Rohde et al., Geoinfor Geostat: An Overview 2013, 1:1
http://dx.doi.org/10.4172/2327-4581.1000101

Geoinformatics & Geostatistics: An Overview

Research Article

A SCITECHNOL JOURNAL

A New Estimate of the Average Earth Surface Land Temperature Spanning 1753 to 2011

Robert Rohde[1], Richard A. Muller[1,2,3*], Robert Jacobsen[2,3], Elizabeth Muller[1], Saul Perlmutter[2,3], Arthur Rosenfeld[2,3], Jonathan Wurtele[2,3], Donald Groom[3] and Charlotte Wickham[4]

Abstract

We report an estimate of the Earth's average land surface temperature for the period 1753 to 2011. To address issues of potential station selection bias, we used a larger sampling of stations than had prior studies. For the period post 1880, our estimate is similar to those previously reported by other groups, although we report smaller uncertainties. The land temperature rise from the 1950s decade to the 2000s decade is 0.90 ± 0.05°C (95% confidence). Both maximum and minimum daily temperatures have increased during the last century. Diurnal variations decreased from 1900 to 1987, and then increased; this increase is significant but not understood. The period of 1753 to 1850 is marked by sudden drops in land surface temperature that are coincident with known volcanism; the response function is approximately 1.5 ± 0.5°C per 100 Tg of atmospheric sulfate. This volcanism, combined with a simple proxy for anthropogenic effects (logarithm of the CO_2 concentration), reproduces much of the variation in the land surface temperature record; the fit is not improved by the addition of a solar forcing term. Thus, for this very simple model, solar forcing does not appear to contribute to the observed global warming of the past 250 years; the entire change can be modeled by a sum of volcanism and a single anthropogenic proxy. The residual variations include interannual and multi-decadal variability very similar to that of the Atlantic Multidecadal Oscillation (AMO).

Keywords: Global warming; Kriging; Atlantic multidecadal oscillation; Amo; Volcanism; Climate change; Earth surface temperature; Diurnal variability

Introduction

The average Earth surface temperature is a key indicator of climate change. Previous estimates have been reported by three major groups: the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration Goddard Institute for Space Studies (NASA GISS), and the Climatic Research Unit of the University of East Anglia (CRU); the analyses of these groups share many common features [1-8]. According to the summary provided by the by the Intergovernmental Panel on Climate Change (IPCC), the mean global surface temperature (including land and oceans) has increased 0.64 ± 0.13°C from 1956 to 2005 at 95% confidence [9]. The IPCC did not provide a similar review of land-only mean temperatures; however, the three groups reported changes that ranged from 0.81 to 0.93°C when estimating the increase in land temperatures during the 2000s decade relative to the 1950s decade. As described below, we estimate this change as 0.90 ± 0.05°C (95% confidence).

*Corresponding author: Richard A. Muller, Berkeley Earth Project 2831 Garber St. Berkeley CA, 94705, USA, Tel: 510 735 6877; E-mail: RAMuller@LBL.gov

Received: September 24, 2012 **Accepted:** December 02, 2012 **Published:** December 07, 2012

Methods and Materials

In this paper we present results for the Earth's land surface temperature only, based on analysis of monthly averages at each station. We gathered and merged monthly and daily thermometer measurements from 14 databases to arrive at a collection of 14.4 million mean monthly temperature observations from 44,455 sites. During this process duplicate stations present in the 14 databases were detected and eliminated. These data have now been posted online in a uniform format at www.BerkeleyEarth.org, along with a description of the merging and duplicate removal method. For stations that report only daily data (and not their own monthly average) we performed the average. We removed only short records (less than 1 year) and records from sites with missing or highly uncertain location metadata; that left 36,866 stations that we used in our analysis.

Our analysis approach differed from that of the previous groups in several ways. Rather than adjust (homogenize) individual records for known and presumed discontinuities (e.g. from instrument changes and station moves), we split the records into portions occurring before and after such apparent discontinuities, creating essentially two records from one. This procedure was completely automated to reduce human bias; we call this approach the *scalpel*. The detection of such breakpoints followed procedures similar to those used by existing groups, but the traditional adjustment step was omitted in favor of simply dividing the time series into two pieces at any apparent breakpoints. We also split records when there was a gap in record continuity greater than 1 year in duration, and at times when changes in station location or time of observation were documented. The scalpel approach avoids explicit adjustment of the data, the process usually called "homogenization", although it increases the number of parameters that are used to create the best fit. It is possible to use the scalpel approach because our reconstruction method depends less on long duration samples than do the methods applied by prior groups. The 36,866 records were split, on average, 3.9 times to create 179,928 record fragments. When we detected other problems (e.g. undocumented changes from Celsius to Fahrenheit) we flagged the changes; the raw uncorrected data are available online in a separate file. As is standard practice for the existing climate analysis groups, seasonality was removed from each time series prior to averaging in order to better isolate the small long-term trends from the large annual cycle. For this purpose each record was adjusted by removing cycles with 1-year periods and higher harmonics; the unadjusted data are also available on the website.

In order to minimize statistical uncertainties, we developed a computer program we call Berkeley Average that could take advantage of all 179,928 record fragments. The Matlab program that implements Berkeley Average is available on www.BerkeleyEarth.org.

To perform the average, the surface of the Earth was divided

doi:http://dx.doi.org/10.4172/2327-4581.1000101

into 15,984 elements of equal area and weighted by the percentage of land at each spot; 5326 of them had >10% land. For each month, Berkeley Average creates an estimated temperature field for the entire land surface of the Earth using Kriging to interpolate the available temperature data. The Kriging process, also known as Gaussian Process Regression, is the best linear unbiased predictor of the underlying field provided the temperature fluctuations at each site are approximately normally distributed and the correlation structure between sites can be estimated [10,11]. This method uses the correlations between temperature stations as a function of distance to estimate the temperature at any intermediate point and naturally avoids the bias that might come from overweighting highly clustered stations (e.g. in the United States and Europe). A monthly estimate for each equal area grid is computed as described below using a minimization process. The final global average temperature, T_{avg}, is then the simple average of the interpolated land temperature field over land during each month.

To obtain the best estimate for the Earth surface land temperature, Berkeley Average performs a process analogous to iterative least-squares minimization. The initial variables are 1) an offset variable ("baseline temperature") for each of the 179,928 temperature time series, referenced to values that take into account latitude and altitude, and 2) the set of T_{avg} numbers (one variable for each month) that will represent our land global average; the values of these variables necessary to minimize the least-squares differences are calculated exactly using matrix inversion. To detect "outliers", that is, observations and stations trends that have large departures from the values expected based on the regional average field, Berkeley Average compares the interpolated temperature field obtained from Kriging to the actual observations. A weight adjustment is applied to stations to reduce the effect of the largest outliers, the variables are recomputed, and then the procedure is iterated. The weighting procedure was applied to reduce the effects of individual measurements that were erroneously recorded (e.g. typographic errors) as well as individual stations that have spurious trends due to effects such as the urban heat island, poor station sitting, and undocumented changes in stations or instruments that were not caught by our scalpel method. Further details of the minimization procedure are presented in the Appendix.

Statistical uncertainties were estimated by randomly subdividing the 179,928 scalpeled stations into 8 smaller sets, calculating Berkeley Average for each of those, and then comparing the results using the "jackknife" statistical method [12,13]. Spatial sampling uncertainties were estimated by simulating poorly sampled periods (e.g. 1800 to 1850) with modern data (1960 to 2010) for which the Earth coverage was better than 97% complete, and measuring the departure from the full site average when using only the limited spatial regions available at early times. This empirical approach implicitly assumes that the spatial relationships between different climate regions remain largely unchanged, and it underestimates the uncertainties if that assumption is false. This could happen, for example, in the period 1750 to 1850 when our evidence shows a strong influence from large volcanic eruptions, a phenomenon for which there are only weak analogs in the 20th century. Thus, although we report "global" land surface results, it should not be forgotten that in the earliest periods that we cover (especially prior to 1850) that sampling is poor, and our results are accurate only to the extent that the spatial structure of temperature does not change significantly with time.

Results

The 1-year and 10-year running averages of our estimated Earth land surface average temperature are shown in figure 1, along with both the 1- and 2-standard-deviation uncertainties that combine those from statistical and spatial sampling effects. The land temperature estimates of the three prior groups are shown for comparison. Although some of those estimates lie outside of our uncertainty bands, they all fall within the uncertainty bands reported by those prior groups; thus there is no statistically significant disagreement. Note that we have extended the estimates back to 1753, although with increased uncertainties. In these early years Earth coverage was minimal; as discussed earlier, the uncertainties were determined by tests using modern data (post 1960) to see the accuracy we obtain for known global land changes when the program is restricted to sparse coverage.

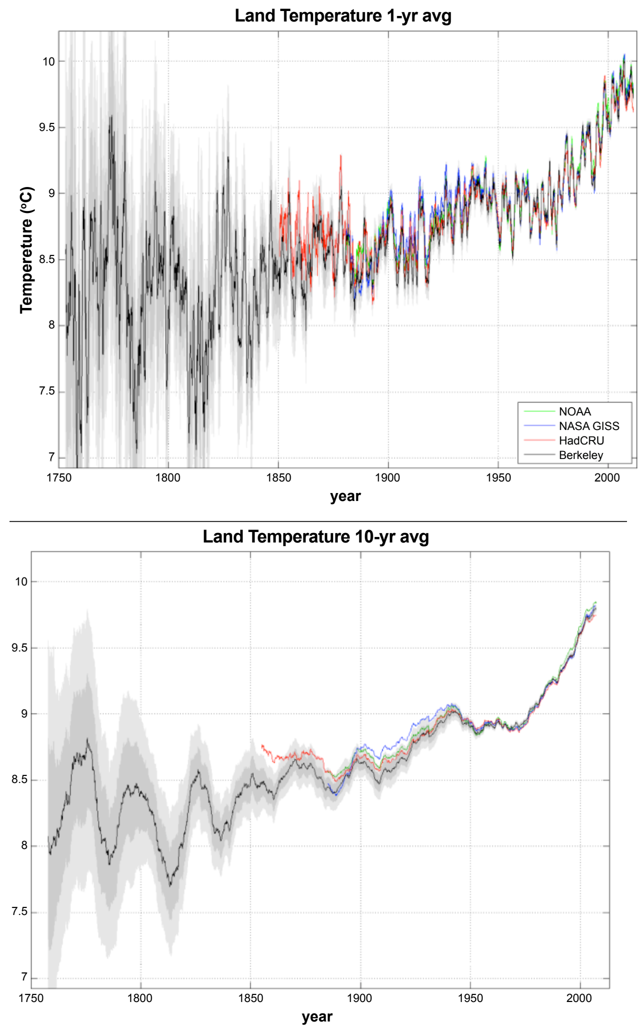

Figure 1: Land temperature with 1- and 10-year running averages. The shaded regions are the one- and two-standard deviation uncertainties calculated including both statistical and spatial sampling errors. Prior land results from the other groups are also plotted. As prior work is generally expressed as anomalies relative to various base periods, a constant factor has been added to each prior result to match the absolute calibration reported here. The NASA GISS record had a land mask applied; the HadCRU curve is the simple land average (CRUTEM). An additional systematic uncertainty of ± 0.12 C affects the absolute calibration of the temperature curves, but does not affect the relative changes through time and is omitted from the error envelope.

We find that the global land mean temperature (comparing the average of the period 2001-2010 with that of 1951-1960) has increased by 0.90 ± 0.05°C (95% confidence). This change is consistent with the global land-surface warming results previously reported, but with reduced uncertainty.

The early part of the record infers, as best as is possible, the fluctuations in global land-only temperature from a sparse network of primarily European and North American observations. This is possible, albeit with the relatively large uncertainties, because the European and North American annual average anomalies are observed to remain within ± 0.5°C of the global land average 95% of the time during the 20th century. The Berkeley Average procedure allows us to use the sparse network of observations from the very longest monitoring stations (10, 25, 46, 101, and 186 sites in the years 1755, 1775, 1800, 1825, and 1850 respectfully) to place limited bounds on the yearly average. These limits imply an Earth that was colder than today during nearly all of the period since 1755.

The large swings seen in the period from the earliest parts of our reconstruction prior to 1850 are statistically significant, though of rather uncertain amplitude, but because of our sparse coverage, may be more closely linked to regional climate changes in Europe and North America rather than to global processes. Similar swings were reported in O-18 measurements in Greenland ice by Chylek et al. [14] who associated them with the Atlantic Multidecadal Oscillation (AMO); we discuss this similarity further later in this paper. The largest excursions also occur at times of significant volcanic events as discussed below.

There are large differences between the surface temperatures of the hemispheres, and among the seven continents, as shown in figure 2. For the period 1950 to the present, the temperature increase in the Southern Hemisphere land areas is lower than that in the Northern; this agrees with prior assessments [9]. Snow-albedo feedbacks and greater average distance from large bodies of water have been previously implicated in the greater rate of warming in the North. This is further corroborated by higher warming in Europe, North America, and Asia. The slowest rate of warming among the continents is observed over Antarctica.

Figure 3 shows a map of our estimated temperature change from the decade 1951-1960 to the decade 2001-2010 for all land regions, and also corroborates the broadly distributed nature of global warming. Nonetheless there are considerable spatial variations, and one cannot simply assume that all regions change uniformly.

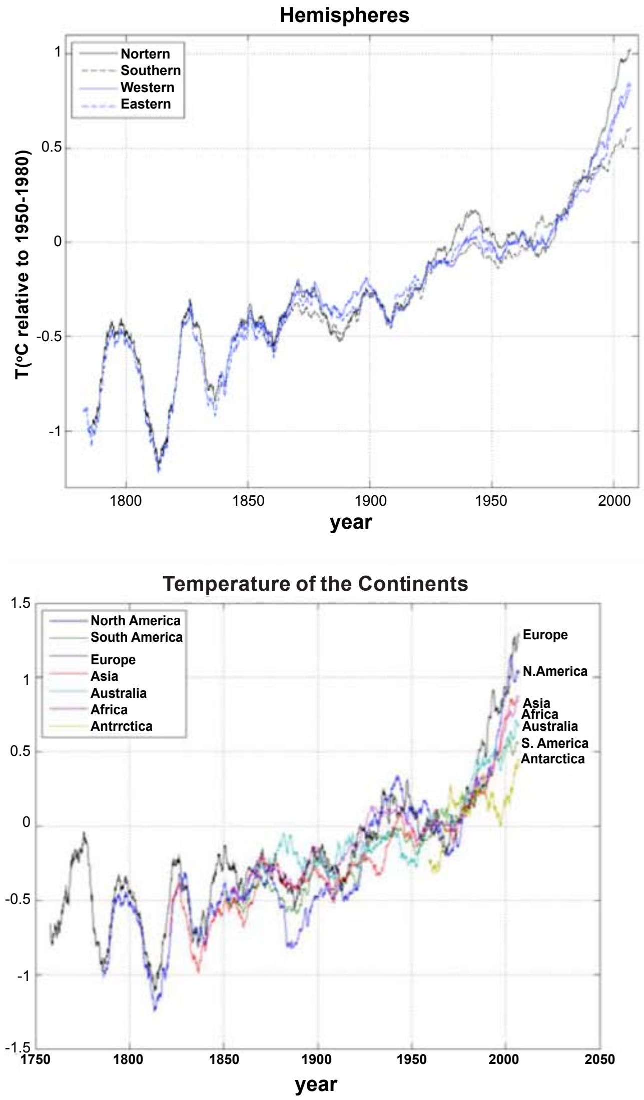

Figure 2: The temperature records of the land divided by hemisphere, and by 7 continents, shown as a 10-year running average. All records were normalized to zero mean for 1951 to 1980.

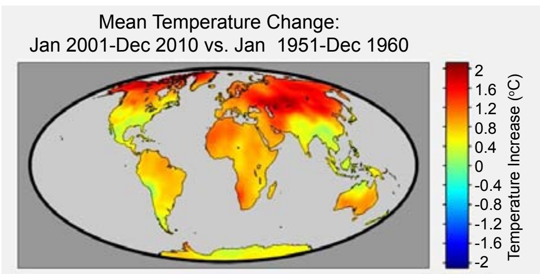

Figure 3: Map of the estimated temperature change from the 1950s decade to the 2000s decade for all land regions.

Diurnal range

In addition to data for T_{avg}, for most sites we have also analyzed data on T_{max} and T_{min}, the daily maximum and minimum temperatures respectively. The reconstructed global land-average temperature time series for T_{max} and T_{min} are similar to T_{avg}. The summary values for the change from 1950s to 2000s are 0.91 ± 0.05°C and 1.06 ± 0.07°C for T_{max} and T_{min} respectively. In general, these time series differ only slightly from T_{avg} and from each other; however, we find that the diurnal range (i.e. T_{max} minus T_{min}) has some surprising properties.

Some of the climate models predict that the diurnal temperature range, that is, the difference between T_{max} and T_{min}, should decrease due to greenhouse warming. The physics is that greenhouse gases have more impact at night when they absorb infrared and reduce the cooling, and that this effect is larger than the additional daytime warming. This predicted change is sometimes cited as one of the "fingerprints" that separates greenhouse warming from other effects such as solar variability. Previous studies [15-18] reported significant decreases in the diurnal temperature range over the period 1948 to 1994. Jones et al. [18] for example described the decrease as 0.08°C per decade for the period 1950 to 1993.

To determine diurnal range changes we used two approaches. The first was to compute global land averages for T_{max} and T_{min} completely independently and then take their difference. The second approach was to construct a diurnal range time series at each station equal to the local difference between T_{max} and T_{min} and then apply the Berkeley Average methodology to these diurnal range time series. These two approaches produced qualitatively the same results. However, the second approach led to significantly smaller uncertainty estimates, presumably because taking the difference locally could sometimes eliminate inhomogeneities that affected both T_{max} and T_{min}.

The result of this calculation is shown in figure 4. The solid line represents the annual average of the diurnal range, and the dashed line shows the 10-year running average. The 1- and 2-standard deviation error uncertainties are shown with the two grey bands for the 10-year average. The behavior of the diurnal range is not simple; it drops from 1900 to 1987, and then it rises. The rise takes place during a period when, according to the IPCC report, the anthropogenic effect of global warming is evident above the background variations from natural causes.

Although the post-1987 rise is not sufficient to undo the drop that took place from 1901 to 1987, the trend of 0.86 ± 0.13°C/century is distinctly upwards with a very high level of confidence. This reversal is particularly odd since it occurs during a period when the rise in T_{avg} was strong and showed no apparent changes in behavior.

From 1950 to 2010, because of the recent rise, the net change we observe is -0.04 ± 0.01°C/decade. We are not aware of any global climate models that predicted the reversal of slope that we observe.

The volcanic Era

As has been widely discussed [19,20], several of the cool periods in the early 1800s have been associated with large volcanic eruptions. Since our work extends the land temperature estimates further back in time than the previous Earth land averages, we can make a somewhat more global comparison than was previously possible. Of course, since most of the older records are in the Northern Hemisphere; this reflects itself in our plots by the large uncertainty limits for the early data.

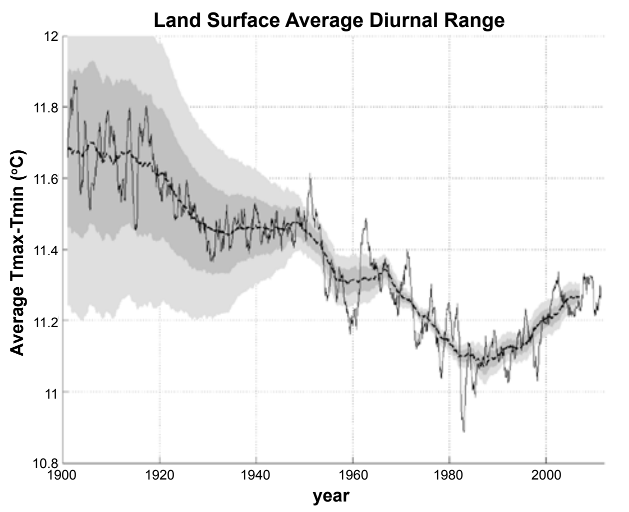

Figure 4: Earth average diurnal range, calculated from records of $D=T_{max}-T_{min}$ using the Berkeley Average estimation program. Shown are both the yearly averages and the 10-year averages, and the 1- and 2-standard deviation uncertainty estimates for the 10-year averages.

We have performed a least squares study in which the land-average temperature is fit to a linear combination of two factors (plus a constant offset). Those factors are a term proportional to the measured volcanic sulfate emissions into the stratosphere from ice cores [21] and a representative anthropogenic term, for which we chose the natural logarithm of the carbon dioxide concentration, log (CO_2). We note that there are many other greenhouse gases and types of anthropogenic forcing besides CO_2; however, nearly all such forcings follow a similar time evolution, and because our fit is so simple (a linear superposition of known curves) there was value in keeping the number of parameters small. For the analysis that follows it is not meaningful to distinguish between anthropogenic forcing that has similar time histories (We tried, for example, including a historic term for methane; the resulting fit was virtually identical, and the data was insufficiently precise to determine the relative components of CO_2 and methane). Consequently using log(CO_2) as the representative anthropogenic term rather than CO_2 concentration, or IPCC estimates of total greenhouse gas forcing or total anthropogenic forcing make no significant difference in the conclusions below.

We also tried fitting to other empirical functions (exponential, parabolic, population growth), but none of these fit the data nearly as well as the log(CO_2) function.

A linear combination of volcanic sulfates and CO_2 changes were fit to the land-surface temperature history to produce figure 5. As we will describe in a moment, the addition of a solar activity proxy did not significantly improve the fit. The large negative excursions are associated with volcanic sulfate emissions, with the four largest eruptions having all occurred pre-1850; thus our extension to the pre-1850 data proved useful for the observation of these events. To perform the fit, we adjusted the sulfate record by applying an exponential decay with a two year half-life following emission. The choice of two-years was motivated by maximizing the fit, and is considerably longer than the 4-8 month half-life observed for sulfate total mass in the atmosphere (but plausible for reflectivity which depends on area not volume). It is likely that longer period reflects dynamic climate responses that are slower than the simple settling time of the total sulfate mass.

Most of the eruptions with significant stratospheric sulfate emissions can be qualitatively associated with periods of low temperature. For most of these events, the volcano and year of emission is historically known. These include the eruptions of Laki in 1783, Tambora in 1815, and Cosiguina in 1835. The sulfate spike at 1809 does not have an associated historical event, and it might consist of two separate events [22,23]. The famous explosion of Krakatau in 1883 is smaller (measured in sulfates) than these other events.

The temperature "forcing" of volcanic aerosols is a complicated function of latitude, altitude, season, and particle size; see Kelly et al. [20]. However, the fit presented here can provide a rough estimate. We observe a response of -1.5 ± 0.5°C per 100 Tg of atmospheric sulfate emitted. The 95% confidence interval quoted here is primarily influenced by the uncertainties in the temperature data; however we also allowed the magnitude of each eruption to have a 1-sigma error of ± 15%. A more sophisticated analysis of the forcing and the details of the climate response may be able to improve upon the crude estimate offered here based solely on the linear combination fit.

In the simple linear combination, the anthropogenic factor, log (CO_2), has a weight equivalent to an effective response of 3.1 ± 0.3°C at doubled CO_2 (95% confidence). However, this parameterization is based on an extremely simple linear combination, using only CO_2 and no other anthropogenic factors and considering only land temperature changes. As such, we don't believe it can be used as an explicit constraint on climate sensitivity other than to acknowledge that the rate of warming we observe is broadly consistent with the IPCC estimates of 2-4.5°C warming (for land plus oceans) at doubled CO_2. The purpose of the anthropogenic term is merely to show that our extended temperature reconstruction is consistent with an anthropogenic explanation, and not to try and detangle the details for those changes. However, more detailed studies of how our land-surface temperature history compares to the various forcing and expected responses should ultimately help constrain parameters critical to the understanding of climate change.

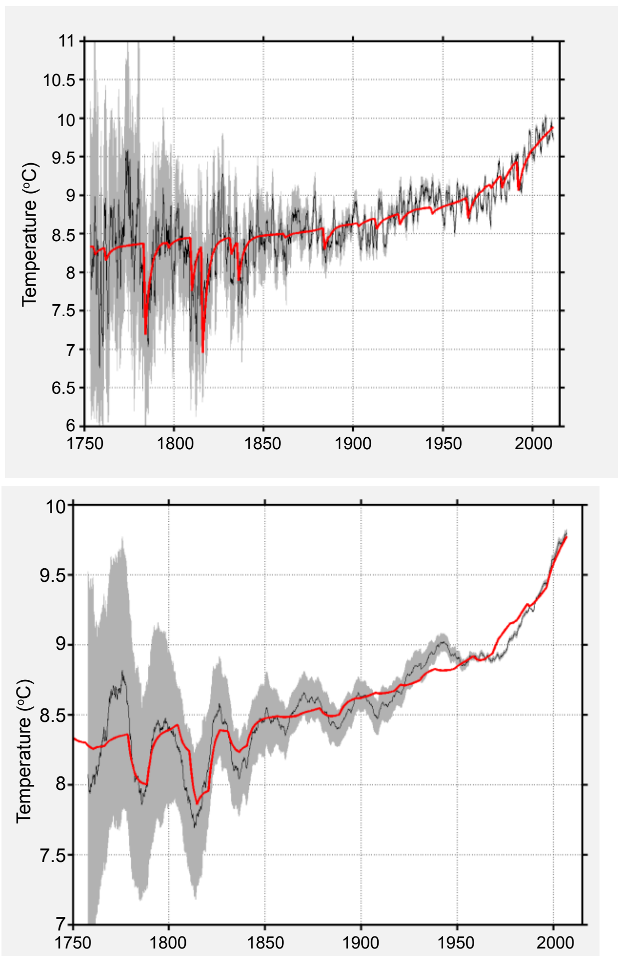

Figure 5: The annual (left) and decadal (right) land surface temperature from the BerkeleyEarth average (black line), compared to a linear combination of volcanic sulfate emissions (responsible for the short dips) and the natural logarithm of CO_2 (responsible for the gradual rise) shown in red. Inclusion of a proxy for solar activity did not significantly improve the fit. Temperature data is the same as figure 1. The grey area is the 95% confidence interval.

In producing the linear fit shown here, we also tested to see whether solar forcing played an important role. We find no significant correlation between the land surface temperature history of the last 250 years and the solar forcing history specified for use in the IPCC fifth assessment report global climate models. Specifically, a linear combination including solar produces a land surface climate sensitivity to the IPCC solar forcing function of 0.03 ± 0.49°C/(W/m^2), which is consistent with zero but also subject to large uncertainty. (Note that for this function the W/m^2 represent the variations assumed by the IPCC radiative forcing model, not actual measured W/m^2.) We also attempted a fit where all parameters were decadally averaged to smooth over the large swings associated with the solar cycle in the IPCC forcing model. This also produced an insignificant result of 0.6 ± 1.7°C/(W/m^2) for solar forcing while CO_2 and volcanic changes remained highly significant. Based on these observations, we conclude that either solar forcing has not been a major component of the changes in the land-surface temperature record or that the assumed history for solar forcing is too inaccurate in shape to make a simple linear fit possible.

Decadal and sub-decadal variations

Figure 6 shows the AMO Index along with the residual temperature record fluctuations after subtracting the fit curve shown in figure 5. The AMO Index is a widely used indicator of North Atlantic variability maintained by NOAA and derived from sea surface temperatures; for the current methodology see Enfield [24].

Although the agreement is not perfect, there is a remarkable correspondence in both the short-term 2-3 year variability, and also in the longer term multi-decadal oscillations that give the AMO its name. Although the variation has sometimes been described as a 70-year cycle (based on the single cycle seen in the data of figure 6 from 1940 to 2010), its behavior does not seem that regular. Because it is seen in the land as well as the North Atlantic, we will refer to it simply as the multidecadal oscillation of the land surface temperature. Note that the amplitudes of the curves in figure 6 have not been rescaled, and hence the apparent correspondence indicates that these fluctuations over land and ocean truly are of similar magnitude in temperature. Of course, it is not too surprising that the AMO—a measure of temperatures in the North Atlantic—match those of the Earth average land temperature, since 2/3 of the land is in the Northern Hemisphere.

It is unknown whether the observed decadal changes in AMO and land-average temperature are the results of natural variability, anthropogenic forcing, or some combination of the two. Since the fit conducted in the previous section only used CO_2 as a crude proxy of anthropogenic change it is entirely possible that a more complete understanding the anthropogenic forcing could explain these variations. However, it is doubtful whether the small temperature fluctuations we observe could be accounted for with any confidence given the relatively large uncertainties associated with many anthropogenic forcings. An alternative is to assume that some or all of these variations represent a form of natural variability. Using the curve from figure 6, we can estimate that such variability on decadal scales is no more than ± 0.17°C, 95% of the time. This can be understood as crude bound on the amount of temperature change that might potentially be ascribed to natural variability. Such a bound is small, but not trivial, compared to the 0.90°C warming since 1950s.

A cross-correlation between the residual multidecadal oscillation and the AMO is shown in figure 7. A sharp peak occurs near zero lag, at 0.1 ± 0.3 years; this is a result of the close correspondence between the decadal and subdecadal variations of the two signals. In addition to this, there is a lower but broad hump rising from lag of -15 yr and finally falling at lag of +30 yr, with a center at about lag = +10 ± 3 years. This broad peak suggests that the multidecadal fluctuations in the AMO lag the land multidecadal structure by about a decade (e.g. Figure 6, bottom panel); however, this second feature is broad, and the primary maximum occurs near zero lag. That can be understood as arising from two components, a rapid part in which the ocean and the land vary together, and a slower one in which long-term trends in ocean temperatures lags that on land.

This behavior, with the two peaks (one at zero, the other at 10 years) can be understood physically if both land and ocean are responding to the same underlying process that has both sub-decadal and multi-decadal fluctuations. The subdecadal changes are rapid, but presumably only affect the shallow mixed layer of the oceans, so the land and the surface layers of the oceans respond essentially simultaneously. The multidecadal variations have time to penetrate into the deeper oceans, and that takes longer, giving rise to the lag between the quick land response and the slow oceanic temperature change.

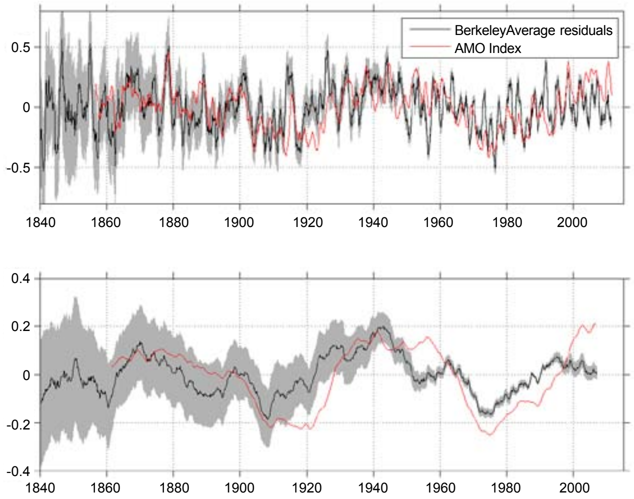

Figure 6: The residual multi-decadal component (MDC) of the Earth's land surface temperature compared to the Atlantic Multidecadal Oscillation (AMO). The upper panel shows both datasets on an annual scale (12-month moving average), while the lower panel applies a 10-year moving average to highlight decadal structure. The MDC was obtained by subtracting the fit curve shown in figure 5. The MDC and the AMO have similar amplitude and structure for both the 2-3 year time scale and for the multi-decadal time scale. Error bands (95% confidence interval) reflect the temperature reconstruction uncertainties only; they do not include any uncertainty associated with the fit.

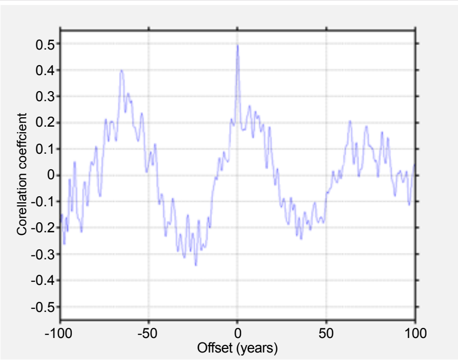

Figure 7: Correlation between the AMO and our observed multidecadal oscillation. The peak near zero represents the strong correlation between the decadal and subdecadal variations in the two sets; the broad peak centered near +10 years indicates that temperature changes in the north Atlantic lag those of the global land average for the multi-decadal time scale.

Discussion

We have obtained an estimate of the Earth land surface temperature from 1753 unto the present. The limited land coverage prior to 1850 results in larger uncertainties in the behavior of the record; despite these, we see behavior that is significant. Most dramatic are the large swings in the earliest period. These dips can be explained as the effect of large volcanic eruptions that took place during that period. The rapid changes in the Earth's temperature at that time are remarkably swift, and at times even greater than the changes taking place in the last 50 years. Our records also show an average temperature during the early 1800s that is on the lower end of what had previously been estimated from proxy measurements, although there are large discrepancies between the values obtained by using different proxy sets.

The behavior changes in the early 1900s, following closely the results that had been previously reported by the three other major groups that analyze historic thermometer records, but with a smaller uncertainty than has been previously achieved. Since the 1950s, we observe a rise in the average land surface temperature of 0.90 ± 0.05°C (95% confidence). This value is in the middle of the comparable values reported by other groups, but with an estimated uncertainty approximately twice as tight as those of prior reports. Exact comparison of uncertainties is slightly complicated because each different group frames the uncertainties in slightly different ways; however, for the year 1951, we estimate an annual land average uncertainty of ± 0.06°C versus ± 0.14°C for CRUTEM and ± 0.17°C for NOAA [7,25]. GISS has never published a comparable land-only uncertainty statement.

We observe that the record of diurnal temperature range, T_{max}-T_{min}, follows an unexpected path, with a slow drop for the period 1900 to the late 1980s, followed by a rise up to the most recent period (2011). This change in direction is unexpected and not anticipated by existing climate models.

Many of the changes in land-surface temperature follow a simple linear combination of volcanic forcing (based on estimates of stratospheric sulfate injection) and an anthropogenic term represented here by the logarithm of the CO_2 concentration. The best fit to a volcanic forcing term is -1.5 ± 0.5°C per 100 Tg of atmospheric sulfate. The anthropogenic forcing parameter is 3.1 ± 0.3°C for CO_2 doubling (compared to pre-industrial levels), broadly consistent with the estimate of ~3°C for the equilibrium warming of land plus ocean at doubled CO_2. When we included solar forcing we found that the solar variability record assumed by the IPCC did not contribute significantly to the fit of historic temperature. This could imply that any effect associated with solar variability is too small to be detected by our simple approach. It might also imply that the shape of solar forcing assumed by the IPCC during the last 250 years is too inaccurate for an effective comparison. However, if the shape of the solar forcing history is accurate, then the impact of solar variability on

doi:http://dx.doi.org/10.4172/2327-4581.1000101

climate would have to be on the low side of present estimates. With an IPCC estimated change in the mean solar cycle irradiance of only 0.16 W/m^2 since 1800, and our model fit of 0.03 ± 0.49°C/(W/m^2) as a response function to solar variation, the resulting 95% upper limit would only be 0.08°C. Though, we note that other assumptions about the solar forcing history could still permit larger response functions.

The residual variability in land-surface temperature which remains after the volcanic and CO_2 correlation is subtracted out is observed to closely mirror and for slower changes, slightly lead variations in the Atlantic Multidecadal Oscillation Index. This is consistent with both the land and North Atlantic responding to the same unknown process. That process may be partially anthropogenic and include effects whose time evolution is not proportional to CO_2. It might also include natural processes. Our analysis does not rule out long-term trends due to natural causes; however, since all of the long-term (century scale) trend in temperature can be explained by a simple response to greenhouse gas changes, there is no need to assume other sources of long-term variation are present. If all of the residual evolution during the last 150 years is assumed to be natural, then it places an upper 95% confidence bound on the scale of decadal natural variability at ± 0.17°C. Though non-trivial, this number is small compared to what our correlation analysis suggests may be anthropogenic changes that occurred during the last century.

Acknowledgements

We thank David Brillinger for important guidance in statistical analysis, Zeke Hausfather, Steven Mosher, and Judith Curry for helpful discussions and suggestions. This work was done as part of the Berkeley Earth project, organized under the auspices of the Novim Group (www.Novim.org). We thank many organizations for their support, including the Lee and Juliet Folger Fund, the Lawrence Berkeley National Laboratory, the William K. Bowes Jr. Foundation, the Fund for Innovative Climate and Energy Research (created by Bill Gates), the Ann and Gordon Getty Foundation, the Charles G. Koch Charitable Foundation, and three private individuals (M.D., N.G. and M.D.). More information on the Berkeley Earth project can be found at www.BerkeleyEarth.org.

References

1. Hansen J, Lebedeff S (1987) Global trends of measured surface air temperature. J Geophys Res 92: 13345-13372.
2. Hansen J, Ruedy R, Glascoe J, Mki Sato (1999) GISS analysis of surface temperature change. J Geophys Res 104: 30997-31022.
3. Hansen J, Ruedy R, Mki Sato, K Lo (2010) Global surface temperature change. Rev Geophys 48: RG4004.
4. Jones PD, Wigley TML, Wright PB (1986) Global temperature variations between 1861 and 1984. Nature 322: 430-434.
5. Jones PD, Moberg A (2003) Hemispheric and Large-Scale Surface Air Temperature Variations: An Extensive Revision and an Update to 2001. J Climate 16: 206-223.
6. Brohan P, Kennedy JJ, Harris I, Tett SFB, Jones PD (2006) Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. J Geophys 111:D12106.
7. Smith TM, Reynolds RW (2005) A global merged land air and sea surface temperature reconstruction based on historical observations (1880–1997). J Climate 18: 2021–2036.
8. Smith TM (2008) Improvements to NOAA's Historical Merged Land-Ocean Surface Temperature Analysis (1880-2006). J Climate 21: 2283-2293.
9. Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D et.al (2007) Observations: Surface and Atmospheric Climate Change. In: Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge, UK.
10. Krige DG (1951) A statistical approach to some mine valuations and allied problems on the Witwatersrand, Master's thesis of the University of Witwatersrand.
11. Cressie N (1990) The Origins of Kriging. Math Geol 22: 239-252.
12. Tukey JW (1958) Bias and confidence in not quite large samples. The Annals of Mathematical Statistics 29: 614.
13. Rupert GM (1974) The Jackknife-A review. Biometrika 61: 1-15.
14. Chylek P, Folland CK, Dijkstra HA, Lesins G, Dubey MK (2011) Ice core data evidence for a prominent near 20 year time-scale of the Atlantic Multidecadal Oscillation. Geophys Res Lett 38: L13704.
15. Karl T, Kukla G, Razuvayev V, Changery M, Quayle R, et.al (1991) Global warming: Evidence for asymmetric diurnal temperature change. Geophys Res Lett 18: 2253-2256.
16. Easterling DR, Horton B, Jones PD, Peterson TC, Karl TR, et.al (1997) Maximum and Minimum Temperature Trends for the Globe. Science 277:364-367.
17. Braganza K, Karoly DJ, Arblaster JM (2004) Diurnal temperature range as an index of global climate change during the twentieth century. Geophys Res Lett 31: L13217.
18. Jones PD, New M, Parker DE, Martin S, Rigor IG (1999) Surface air temperature and its changes over the past 150 years. Rev Geophys 37: 173-199.
19. Hansen J,Lacis A, Ruedy R, Sato M (1992) Potential climate impact of Mount Pinatubo eruption. Geophys Res Lett 19: 215-218.
20. Kelly PM, Jones PD, Pengqun J (1996) The Spatial Response of the Climate System to Explosive Volcanic Eruptions. International J Climatol 16: 537-550.
21. Gao C, Robock A, Ammann C (2008) Volcanic forcing of climate over the past 1500 years: An improved ice-core-based index for climate models. J Geophys Res 113: D23111.
22. Yalcin K, Wake CP, Kreutz KJ, Germani MS, Whitlow SI (2006) Ice core evidence for a second volcanic eruption around 1809 in the Northern Hemisphere, Geophs Res Lett 33: L14706.
23. Cole-Dai J, Ferris D, Lanciki A, Savarino J, Baroni M, et. al (2009) Cold decade (AD 1810–1819) caused by Tambora (1815) and another (1809) stratospheric volcanic eruption. Geophys Res Lett 36: L22703.
24. Enfield DB, Mestas-Nunez AM, Trimble PJ (2001) The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental US. Geophys Res Lett 28: 2077-2080.
25. Morice CP, Kennedy JJ, Rayner NA, Jones PD (2012) Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 dataset. J Geophys Res 117: D08101.

Author Affiliations

Top

[1]*Berkeley Earth Surface Temperature Project, Novim Group, USA*
[2]*University of California, Berkeley, USA*
[3]*Lawrence Berkeley National Laboratory, USA*
[4]*Oregon State University, USA*