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Deducing Multi-decadal Anthropogenic Global Warming Trends Using Multiple Regression Analysis

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ABSTRACT

In order to unmask the anthropogenic global warming trend imbedded in the climate data, multiple linear regression analysis is often employed to filter out short-term fluctuations caused by El Nino-Southern Oscillation (ENSO), volcano aerosols and solar forcing. These fluctuations are unimportant as far as their impact on the deduced multidecadal anthropogenic trends is concerned: ENSO and volcano aerosols have very little multi-decadal trend. Solar variations do have a secular trend, but it is very small and uncertain. What is important, but is left out of all multiple regression analysis of global warming so far, is a long-perioded oscillation called the Atlantic Multi-decadal Oscillation (AMO). When the AMO Index is included as a regressor (i.e. explanatory variable), the deduced multi-decadal anthropogenic global warming trend is so impacted that previously deduced anthropogenic warming rates need to be substantially revised. The deduced net anthropogenic global warming trend has been remarkably steady and statistically significant for the past 100 years.

1. Introduction

The observed global warming is non- uniform. After a period of cooling in the 1960s and 70s, the global warming accelerated until 2005 (Solomon *et al.* [2007]). The most recent speculation concerns the possible "stalling" of the rate of warming of the global-mean surface temperature. As shown in Figure 1 of Foster and Rahmstorf [2011] , 1998 was the warmest year in some datasets (such as CRU), while in others it was 2005 or 2010 (NCDC or GISS). Undoubtedly short-term natural climate fluctuations play a role: The "super" El Nino in 1998 made that year either the warmest or close to the warmest on record and the La Nina in 2008 contributed to that year being not as warm. It is understood that these, and possibly other, natural fluctuations should be filtered out to reveal the underlying anthropogenic warming. Multiple Linear Regression (MLR) analysis is often employed for this purpose. Typical *regressors* (also called explanatory or predictor variables) are El Nino-Southern Oscillation (ENSO), volcano aerosol optical depth, total solar irradiance (TSI) (11-year solar cycle plus the secular solar forcing trend) and the anthropogenic warming trend. These are specified as a function of time. MLR is used to fit the observed temperature time series using these regressors, with the residual assumed to be a white or red noise. When the residual is tested to be a noise, the MLR provides an explanation of the observed time series as comprised of these known variations plus climate noise.

There are two approaches to constructing the anthropogenic warming regressor. One, typified by the work of Lean and Rind [2008] , constructs the time series of anthropogenic regressor from an inventory of greenhouse gas concentrations, tropospheric aerosols and land surface plus snow albedo changes, and was the same as that used in the GISS model for simulating 20th century climate (Hansen [2007]). This approach predetermines the time behavior of the anthropogenic warming, even though the uncertainty in the tropospheric aerosol is high. This construction yields a strong anthropogenic warming rate after 1978 from a much slower pace before that. Their conclusion that the anthropogenic warming rate has accelerated, from the 50-year trend of 0.136±0.003°C/decade to the 25-year trend of 0.199±0.005°C/decade, is a direct consequence of the shape in time of the anthropogenic regressor used. To answer specifically whether the anthropogenic warming has slowed in recent years, Foster and Rahmstorf [2011] takes a second approach. They replaced the anthropogenic time series by a linear function of time. The linear trend is determined by the MLR process. Then the regressed linear trend is added back to the residual, and the sum is displayed. They called this sum the "adjusted data". If the anthropogenic warming rate is nonuniform, it should show up as such in the sum. Nevertheless they found that the anthropogenic warming rate has been "remarkably steady" for the period analyzed, 1979-2010. We shall first use this second approach and reexamine the deduced anthropogenic warming rate. This approach has the advantage of not predetermining the answer, allowing for the possibility that we may not know how to construct the anthropogenic forcing index precisely.

2. The residual in the multiple regression analysis

Foster and Rahmstorf [2011] studied five datasets: three surface temperature records and two satellite records. The anthropogenic warming rates are found to be consistent with each other. The 32-year trend for the adjusted global mean surface temperature from HadCRUT3v is 0.170°C/decade. The results are approximately the same using other surface temperature records: GISS at 0.171°C/decade and NCDC at 0.175°C/decade. We have repeated their analysis for the short period 1979-2010 and found very similar results. The results shown here are for the longer period of 1856-2010 using the latest global mean data HadCRUT4 (Morce *et al.* [2012]).

The explanatory variables used in our analysis include the total solar irradiance (TSI), volcano aerosol optical depth (Sato *et al.* [1993]), cold tongue index (CTI) for the ENSO effect (available at http://jisao.washington.edu/data/cti/), and a linear trend. The Multivariate ENSO Index (MEI) that Foster and Rahmstorf [2011] used is available only for the recent decades, and so we used the Cold Tongue Index instead, which is available for the longer record that we will be examining. We characterize the solar variability by the TSI reconstruction up to 2009 based on Lean et al. (2005) and Wang *et al.* [2005] . Its recent values are filled in using the daily measurements from the Total Irradiance Monitor (TIM) on NASA's Solar Radiation and Climate Experiment (SORCE) available from http://lasp.colorado.edu/sorce/data/tsi_data.htm (Kopp and Lean [2011]). We do not use a sinusoid with an annual period as a regressor as in Foster and Rahmstorf [2011] . The noise model is adaptive autoregressive noise of order p (AR(p)) (vs their ARMA(1,1) model).

Figure 1a shows the *adjusted data* (with ENSO, volcano aerosols and solar influence removed) for the longer period 1856-2010, following the analysis of Foster and Rahmstorf [2011] . The recent 32-year trend is found to be 0.169±0.019°C/decade, very close to that found by Foster and Rahmstorf [2011] . It also seems to be "remarkably steady", with no acceleration or stalling of the global warming trends. However, over the extended 160-year period, one can clearly see that there is a long-perioded oscillation still present in the residual. The running-time mean (in blue) reveals a 70-year oscillation in the global mean temperature of a significant structured variation of 0.3°C that has not been "explained" by the MLR analysis. This oscillation happens to be in a positive half cycle during the 32 years analyzed by Foster and Rahmstorf [2011] . Possibility exists that the oscillation was treated as a trend in the shorter record.

Folland *et al.* [1984]; Schlesinger and Ramankutty [1994] were the first to point out that there is a multi-decadal oscillation in the global mean-temperature record. Wu *et al.* [2011] , using the method of Empirical Mode Decomposition (Wu and Huang [2009]; Huang *et al.* [1998]), found that this mode has a period of 65 years in the 150 year global mean temperature. They called this mode the Atlantic Multi-decadal Oscillation (AMO), following the previous work of Delworth and Mann [2000] that this global-mean oscillation has its origin in the North Atlantic. They further showed the impact that this mode has on the perceived global warming trend: when the AMO is removed as an oscillatory mode, the remaining trend is smaller, at 0.08° C/decade since 1980.

3. A new multiple regression analysis

The inset of **Figure 1a** shows the detrended running-time mean in the adjusted data from Figure 1a (the blue line) against the AMO Index (Enfield *et al.* [2001]), which is defined as the detrended sea-surface temperature averaged over the North Atlantic. We see that the two follow each other closely. **Figure 1b** shows the result when we repeat the MLR analysis, but now include the smoothed AMO Index as an additional regressor (http://www.esrl.noaa.gov/psd/data/timeseries/AMO/). The global-mean temperature adjusted this way shows mostly a monotonic trend with some scatter. This anthropogenic warming has been remarkably steady since 1910. The 100-year trend is 0.068±0.013° C/decade, 75-year trend is 0.080±0.015° C/decade, and the 50-year is 0.083±0.011°C/decade .The 32-year trend now is 0.070±0.019°C/decade, which is less than one-half the value found by Foster and Rahmstorf [2011] , and almost one-third that found by Lean and Rind [2008] . It is consistent with the finding of Wu *et al.* [2011] . Our linear trends are found to be statistically significant and deterministic according to the Woodward and Gray [1995] test.

We do not wish to conclude that the anthropogenic warming rate has slowed, from the 50-year trend of 0.083 °C/decade to the 32-year trend of 0.070°C/decade. When the error bars are taken into account, there is no basis for that conclusion. The conclusion that we can draw is that for the past 100 years, the net anthropogenic trend has been steady at approximately 0.08 °C/decade.

4. Justification for including the AMO as a regressor

The remaining question is whether the AMO is a natural oscillation or the consequence of a time varying anthropogenic forcing. Recently Booth *et al.* [2012] simulated 76% of the two cycles of the AMO in the industrial era using the HadGEM2-ES model and attributed the North Atlantic variability to the indirect effect of anthropogenic aerosol's time varying forcing. However, Zhang *et al.* [2012] pointed out that the indirect aerosol effects in Booth *et al.* [2012] are probably overestimated, and the time and spatial signatures in the model's upper ocean are contrary to the observed.

Using 330 years of multi-proxy data of near global coverage, Delworth and Mann [2000] found almost 4.5 cycles of the AMO, with 2 cycles in the pre-industrial era. Tung and Zhou [2012] found 5 cycles of 70-year oscillation in the world's longest instrumental temperature record from Central England. These long records argue in favor of the natural and recurrent nature of the AMO.

There are a couple realizations of a coupled atmosphere-ocean general circulation model calculation containing an AMO of the right phase as the observed (Delworth and Knutson [2000]; Delworth and Mann [2000]), but many other realizations that do not. So when ensemble averaged, this internal variability is much reduced. Nevertheless it shows that some models can produce such a multi-decadal oscillation without anthropogenic forcing. To circumvent the known difficulty of model internal variability not always of the right phase and amplitude as the one realization that is our observed world, DelSol *et al.* [2011] analyzed the control runs of the coupled atmosphere-ocean general circulation models in the CMIP3 archive (Meehl *et al.* [2007]). They found, by maximizing average predictability time, a dominant spatial pattern that they called Internal Multi-decadal Pattern, which is centered at the North Atlantic but also extends to the Pacific. When the global temperature data is projected onto this spatial pattern they obtain 2.5 cycles of a multi-decadal oscillation very similar to the AMO Index. Their result suggests that the oscillation is not anthropogenically forced. The variability appears to be caused by fluctuations in the thermohaline circulation (Dima and Lohmann [2007]; Delworth and Mann [2000]; Enfield *et al.* [2001]; Knight *et al.* [2005]; Schlesinger and Ramankutty [1994]; Wei and Lohmann [2012]; Semenov *et al.* [2010]).

5. The shape of the anthropogenic regressor

We argue that the time shape of the anthropogenic forcing used by Lean and Rind [2008] is not consistent with the observed anthropogenic response (see **Figure 2a)**. The evidence is in the residual of their MLR, which was not shown. Compared to the almost linear behavior of the deduced anthropogenic trend in our Figure 1b, their assumed trend accelerated after the 1970s. The residual of the MLR analysis repeated by us using monthly HadCRUT4 global mean temperature is shown in **Figure 2b.** (The result is similar using HadCRUT3v, except for the much sharper data discontinuity in 1945 that was not yet corrected (Thompson *et al.* [2008]).) The residual, which should only consist of climate noise if the MLR is successful, shows a negative trend after 1970 and a positive trend before that time, suggesting that their regressor for anthropopgenic forcing is increasing too rapidly after 1970 and too slow before that time. Since the MLR analysis depends critically on the time behavior of the regressors assumed, the spatial pattern deduced could be wrong if the real anthropogenic warming rate is not the same as what was assumed. One of the highlighted results of Lean and Rind's MLR analysis is that the deduced spatial patterns of anthropogenic warming and solar forcing "differ distinctly" from those indicated by IPCC. In particular, instead of finding polar amplification of warming, which is a robust feature across IPCC models, their deduced warming pattern is more pronounced between 45°S and 50°N than at higher latitudes.

6. Conclusion

It is pointed out that the Atlantic Multidecadal Oscillation, a likely natural and recurrent phenomenon, has not been taken into account in any Multiple Linear Regression analysis of the global warming trends using observational data in published literature. Yet over any multi-decadal period the AMO is the most important factor affecting the deduced "anthropogenic trend", since other, shorter-term internal variability, such as ENSO or volcano aerosols, usually do not contain any multi-decadal trend, and solar forcing's secular trend is small. When the AMO is included, in addition to the other explanatory variables such as ENSO, volcano and solar influences commonly included in the multiple linear regression analysis, the recent 50-year and 32-year anthropogenic warming trends are reduced by a factor of at least two. There is no statistical evidence of a recent slow-down of global warming, nor is there evidence of accelerated warming since the mid-20th century. The anomalous early twentieth century warming is also explained as caused by the AMO's upswing on top of the same anthropogenic warming trend. This deduced time behavior of anthropogenic warming is different from that previously constructed by GISS and used by Lean and Rind [2008] in deducing the latitudinal structure of anthropogenic warming.

It is known (see Benestad and Schmidt [2009]) that the method of MLR may give erroneous attribution for small forcing, and for collinear forcings. Secular solar forcing is small and, with a positive trend may be collinear with greenhouse forcing. So this method should not be relied upon for attribution of solar response. Fortunately, solar secular trend is so small that whether or not it is included in MLR does not affect the other results. Furthermore, MLR is used here only as a means to "adjust" the data, following the approach of Foster and Rahmstorf [2011] . That is, to remove fluctuations to better reveal the underlying trend. Whether or not this method is successful can be judged by the reduced scatter in the adjusted data and by the residual's resemblance to random noise.

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References

Benestad, R. E. and G. A. Schmidt, 2009: Solar trends and global warming. *J. Geophys. Res.*, **114,** doi:10.1029/2008JD011639.

Booth, B. B. B., N. J. Dunstone, P. R. Halloran, T. Andrews, and N. Bellouin, 2012: Aerosols implicated as a prime dirver of twentieth-century North Atlantic climate variability. *Nature*, **484,** 228-232.

DelSol, T., M. K. Tippett, and J. Shukla, 2011: A significant component of unforced multidecadal variability in the recent acceleration of global warming. *J. Climate*, **24,** 909-026.

Delworth, T. L. and M. E. Mann, 2000: Observed and simulated multidecadal variability in the Northern Hemisphere. *Clim. Dyn.*, **16,** 661-676.

Delworth, T. L. and T. R. Knutson, 2000: Simulation of Early 20th Century Global Warming. *Science*, **287,** 2246-2250.

Dima, M. and G. Lohmann, 2007: A Hemispheric Mechanism for the Atlantic Multidecadal Oscillation. *Journal of Climate*, **20,** 2706-2719.

Enfield, D. B., A. M. Mestas-Nunez, and P. J. Trimble, 2001: The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U. S. *Geophys. Research. Lett.*, **28,** 2077-2080.

Folland, C. K., D. E. Parker, and F. E. Kates, 1984: Worldwide marine temperature fluctuations 1856-1981. *Nature***,** 670-673.

Foster, G. and S. Rahmstorf, 2011: Global temperature evolution 1979-2010. *Environmental Research Letters*, **6,** 1-8.

Hansen, J. e. a., 2007: Climate simulations for 1880-2003 with GISS modelE. *Clim. Dyn.*, **29,** 661-696.

Huang, N. E., Z. Shen, S. R. Long, M. L. C. Wu, H. H. Shih, Q. N. Zheng, N. C. Yen, C. C. Tung, and H. H. Liu, 1998: The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. *Proc. R. Soc. London Ser. A-Math. Phys. Eng. Sci.*, **454,** 903-995.

Knight, J. R., R. J. Allan, C. K. Folland, and M. Vellinga, 2005: A signature of persistent natural thermohaline circulation cycles in observed climate. *Geophys. Research. Lett.*, **32**.

Kopp, G. and J. Lean, 2011: A new, lower value of Total Solar Irradiance: evidence and climate significance. *Geophys. Research. Lett. Frontier article*, **38,** doi:10.1029/2010GL045777.

Lean, J. and D. Rind, 2008: How natural and anthropogenic influences alter global and regional surface temperatures: 1889-2006. *Geophys. Research. Lett.*, **35**.

Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor, 2007: The WCRP CMIP3 multi-model dataset: A new era in climate change research. *Bull. Amer. Meteorol. Soc.*, **88,** 1383-1394.

Morce, C. P., J. J. Kennedy, N. A. Rayner, and P. D. Jones, 2012: Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: the HadCRUT4 data set. *J. Geophys. Res.***,** doi:10.1029/2011JD017187.

Sato, K., J. E. Hansen, M. P. McCormick, and J. B. Pollack, 1993: Stratospheric aerosol optical depths, 1850-1990. *J. Geophys. Res.*, **98,** 22987-22994.

Schlesinger, M. E. and N. Ramankutty, 1994: An oscillation in the global climate system of period 65-70 years. *Nature*, **367,** 723-726.

Semenov, V. A., M. Latif, D. Dommenget, N. Keenlyside, A. Strehz, T. Martin, and W. Park, 2010: The impact of North Atlantic-Arctic multidecadal variability on Northern Hemisphere surface air temperature. *J. Climate*, **23,** 5668-5677.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Avery, M. Tignor, and H. L. Miller, Eds., 2007: *Climate Change 2007: Working Group I:The Physical Science Basis*. 996 pp.

Thompson, D. W. J., J. J. Kennedy, J. M. Wallace, and P. D. Jones, 2008: A large discontinuity in the mid-twentieth century in observed global mean surface temperature. *Nature*, **453,** doi:10.1038/nature06982.

Tung, K. K. and J. Zhou, 2012: Using Data to Attribute Episodes of Warming and Cooling in Instrumental Record. *Proc. Natl. Acad. Sci., USA*, **submitted**.

Wang, Y.-M., J. Lean, and N. R. Sheeley Jr, 2005: Modeling the Sun's magnetic field and irradiance since 1713. *Astrophys. J.*, **625,** 522-538.

Wei, W. and Lohmann, 2012: Simulated Atlantic Multidecadal Oscillation during the Holocene. *J. Climate*, doi:10.1175/JCLI-D-11-00667.1.

Woodward, W. A. and H. L. Gray, 1995: Selecting a Model for Detecting the Presence of a Trend. *Journal of Climate*, **8,** 1929-1937.

Wu, Z. and N. E. Huang, 2009: Ensemble empirical mode decomposition: a noise-assisted data analysis method. *Adv. Adapt. Data Anal.*, **1,** 1-14.

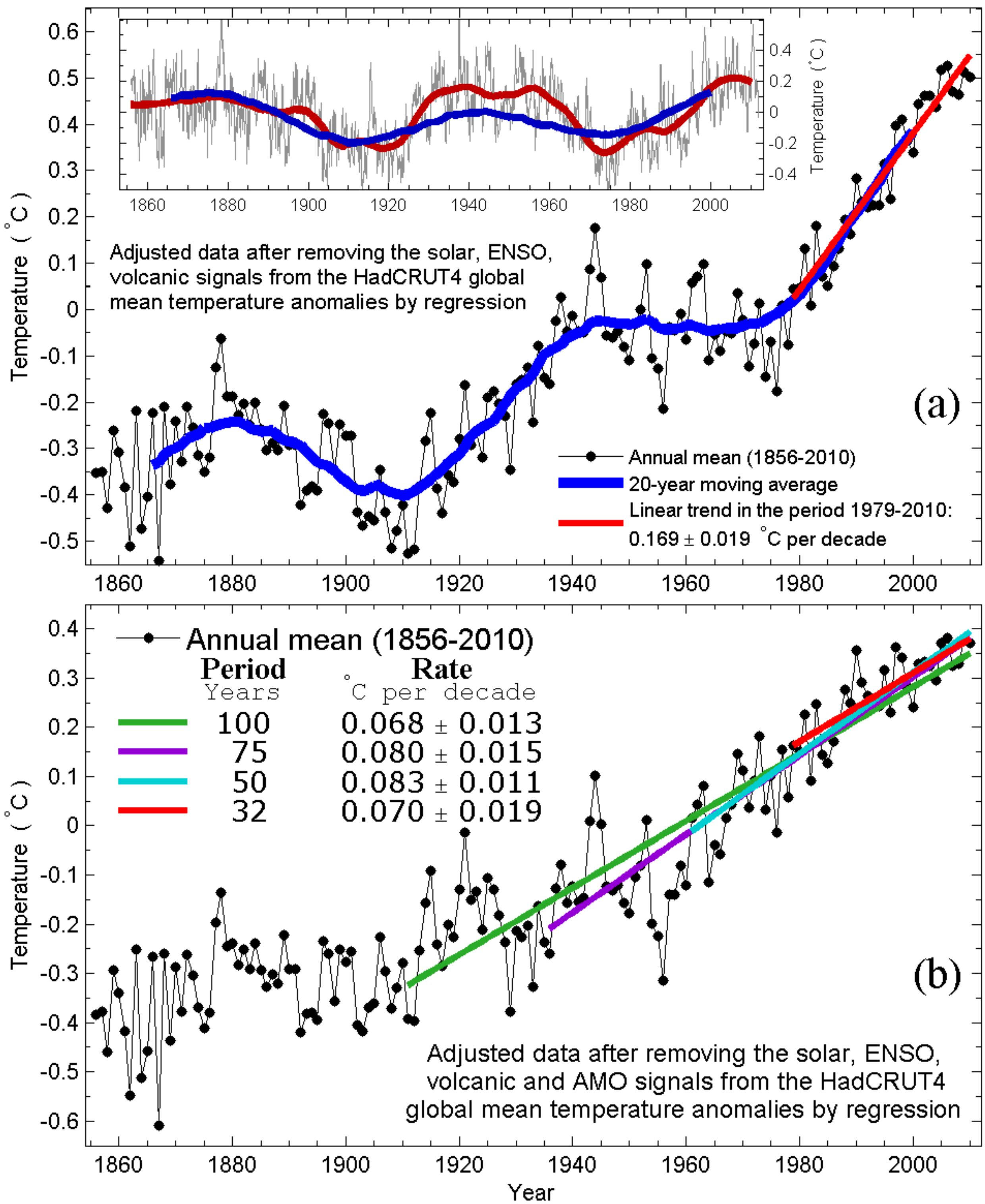
Wu, Z., N. E. Huang, J. M. Wallace, B. Smoliak, and X. Chen, 2011: On the time-varying trend in global-mean surface temperature. *Clim. Dyn.*

Zhang, R., T. Delworth, R. Sutton, D. L. R. Hodson, K. W. Dixon, I. M. H. Held, Y., J. Marshall, Y. Ming, R. Msadeck, J. Robson, A. J. Rosati, M. Ting, and G. A. Vecchi, 2012: Have aerosols caused the observed Atlantic Multidecadal Variability? *Nature*, **submitted**.

Figure Legend

Figure 1. a. Adjusted global-mean annual-mean temperature for the period 1856-2010, after ENSO, volcano aerosol and solar influences have been removed by regression. The order of the noise is found to be *p*=4.The 20-year moving average is shown in blue and the linear trend is fitted to the period 1979-2010 in red. **Inset:** The detrended running-time mean of the adjusted data in Figure 1a in blue. The AMO Index to be used later in the multiple linear regression is in red. The thin line is the raw monthly AMO Index from http://www.esrl.noaa.gov/psd/data/timeseries/AMO/. The red curve is a smoothed version of it using a modified running time mean, called Locally Weighted Scatterplot Smoothing (LOWESS), that allows the mean index to be extended to the beginning and end of the record of the monthly data. Quadratic fitting over a 25-year period is used. Time lags are found to be 5 months for volcano and ENSO responses. **b.** Adjusted global-mean annual-mean temperature, after ENSO, volcano, solar and AMO influences have been removed by regression. *p*=2.

Figure 2. Multiple linear regression analysis using the same regressors and time lags, and white noise model as Lean and Rind [2008] , and monthly HadCRUT4 global mean temperature. **a** shows the adjusted data after removal of solar, ENSO, volcano and AMO. It should contain the anthropogenic trend and climate noise. Their prescribed anthropogenic forcing index is superimposed in green. **b**. The residual is what remains after removing the regressed effects of ENSO, solar, volcano, AMO and their prescribed anthropogenic forcing. It should contain only climate noise if the MLR analysis is successful, but there is a negative trend remaining in recent decades (in red).


Adjusted data after removing the solar, ENSO, volcanic signals from the HadCRUT4 global mean temperature anomalies by regression
(a)
Annual mean (1856-2010)
20-year moving average
Linear trend in the period 1979-2010: 0.169 ± 0.019 °C per decade
Temperature (°C)
Annual mean (1856-2010)
Period
Years
Rate
°C per decade
100
0.068 ± 0.013
75
0.080 ± 0.015
50
0.083 ± 0.011
32
0.070 ± 0.019
(b)
Adjusted data after removing the solar, ENSO, volcanic and AMO signals from the HadCRUT4 global mean temperature anomalies by regression
Year

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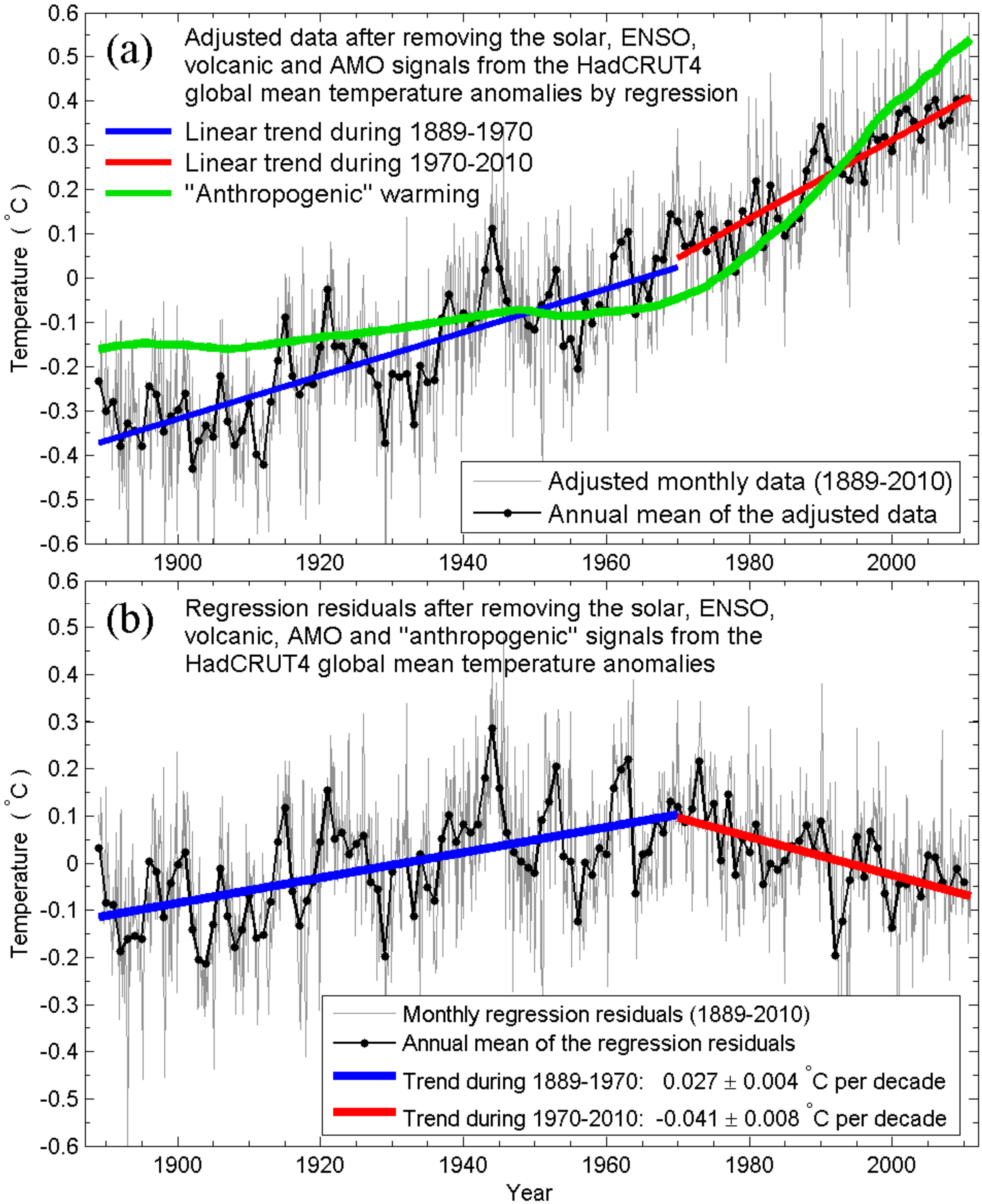

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