How Will Earth's Surface Temperature Change in Future Decades?

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Abstract

Reliable forecasts of climate change in the immediate future are difficult, especially on regional scales, where natural climate variations may amplify or mitigate anthropogenic warming in ways that numerical models capture poorly. By decomposing recent observed surface temperatures into components associated with ENSO, volcanic and solar activity, and anthropogenic influences, we anticipate global and regional changes in the next two decades. From 2009 to 2014, projected rises in anthropogenic influences and solar irradiance will increase global surface temperature 0.15±0.03°C, at a rate 50% greater than predicted by IPCC. But as a result of declining solar activity in the subsequent five years, average temperature in 2019 is only 0.03±0.01°C warmer than in 2014. This lack of overall warming is analogous to the period from 2002 to 2008 when decreasing solar irradiance also countered much of the anthropogenic warming. We further illustrate how a major volcanic eruption and a super ENSO would modify our global and regional temperature projections.

1. Introduction

Global surface temperature increased 0.7°C during the twentieth century and is projected to cause a further 1 to 4°C increase during the twenty first century, primarily as a result of increasing concentrations of greenhouse gases [*IPCC*, 2007]. Yet as Figure 1 shows, global surface temperatures warmed little, if at all, from 2002 to 2008, even as greenhouse gas concentrations have increased, causing some to question the reality of anthropogenic global warming. Natural influences also alter surface temperatures, producing as much as 0.2°C global warming during major ENSO events, near 0.3°C cooling following large volcanic eruptions, and 0.1°C warming from minima to maxima of recent solar cycles [*Lean and Rind*, 2008]. On time scales of years to a decade, naturally induced surface temperature changes can dominate current anthropogenic warming of 0.2°C per decade [*Easterling and Wehner*, 2009], especially in some locations, where regional changes can exceed the global response by an order of magnitude. With adverse effects of warming temperatures already apparent, for example in wildfire duration and intensity [*Running*, 2006], knowledge of surface temperatures is sought in the immediate decades not just for the long-term future, for application to land management and crop productivity [*Mendelsohn et al*., 2007], energy usage, tourism and public health [*Khasnis and Nettleman*, 2005].

On time scales of 10 to 50 years (and longer) decadal climate forecasts are difficult to make with general circulation climate models due to their many uncertainties [*IPCC*, 2007]. By including overturning of the ocean's meridional circulation in a numerical model and using observed distributions of ocean heat content for initialization, *Smith et al*. [2007] forecast rapid warming after 2008, with "at least half of the 5 years after 2009 ..… predicted to exceed (1998) the warmest year currently on record". But another model that also attempts to account for meridional overturning circulation [*Keenlyside et al*., 2008] forecasts the opposite, "that global surface temperature may not increase over the next decade, as natural climate variations in the North Atlantic and tropical Pacific temporarily offset the projected anthropogenic warming".

An alternative approach to numerical model simulations for assessing recent climate change and forecasting future change in the next two decades is direct analysis of surface temperature observations. By isolating and quantifying the specific changes arising from individual natural and anthropogenic influences, the causes of past change are identified, thereby rendering forecasts for future decades possible, assuming plausible future scenarios expected for each influence. We use this empirical approach to develop global and regional surface temperature scenarios for the next two decades.

Climate system nonlinearities have the potential to perturb such an approach, but are less likely over the time-scale of the next decade or two. There could, however, be 'tipping points' in which processes heretofore unimportant become activated, or simply grow in importance relative to their historical contribution. An example of the former is changing Arctic sea ice, which may lead to a rapid amplification of the high latitude response. An example of the latter is reduction in the overturning circulation in the North Atlantic, the reason for IPCC's forecast of minimal warming in parts of the North Atlantic Ocean, and the *Keenlyside et al.* [2008] reduced warming. But as the state of both ocean/sea ice modeling and ocean initialization is still far from mature, there is as yet little quantitative predictability for these features.

2. Analysis

Using the most recently available characterizations of ENSO, *E*, volcanic aerosols, *V*, solar irradiance, *S*, and anthropogenic influences, *A*, we perform multiple linear regression analyses to decompose monthly mean surface temperature anomalies since 1980 into four components. The decomposition is conducted on a global scale, as well as on a $5^o \times 5^o$ latitude-longitude grid to determine the corresponding geographical patterns. During this recent epoch, in addition to surface temperature observations covering ~80% of the globe, the ENSO, volcanic and solar cycle signals are the strongest of the past century and are specified with confidence because of direct observations. Such a decomposition of observations since 1980 is consistent with analysis of historical surface temperature records since 1889 [*Lean and Rind*, 2008] and it facilitates direct comparison with the same base period that *Hansen et al.*, [2006] utilize, the average of the prior 30 years, 1951-1980.

Monthly mean surface temperature anomalies are reconstructed as $T_R(t) = c_0+c_E E(t-\Delta t_E)+c_V V(t-\Delta t_V)+c_S S(t-\Delta t_S)+c_A A(t-\Delta t_A)$ where *E*, *V*, *S* and *A* are zero mean, unit variance time series and the lags (in months) are Δt_E=4, Δt_V=7, Δt_S=1 and Δt_A=120. The lags are chosen to maximize the proportion of global variability that the statistical model captures and are spatially invariant (although a geographical dependence is expected). The fitted coefficients, c_0..., are obtained by multiple linear regression against the instrumental surface temperature record (HadCRUT3v) available from the University of East Anglia Climatic Research Unit (CRU) [*Brohan et al.*, 2006]. The multivariate ENSO index, *E*, is a weighted average of the main ENSO features contained in sea-level pressure, surface wind, surface sea and air temperature, and cloudiness [*Walter and Timlin*, 1998]. Volcanic aerosols, *V*, in the stratosphere are compiled by [*Sato et al.*, 1993] since 1850, updated from giss.nasa.gov to 1999 and extended to the present with zero values. Although some volcanic activity occurred between 2006 and 2008, it is difficult to calculate the aerosol optical depth because of the lack of direct quantitative space-based observations [*Thomason and Pitts*, 2009]. Solar irradiance, *S*, is estimated as the competing effects of sunspots and facular, identified in observations made by space-based radiometers [*Lean et al.*, 2005]. The anthropogenic influence, *A*, is the net effect of eight different components, including greenhouse gases, land use and snow albedo changes, and (admittedly uncertain) tropospheric aerosols [*Hansen et al.*, 2007].

The combination of natural and anthropogenic influences (at appropriate lags) in the empirical model captures 76% of the variance in the monthly global surface temperature record. Figure 1 illustrates that this statistical model tracks closely the observed global surface temperatures from 1980 to 2008, including the lack of overall warming during the past decade. The individual contributions to the net global surface temperatures of the natural and anthropogenic influences are also shown in Figure 1, including 0.2^{o}C warming during the 1997-98 ENSO, cooling approaching 0.3^{o}C in 1992 following Pinatubo, and ~0.1^{o}C warming near peak solar cycle activity.

To test our empirical approach, we determine the model parameters using observations from 1970 to 1999, and compare the observed surface temperature change with our empirical determination averaged over the subsequent five-year period from 2001 to 2005 (for direct comparison with *Hansen et al.*, 2006, Figure 1B). Relative to the base period, observed global surface temperature increased 0.56±0.03^{o}C compared with 0.53±0.03^{o}C projected by our empirical model, where the uncertainties are obtained by combining the uncertainties of the means. Figure 2 shows that the observed and model-projected regional pattern change for 2001-2005 (relative to 1951-1980) and the (area-weighted) zonal surface temperatures are very similar. Note that our model is limited to those latitudes (approximately 60^{o}S to 70^{o}N, Figure 2) where actual observations are available for 50% of all months over the 30-year model regression period.

Using global and regional surface temperature responses to the four individual influences parameterized by regression against the observations from 1980 to 2008, we forecast change from 2009 to 2030 by adopting the best estimate of how each influence will change in the future. The anthropogenic forcing in the past 40 years is well represented by a linear trend that we extrapolate into the future, as shown in Figure 1. We assume that future solar irradiance cycles replicate cycle 23, with cycle 24 commencing at the beginning of 2009. Although solar activity (as indicted by sunspot numbers) was less in cycle 23 than in cycles 21 and 22, the total irradiance amplitude (near 0.1%) is similar in the three past cycles since it is the net effect of sunspot darkening and facular brightening, both of which are altered by solar activity. Since ENSO fluctuations and volcanic eruptions are not predictable on decadal time scales, we estimate their maximum likely future impact with a scenario that includes a Pinatubo-like eruption with peak impact in 2014 and a super ENSO with maximum impact in 2019, mimicking a similar sequence that occurred from 1992 to 1997 (Figure 1).

3. Results

With the solar and anthropogenic scenarios in Figure 1, our empirical model predicts that global surface temperatures will increase at an average rate of 0.17±0.03^{o}C per decade in the next two decades. The uncertainty given in our prediction is the standard deviation of forecasts made with statistical models of three different epochs, the current epoch 1980-2008, our test epoch 1970-1999 and the historical record from 1890-2008. Within the uncertainties, the average warming rate in the next two decades is consistent with the 0.2^{o}C per decade warming forecast by IPCC [2007], also shown in Figure 1. The warming trend is opposite to recent projections of *Keenlyside et al.* [2008], who forecast an absence of warming in the next decade based on weakening of the Atlantic Ocean meridional overturning circulation (a change not explicitly included in our empirical model).

The predicted warming rate will not, however, be constant on sub-decadal time scales over the next two decades. As both the anthropogenic influence continues and solar irradiance increases from the onset to the maximum of cycle 24, global surface temperature is projected to increase 0.15±0.03^{o}C in the five years from 2009 to 2014, with global annual temperatures 0.7^{o}C above the base period by 2014. However, our estimated annual temperate increase of 0.19±0.03^{o}C from 2004 to 2014 (Figure 1) is less than the 0.3^{o}C warming that *Smith et al.* [2007] predict over the same interval. From 2014 to 2019, global annual surface temperatures increase only minimally (0.03±0.01^{o}C), because declining solar irradiance is expected to cancel much of the anthropogenic warming. This lack of overall warming is analogous to the recent period from 2002 to 2008 when decreasing solar irradiance during the descending phase of the 11-year cycle countered much of the anthropogenic warming.

According to our projections of annual mean regional surface temperature changes, shown in Figure 3, the increase from 2009 to 2014 will be largest from 30 to ~70^{o}N, especially over land but also over the ocean, except in the north east Pacific. As solar irradiance decreases and global surface temperatures increase minimally between 2014 and 2019, the anthropogenic influence nevertheless will continue to warm the Northern mid latitudes, but less uniformly and at a slower rate because of cooling in those regions most sensitive to solar variability (Figure 3, bottom). Our projections are consistent with *IPCC*'s long-range forecast that warming will be greatest over land and at most high northern latitudes. But whereas *IPCC* asserts minimal warming in parts of the North Atlantic Ocean, our forecast suggests that this region will warm throughout the next decade, in response to both solar and anthropogenic influences.

A major volcanic eruption or a super ENSO will modify significantly the temperature change scenarios in Figure 3, both globally and regionally, as shown in Figure 4. A large volcanic eruption with peak climate impact in 2014 will cool much of the Americas and the mid Atlantic Ocean, parts of Australia, the tropical Pacific Ocean and the western India Ocean relative to the base period (1951-1980). A "super" El Nino peaking in 2019 would produce significant warming over many regions of the globe, as shown in Figure 4. Such a combination of an ENSO event following a Pinatubo-like eruption would mean that rather than remaining approximately level from 2014 to 2019, global surface temperatures would increase 0.4±0.02^{o}C (Figure 1), but from entirely natural (not anthropogenic) causes. A similar sequence occurred in the recent past from mid 1992 to mid 1997, when global surface temperatures increased 0.5^{o}C, significantly more than the 0.1^{o}C, attributable to anthropogenic warming over this period.

4. Summary

By representing monthly mean surface temperatures in terms of their combined linear responses to ENSO, volcanic and solar activity and anthropogenic influences, we account for 76% of the variance observed since 1980 (and since 1889, *Lean and Rind*, 2008) and forecast global and regional temperatures in the next two decades. According to our prediction, which is anchored in the reality of observed changes in the recent past, warming from 2009 to 2014 will exceed that due to anthropogenic influences alone but global temperatures will increase only slightly from 2014 to 2019, and some regions may even cool.

Northern mid latitudes, especially western Europe, will experience the largest warming (of as much as 1^{o}C), since this region responds positively to both solar and anthropogenic influences. Minimal warming is likely in the eastern Pacific ocean and adjacent west coast of South America, and parts of the mid latitude Atlantic ocean, which may cool slightly at southern latitudes in future decades.

The major assumption associated with our forecasts is that 'past is prologue'; climate will continue to respond in the future to the same factors that have influenced it in the recent past and the response will continue to be linear over the next several decades. The demonstrated ability of our empirical model to reproduce the historical record of monthly surface temperature changes on a range of time scales from annual to multidecadal suggests that the same atmosphere-ocean interchange (both internal and forced) that governs annual surface temperature changes may also control climate change in the immediate future.

While the ability of the climate system to depart from its historical response should not be underestimated (e.g., ocean circulation changes), the demonstrated ability of our empirical model to reproduce with some fidelity the historical surface temperature record, and in particular the geographic variations of the last decade, provides cautious confidence that a similar capability may be available for the next two decades in association with the expected climate forcings. Over this time scale, anthropogenic radiative forcing is forecast to continue growing at close to current trends with all of the different trace gas emission scenarios currently being employed, while the solar cycle changes can be anticipated within a range of uncertainty. If strong ENSO cycle events and/or volcanoes arise, they can be factored into the forecasts with the method described here. In future work we plan to characterize and forecast the seasonal responses to the natural and anthropogenic effects.

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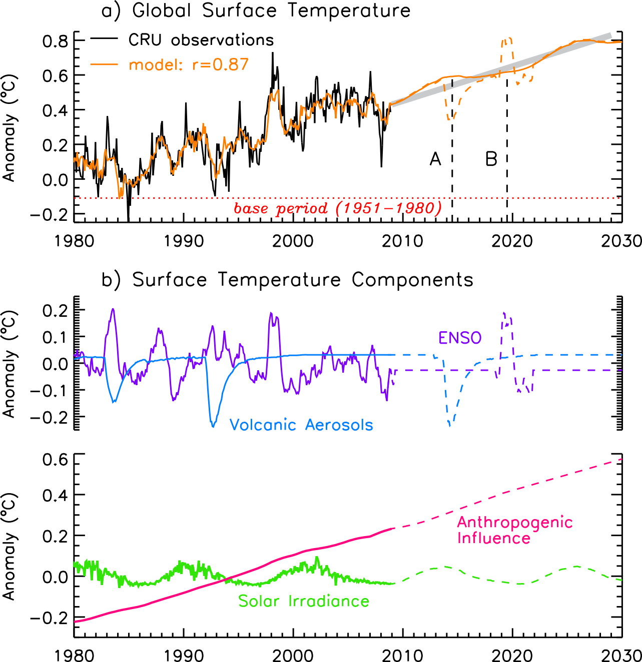
Figure 1. Compared in a) are observed monthly mean global temperatures (black) and an empirical model (orange) that combines four different influences. In b) are shown the individual contributions of these influences, namely ENSO (purple), volcanic aerosols (blue), solar irradiance (green) and anthropogenic effects (red). Together the four influences explain 76% (r^2) of the variance in the global temperature observations. Future scenarios are shown as dashed lines. The vertical black dashed lines in a) denote 2014 (A) and 2019 (B), at which times corresponding spatial temperature patterns are shown in Figures 3 and 4.

Figure 2. Compared (on the left) are geographical patterns of surface temperatures averaged over the 5-year period 2001 to 2005 relative to the base period from 1951 to 1980 (following *Hansen et al.,* 2006), determined from observations (top panel) and forecast using a model of the monthly mean observations between 1970 and 1999 (bottom panel). Also shown (on the right) are the (area-weighted) zonal means. Grey regions indicate where temperature observations are considered inadequate for the analysis because less than 50% of monthly mean values are available.

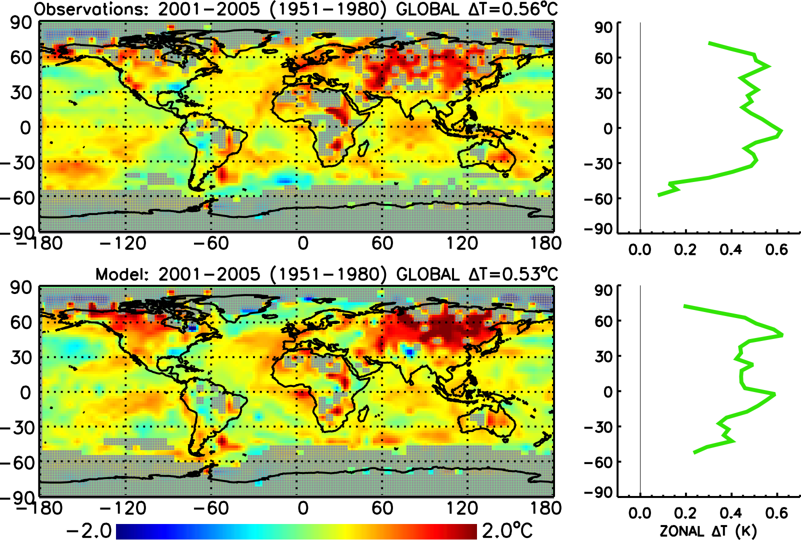
Figure 3. Compared are the regional changes in annual surface temperature forecast for 2014 and 2019, relative to the base period of 1951-1980, corresponding to the global changes in Figure 1. The patterns are derived by using the parameterizations of HadCRUT3v monthly historical surface temperature records

from 1980 to 2008 with ENSO, volcanic and solar activity and anthropogenic forcing on a $5^{o}\times5^{o}$ latitude-longitude grid, together with the forecast anthropogenic and solar time series in Figure 1b. Grey regions indicate where temperature observations are considered inadequate to construct the model because less than 50% of monthly mean values are available.

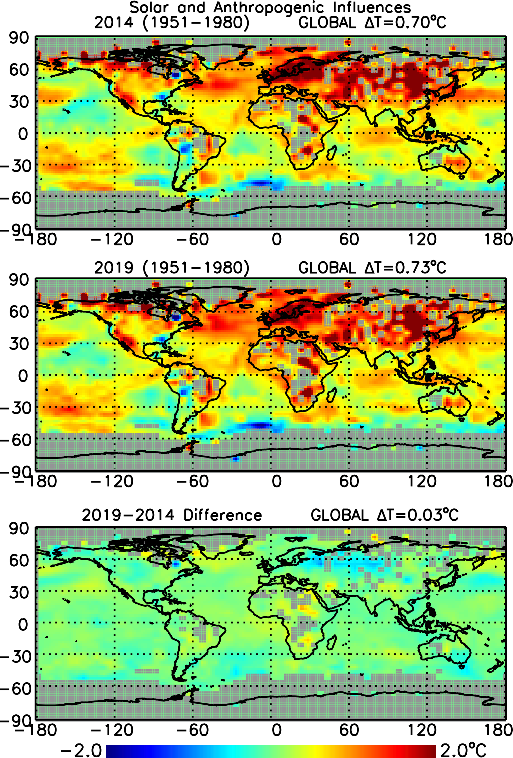
Figure 4. Shown in the upper image is the annual surface temperature pattern estimated for 2014 from the combined anthropogenic and solar effects (Figure 3) with the addition of a Pinatubo-type volcanic eruption with peak impact in 2014. In the middle image, the annual surface temperature pattern estimated for 2019 from the anthropogenic and solar effects (Figure 3) is combined with a "super" ENSO (like that of 1997-98). In the bottom image is the pattern of change resulting from the transition of volcanic cooling to ENSO warming, superimposed on the solar and anthropogenic influences. Grey regions indicate where temperature observations are considered inadequate to construct the model because less than 50% of monthly mean values are available.

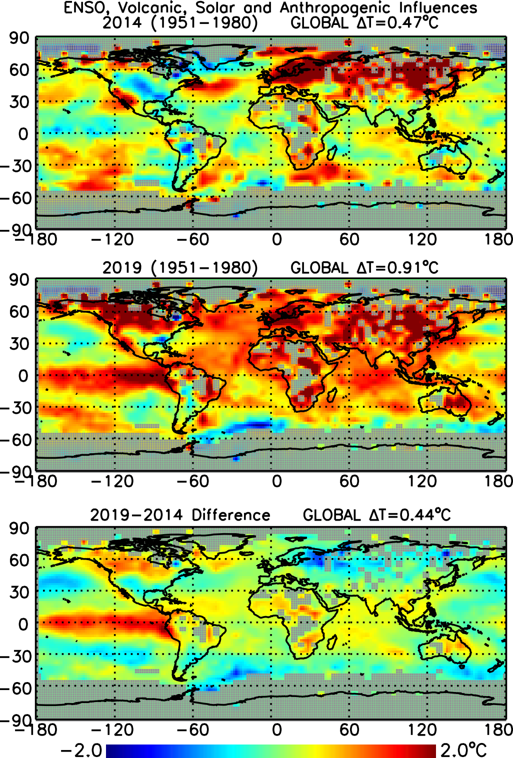


a) Global Surface Temperature
CRU observations
model: r=0.87
Anomaly (°C)
0.8
0.6
0.4
0.2
0.0
−0.2
A
B
base period (1951−1980)
1980
1990
2000
2010
2020
2030
b) Surface Temperature Components
ENSO
Volcanic Aerosols
Anomaly (°C)
0.2
0.1
0.0
−0.1
−0.2
Anthropogenic
Influence
Solar Irradiance
0.6
0.4
0.2
0.0
−0.2



Observations: 2001−2005 (1951−1980) GLOBAL ΔT=0.56°C
Model: 2001−2005 (1951−1980) GLOBAL ΔT=0.53°C
90
60
30
0
−30
−60
−90
−180
−120
−60
0
60
120
180
0.0
0.2
0.4
0.6
ZONAL ΔT (K)
−2.0
2.0°C


Solar and Anthropogenic Influences
2014 (1951-1980) GLOBAL ΔT=0.70°C
2019 (1951-1980) GLOBAL ΔT=0.73°C
2019-2014 Difference GLOBAL ΔT=0.03°C
90 60 30 0 -30 -60 -90
-180 -120 -60 0 60 120 180
-2.0 2.0°C


ENSO, Volcanic, Solar and Anthropogenic Influences
2014 (1951-1980) GLOBAL ΔT=0.47°C
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
2019 (1951-1980) GLOBAL ΔT=0.91°C
2019-2014 Difference GLOBAL ΔT=0.44°C
-2.0
2.0°C