly perturbing the annual
 146 values. The magnitude of each annual perturbation is computed by multiplying a random
 147 standard normal deviate by the year's estimated standard error value (31). The annual standard
 148 error estimate includes SST measurement biases (13), sampling errors (32), and ship-buoy
 149 corrections (13). For each of the 1000 simulations, the ordinary least squares trend is computed
 150 for the perturbed values, and s_{ts} is estimated as the standard deviation of the 1000 simulated
 151 trends. The trend is guided by our best estimate of each observed annual global temperature and
 152 its time-varying annual standard error for that specific year (32).

153
 154 The total trend uncertainty, s_{tot} , is computed by combining the errors s_{tr} and s_{ts} as
 155 follows:
 156

$$s_{tot} = \sqrt{s_{tr}^2 + s_{ts}^2} \quad [4]$$

157
 158 The 90% confidence intervals (CIs) are determined presuming s_{tot} follows a Student's t-
 159 distribution with N_e degrees of freedom (see Table S1). We assume s_{tr} and s_{ts} are independent,
 160 but to the extent they are not completely independent our estimate of the CIs will be larger than
 161 the true CIs. We know of no reason as to why they would be dependent.
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Table S1. Trends of temperature ($^{\circ}\text{C}/\text{decade}$) and the 90% confidence intervals for various time periods, subsets of the globe, and dataset versions. For ocean data, “old” refers to ERSSTv3b and “new” refers to ERSSTv4 of sea surface temperature (13). For land surface air temperature, “old” refers to GHCNMv3 and “new” refers to ISTI (14) with corrections as in (21). “Global” data is land and ocean combined as indicated. The 90% confidence interval (derived from s_{tr}) is calculated using the IPCC methodology. In parentheses is a 90% confidence interval (derived from s_{tot}) which accounts for the uncertainty of trend estimation as well as additional error due to the uncertainty of the underlying annual values in NOAA’s global temperature time series. Boldface indicates trends that are significant at the 0.10 significance level. An asterisk notes that the trend is significant at the 0.10 level based on the uncertainty in the trend estimate using the IPCC methodology only.

	Analysis	Global	Land	Ocean
1880-2014	New	0.068 +/- 0.017 (0.017)	0.106 +/- 0.017 (0.017)	0.055 +/- 0.017 (0.017)
	Old	0.065 +/- 0.015 (0.015)	0.096 +/- 0.016 (0.017)	0.055 +/- 0.015 (0.015)
1950-1999	New	0.113 +/- 0.027 (0.030)	0.169 +/- 0.037 (0.038)	0.091 +/- 0.025 (0.029)
	Old	0.101 +/- 0.026 (0.027)	0.159 +/- 0.038 (0.039)	0.079 +/- 0.022 (0.022)
1951-2012	New	0.129 +/- 0.020 (0.022)	0.207 +/- 0.031 (0.032)	0.100 +/- 0.017 (0.020)
	Old	0.117 +/- 0.021 (0.021)	0.194 +/- 0.031 (0.032)	0.088 +/- 0.017 (0.017)
1998-2012	New	0.086 * +/- 0.075 (0.100)	0.117 +/- 0.119 (0.153)	0.075 +/- 0.075 (0.097)
	Old	0.039 +/- 0.082 (0.094)	0.112 +/- 0.119 (0.150)	0.014 +/- 0.090 (0.092)
1998-2014	New	0.106 +/- 0.058 (0.079)	0.134 +/- 0.092 (0.122)	0.097 +/- 0.059 (0.076)
	Old	0.059 +/- 0.063 (0.074)	0.119 +/- 0.091 (0.118)	0.038 +/- 0.071 (0.073)
2000-2014	New	0.116 +/- 0.067 (0.093)	0.164 +/- 0.109 (0.148)	0.099 +/- 0.078 (0.097)
	Old	0.066 +/- 0.076 (0.090)	0.150 +/- 0.111 (0.146)	0.036 +/- 0.097 (0.099)

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