Reconciling anthropogenic climate change with observed temperature 1998–2008

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Given the widely noted increase in the warming effects of rising greenhouse gas concentrations, it has been unclear why global surface temperatures did not rise between 1998 and 2008. We find that this hiatus in warming coincides with a period of little increase in the sum of anthropogenic and natural forcings. Declining solar insolation as part of a normal eleven-year cycle, and a cyclical change from an El Nino to a La Nina dominate our measure of anthropogenic effects because rapid growth in short-lived sulfur emissions partially offsets rising greenhouse gas concentrations. As such, we find that recent global temperature records are consistent with the existing understanding of the relationship among global surface temperature, internal variability, and radiative forcing, which includes anthropogenic factors with well known warming and cooling effects.

aerosol emissions | carbon emissions | coal consumption | black carbon | stratospheric water vapor

Data for global surface temperature indicate little warming between 1998 and 2008 (1). Furthermore, global surface temperature declines 0.2 °C between 2005 and 2008. Although temperature increases in 2009 and 2010, the lack of a clear increase in global surface temperature between 1998 and 2008 (1), combined with rising concentrations of atmospheric CO_2 and other greenhouse gases, prompts some popular commentators (2, 3) to doubt the existing understanding of the relationship among radiative forcing, internal variability, and global surface temperature. This seeming disconnect may be one reason why the public is increasingly sceptical about anthropogenic climate change (4).

Recent analyses address this source of scepticism by focusing on internal variability or expanding the list of forcings. Model simulations are used to suggest that internal variability can generate extended periods of stable temperature similar to 1999–2008 (5). Alternatively, expanding the list of forcings to include recent changes in stratospheric water vapor (6) may account for the recent lack of warming. But neither approach evaluates whether the current understanding of the relationship among radiative forcing, internal variability, and global surface temperature can account for the timing and magnitude of the 1999–2008 hiatus in warming.

Here we use a previously published statistical model (7) to evaluate whether anthropogenic emissions of radiatively active gases, along with natural variables, can account for the 1999–2008 hiatus in warming. To do so, we compile information on anthropogenic and natural drivers of global surface temperature, use these data to estimate the statistical model through 1998, and use the model to simulate global surface temperature between 1999 and 2008. Results indicate that net anthropogenic forcing rises slower than previous decades because the cooling effects of sulfur emissions grow in tandem with the warming effects greenhouse gas concentrations. This slow-down, along with declining solar insolation and a change from El Nino to La Nina conditions, enables the model to simulate the lack of warming after 1998. These findings are not sensitive to a wide range of assumptions, including the time series used to measure temperature, the omission of black carbon and stratospheric water vapor, and uncertainty about anthropogenic sulfur emissions and its effect on radiative forcing (SI Appendix: Sections 2.4–7).

Results

Increasing emissions and concentrations of carbon dioxide receive considerable attention, but our analyses identify an important change in another pathway for anthropogenic climate change —a rapid rise in anthropogenic sulfur emissions driven by large increases in coal consumption in Asia in general, and China in particular. Chinese coal consumption more than doubles in the 4 y from 2003 to 2007 (the previous doubling takes 22 y, 1980–2002). In this four year period, Chinese coal consumption accounts for 77% of the 26% rise in global coal consumption (8). These increases are large relative to previous growth rates. For example, global coal consumption increases only 27% in the twenty two years between 1980 and 2002 (8). Because of the resultant increase in anthropogenic sulfur emissions, there is a 0.06 W/m² (absolute) increase in their cooling effect since 2002 (Fig. 1). This increase partly reverses a period of declining sulfur emissions that had a warming effect of 0.19 W/m² between 1990 and 2002.

The increase in sulfur emissions slows the increase in radiative forcing due to rising greenhouse gas concentrations (Fig. 1). Net anthropogenic forcing rises 0.13 W/m² between 2002 and 2007, which is smaller than the 0.24 W/m² rise between 1997 and 2002. The smaller net increase in anthropogenic forcing is accompanied by a 0.18 W/m² decline in solar insolation caused by the declining phase of the eleven year solar cycle, such that the sum of modeled forcings increases little after 1998 and declines after 2002 (Fig. 1). This cooling effect is amplified by a net increase in the Southern Oscillation Index (SOI) (9).

The effect of changes in anthropogenic and natural forcings on global surface temperature after 1998 is assessed with a statistical model that is estimated with a sample that ends in 1998. As indicated in Fig. 2, the model simulation for global surface temperature is consistent with observations. In short, net forcing does not rise between 1999 and 2008, nor does global surface temperature. The hypothesis that the post 1998 period is consistent with the existing understanding of anthropogenic climate change is evaluated with a test statistic that evaluates the null hypothesis that the long-run relationship between global surface temperature and radiative forcing is unchanged after 1998. We fail to reject this null in two of three sample periods analyzed (SI Appendix: Table S3 and Section 2.3).
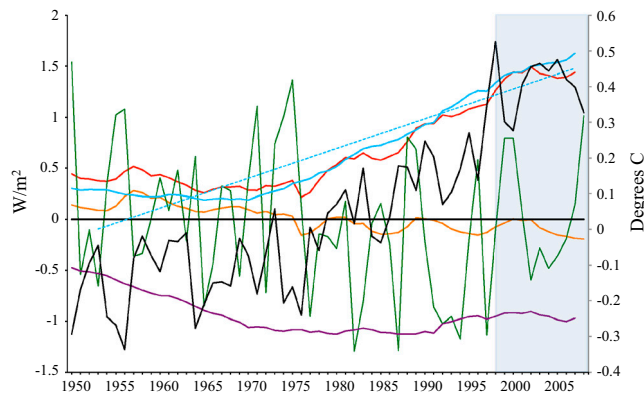
Fig. 1. Radiative forcing of anthropogenic sulfur emissions (purple line), net anthropogenic forcing (blue line), linear estimate of net anthropogenic forcing (blue dash), total radiative forcing (red line), radiative forcing of solar insolation (orange line), and observed temperature (black). The SOI (divided by 10) is given in green. SOI data are presented as annual mean sea level pressure anomalies at Tahiti and Darwin. Post-1998 period of interest (highlighted gray).

The 95% confidence intervals in Figs. 2 and 3 represent uncertainty in the statistical estimates of the regression model for observed paths of forcings, SOI, and volcanic sulfates. Uncertainty about the forcings calculated with observed values for greenhouse gas concentrations, solar insolation, and the SOI is small relative to the uncertainty about observations for anthropogenic sulfur emissions. Sensitivity analysis indicates that uncertainty about the measure of surface temperature, anthropogenic sulfur emissions, or its conversion to radiative forcing has a small effect on the model's simulated forecast for global surface temperature (*SI Appendix: Section 2.4 and Figs S3, S4*). Similarly, the year in which the simulation starts (*SI Appendix: Fig. S6*) or the sample period used to estimate the model (*SI Appendix: Fig. S5*) has little effect. As expected, the ability of the model to simulate observed changes in global surface temperature after 1998 improves as less reliable observations from the early portion of the sample period are eliminated from the estimation sample (Fig. 2). This improved accuracy is especially clear for the sample period that starts in 1960, when direct measurements of greenhouse gas concentrations become available and temperature measures have
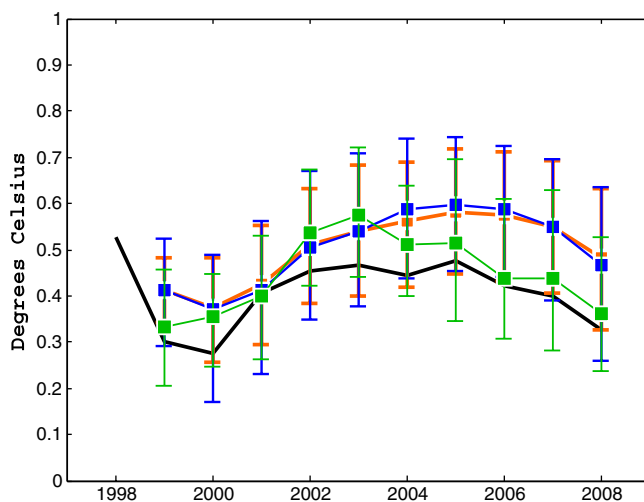
better coverage and are more reliable. The improved accuracy associated with more reliable measures of radiative forcing and temperature is consistent with the hypothesis that anthropogenic activities, which alter the Earth's heat balance, affect global surface temperature.

Drivers of global surface temperature after 1998 are identified by simulating the model with observed values for the independent variables of interest and estimated parameters, while the 1999–2008 values for the other variables are held at their 1998 level. To identify the effects of human activity on temperature, we simulate the model (estimation sample 1960–1998) with post 1998 values of solar insolation, SOI, and volcanic sulfates held at their 1998 level while allowing greenhouse gas concentrations and sulfur emissions to evolve as observed. On net, human activity has a small positive effect on temperature after 1999 because of slight increases in anthropogenic forcing and on-going adjustments to postindustrial increases in anthropogenic forcings (Fig. 3). Note that observed temperature moves below the 95% confidence interval in 2000 and 2008 for the global surface temperature as driven by anthropogenic changes only (red line).

Conversely, holding greenhouse gas concentrations and sulfur emissions at their 1998 values and allowing solar insolation, SOI, and volcanic sulfates to evolve as observed generates a forecast that is consistent with the observed pattern of temperature change. Between 1998 and 2000, global surface temperature declines due to a change in circulation from an El Nino to a La Nina and a decline in insolation associated with the eleven year solar cycle. Another El Nino warms the planet in 2002. The planet cools thereafter as solar insolation declines and a strong La Nina occurs in 2008.

Discussion

Our explanation for the lack of warming can be evaluated against alternative hypotheses. A recent analysis argues that the concentration of water vapor in the stratosphere decreases by about 10% after 2000 and this slows the rate of temperature increase by about 25% relative to the increase that would have occurred due to CO_2 and other greenhouse gases (6). If this hypothesis is correct, the omission of stratospheric water vapor (or black carbon) would bias the statistical estimates and/or the model forecast.

To evaluate this hypothesis, we test whether stratospheric water vapor (or black carbon) is related to either; (*i*) errors in the long-run relation between radiative forcing and surface temperature, (*ii*) errors in the error correction model that represents

Fig. 2. Observed temperature (black line), the out-of-sample simulation generated by the model estimated with a sample period 1864–1998 (orange line), the out-of-sample simulation generated by the model estimated with a sample period 1920–1998 (blue line), and the out-of-sample simulation generated by the model estimated with a sample period 1960–1998 (green line). Error bars represent 95% confidence intervals (see *SI Appendix*).
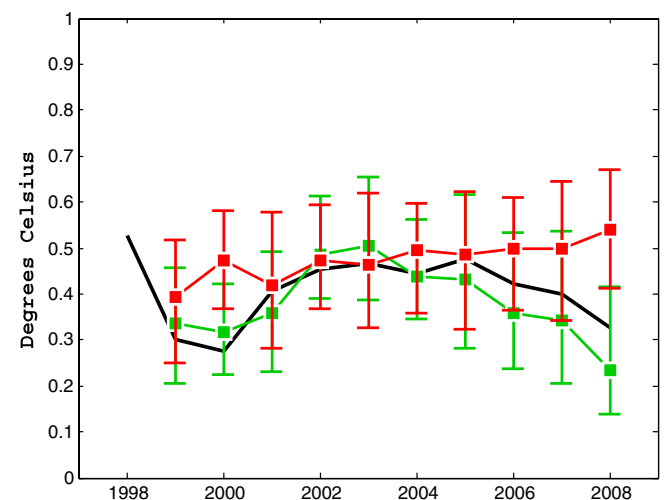

Fig. 3. Observed temperature (black line), the out-of-sample forecast for global surface temperature driven by anthropogenic changes in radiative forcing (red line) and the out-of-sample forecast for global surface temperature driven by natural variables (solar insolation, SOI, and volcanic sulfates) (green line). Error bars represent 95% confidence intervals (see *SI Appendix*).

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the dynamics by which surface temperature adjusts to long- and short-run determinants, or (iii) errors in the forecast that is generated by the full statistical model (*SI Appendix: Section 2.7*). For stratospheric water vapor, the analysis suggests a small negative correlation with the error from the long-run cointegrating relation, but the negative sign is inconsistent with the warming effect of stratospheric water vapor. We find no relation between stratospheric water vapor and error in the dynamics by which surface temperature adjusts to long- and short-run determinants, or the simulation errors generated by the full statistical model. For black carbon there is no relation with the residuals from the statistical estimates, but there is evidence for a negligible ($r^2 = 0.017$) positive correlation between black carbon and the forecast error. Together, these results suggest that stratospheric water vapor (and black carbon) does not have a statistically significant effect on surface temperature relative to the forcings included in the statistical model. The results are moot regarding the effect of stratospheric water vapor (or black carbon) on global surface temperature in general.

Another explanation for the recent hiatus in warming focuses on the internal variability of the climate system. To quantify the effect of internal variability, simulations generated by climate models are analyzed to determine the probability of ten year periods with zero or negative trends in surface temperature (5). Analysis of a twentieth century simulation indicates that ten year periods with zero or negative temperature trends are likely ($p > 0.05$). This relatively high probability is partially attributed to natural variability.

While it is possible that internal variability is responsible for the 1999–2008 hiatus in warming, we suggest an alternative interpretation of the simulations described by ref. 5 that is consistent with our results. During the twentieth century, our measure of net anthropogenic forcing does not rise steadily. For example, there is no net increase in anthropogenic forcing between 1944 and 1976; this period is associated with stable or declining surface temperatures (Fig. 1). This balance probably is not affected by the omission of black carbon emissions because they increase little between 1940 and 1970 relative to increases during other decades of the 1850–2000 period for which data are available (10). Under these conditions, periods of zero or negative ten year temperature trends reported by ref. 5 may coincide with prolonged periods when anthropogenic forcing is stable or declining, and are therefore not likely generated by internal variability. Our interpretation is bolstered by the analysis of scenario A2 from the IPCC Special Report on Emissions Scenarios in which net anthropogenic forcing increases steadily. For these simulations, results indicate that ten year periods when temperature has no trend, or a negative trend, are unlikely- less than 5% (5). This lack of stable periods implies that the higher probability of ten year periods with little or no temperature increase in the twentieth century simulations are associated with prolonged periods when forcings do not rise. Together these results are consistent with ours- that a slowing in net forcing due to both anthropogenic activities and natural variability is responsible for the 1999–2008 hiatus in warming.

The finding that declining solar insolation and El Niño/South Oscillation (ENSO) events dominate anthropogenic changes and therefore create the 1999–2008 pattern in surface temperature also is generated by another statistical model (11, 12). But this model represents net anthropogenic forcing with a deterministic time trend between 1953 and 2007. This representation is flawed both statistically, because time series that contain a stochastic trend *cannot* be approximated by a deterministic trend (13), and historically, because the time trend overstates gains in radiative forcing during the 1950's and overstates gains during the last 10 y (Fig. 1). As such, it cannot capture the slow-down in net anthropogenic forcings that allows the effects of declining solar

radiation and changes from El Nino or La Nina to dominate the 1999–2008 period.

Conclusion

The finding that the recent hiatus in warming is driven largely by natural factors does not contradict the hypothesis: "most of the observed increase in global average temperature since the mid 20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations (14)." As indicated in Fig. 1, anthropogenic activities that warm and cool the planet largely cancel after 1998, which allows natural variables to play a more significant role. The 1998-2008 hiatus is not the first period in the instrumental temperature record when the effects of anthropogenic changes in greenhouse gases and sulfur emissions on radiative forcing largely cancel. In-sample simulations indicate that temperature does not rise between the 1940's and 1970's because the cooling effects of sulfur emissions rise slightly faster than the warming effect of greenhouse gases. The post 1970 period of warming, which constitutes a significant portion of the increase in global surface temperature since the mid 20th century, is driven by efforts to reduce air pollution in general and acid deposition in particular, which cause sulfur emissions to decline while the concentration of greenhouse gases continues to rise (7).

The results of this analysis indicate that observed temperature after 1998 is consistent with the current understanding of the relationship among global surface temperature, internal variability, and radiative forcing, which includes anthropogenic factors that have well known warming and cooling effects. Both of these effects, along with changes in natural variables must be examined explicitly by efforts to understand climate change and devise policy that complies with the objective of Article 2 of the 1992 United Nations Framework Convention on Climate Change to stabilize "greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference in the climate system."

Methods

To estimate the statistical model through 1998 and simulate global surface temperature through 2008, we update the datasets used to estimate the original model (15). These data include annual observations for the atmospheric concentration of five greenhouse gases as measured by instruments located at Mauna Loa, CO_2 (16) and Samoa; CH_4, N_2O, CFC11, and CFC12 (17). Time series for solar insolation (18), SOI (19), and the radiative forcing of volcanic sulfates (20) are updated with values from sources that are used to generate the original dataset. Data for anthropogenic sulfur emissions (21) are calculated using measures of economic activity that emit sulfur (see *SI Appendix: Section 1*). Variables other than SOI are converted to radiative forcing using formulae (22, 23) that are described in Stern and Kaufmann (24). For sulfur, the conversion to radiative forcing includes both direct and indirect effects.

To update the time series for anthropogenic sulfur emissions (21), we obtain the share of 2000 global sulfur emissions for six categories of sulfur emitting activities; coal consumption, petroleum consumption, metal smelting, marine bunkers, natural gas consumption, and other (25). These shares are used to update the last observation ('00) for emissions by updating each category of emissions with data that relate to anthropogenic activities (e.g., sulfur emissions from coal consumption are updated based on global data for coal consumption). A detailed description of the methodology and its sensitivity to assumptions about the rate at which sulfur is removed from the emission stream are given in the *SI Appendix*.

The original statistical model (7) is estimated with data through 1994. Here, we update the model by estimating it with data through 1998. The selected sample ends just before the recent period of slowed warming. As such, the parameter estimates do not use information about the post-1998 period. Model simulations reflect these pre-1998 parameters and post-1998 observed levels of radiative forcings, SOI, and volcanic sulphates.

Estimation results through 1998 confirm original model findings (*SI Appendix: Table S3*). Global surface temperature cointegrates with aggregate radiative forcing, which includes the effect of greenhouse gas concentrations, sulfur emissions, and solar insolation. Cointegration indicates that internal climate variability and/or the omission of some components of radiative forcing (e.g., stratospheric water vapor, black or organic carbon, nitrite aerosols, etc.) do not impart a stochastic or deterministic trend that would

interfere with the interpretation of temperature changes at the subdecadal scale (*SI Appendix*).

The physical interpretation of the statistical model is available in papers that describe the statistical model. For example, the reliability of data for emissions/concentrations and their conversion to radiative forcing is validated by our inability to reject a restriction that equalizes the temperature effect of a change in radiative forcing across gases (7). That same reference finds that the statistical estimates for the temperature effect of volcanic sulfates and ENSO (and effects of ENSO on atmospheric CO_2) are consistent with estimates derived from climate models and empirical analyses. Finally, the statistical estimate for the transient climate response falls within the range of estimates generated by climate models run for the Coupled Model Intercomparison Project (CMIP) (26). Furthermore, the statistical methodology that is used to estimate the model can successfully recover the values for the transient climate response from temperature simulations generated by the coupled atmosphere-ocean general circulation models run for CMIP (26). As such, the statistical model provides a direct and transparent methodology to test whether changes in anthropogenic and natural forcings can account for the recent pattern of temperature changes.

The model cannot be used to close the planet's energy balance and so is moot on issues such as the energy missing from the global energy budget

between 2004 and 2008 (27). This inability has little effect on the results—statistical estimates are based on the notion of cointegration, which uses stochastic trends as fingerprints to match temporal changes in temperature and radiative forcing. This matching does not depend on energy balance at any point in time. Nonetheless, the notion of energy balance can be used to evaluate importance of anthropogenic aerosols described by the statistical model. For example, quarterly anomalies for net top of the atmosphere radiation (28) show no statistically measurable change between 2000 and 2008, which is consistent with the lack of a statistically measurable change in our estimate for radiative forcing between 2000 and 2007 (*SI Appendix: Section 2.8*). Furthermore, estimating the direct and indirect aerosol effects (29) through 2008 as a residual from the Earth's energy balance (as was done for 1954–2000) would generate results that either support or contradict the increased importance of anthropogenic sulfur emissions discussed above.

The *SI Appendix* on research methods is available online.

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