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Impact of the Atlantic Multidecadal Oscillation (AMO) on deriving anthropogenic warming rates from the instrumental temperature record

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Abstract

The instrumental surface air temperature record has been used in several statistical studies to assess the relative role of natural and anthropogenic drivers of climate change. The results of those studies varied considerably, with anthropogenic temperature trends over the past 25–30 years suggested to range from 0.07 to 0.20 °C decade^{-1}. In this short communication we assess the origin of these differences and highlight the inverse relation between the derived anthropogenic temperature trend of the past 30 years and the weight given to the Atlantic Multidecadal Oscillation (AMO) as an explanatory factor in the multiple linear regression (MLR) tool that is usually employed. We highlight that robust MLR outcomes require a better understanding of the AMO in general and more specifically its characterization. Our results indicate that both the high- and low end of the anthropogenic trend over the past 30 years found in previous studies are unlikely and that a transient climate response with best estimates centred around 1.3 °C per CO_2 doubling best captures the historic instrumental temperature record.

1 Introduction

The surface air temperature of the earth is influenced by a large number of natural and anthropogenic factors (Bindoff et al., 2013). The relative role of these has been the subject of much debate, both in the scientific community and in the public domain. Climate models rooted in physics are the preferred tool to perform attribution studies and project future climate, but have difficulty in predicting variability related to natural processes such as the El Niño Southern Oscillation (ENSO). Simple statistical models have therefore also been used to explain the evolution of the temperature record (Foster and Rahmstorf, 2011; Lean and Rind, 2008; Santer et al., 2001; Tung and Zhou, 2013).

Most of these studies use a multiple linear regression (MLR) where a dependent variable (in this case temperature) is explained by a number of explanatory variables using co-variations in the dependent and explanatory variables. One recent outcome highlighted by Zhou and Tung (2013) and Chylek et al. (2014) is that the residuals of an MLR exercise using anthropogenic forcing, solar radiation, volcanic activity, and ENSO as explanatory variables correlates strongly with the Atlantic Multidecadal Oscillation (AMO). Including the AMO therefore increases the correlation with observed global temperature. The AMO is in a warming mode since about 1980 so it "competes" with anthropogenic forcings to explain the warming since then. The implications are that, depending on whether or not the AMO was included, the calculated anthropogenic warming rate of the recent 25–30 year period varied considerably between 0.07 K decade^{-1} (Zhou and Tung, 2013) and 0.20 K decade^{-1} (Lean and Rind, 2008), although the time periods considered do not overlap completely.

The term AMO was introduced by Kerr (2000) but the oscillation was identified earlier (Bjerknes, 1964; Schlesinger and Ramankutty, 1994). Variability in AMO has been traced back in the instrumental record to over 350 years ago (Tung and Zhou, 2013) and using different types of proxy data up to 8000 years ago (Chylek et al., 2012; Delworth and Mann, 2000; Knudsen et al., 2011). However, Booth et al. (2012) argued that since 1860 the AMO was for a large part related to changes in aerosol loads driven mostly by anthropogenic emissions. These two lines of thought (natural vs. anthropogenic) are difficult to reconcile but given the multiple lines of evidence showing a natural component we assume here that the AMO represents a natural oscillation modified by anthropogenic factors.

The uncertain nature of this oceanic oscillation makes it difficult to characterize the AMO for use in MLR studies. In its simplest form the AMO is based on the North Atlantic sea surface temperature (NA SST) but linearly detrended to compensate for anthropogenic warming. This is also the characterization used in the MLR studies of Zhou and Tung (2013) and Chylek et al. (2014). However, the NA SST itself is influenced by short-term variability such as volcanic activity and ENSO. Enfield et al. (2001) therefore proposed to use a 10 year running mean of the detrended NA SST. Going one step further and also aiming to account for non-linearities in detrending the NA SST, Van Oldenborgh et al. (2009) computed an AMO index based on the averaged SST in the North Atlantic minus the regression of this SST on global mean temperature. This approach supersedes that of Trenberth and Shea (2006) which includes more influence of the tropical regions. This short communication aims to identify how important these different characterizations of the AMO as well as the shape of the anthropogenic influence are for the outcomes of MLR studies.

2 Data and methods

We repeated the analyses of Chylek et al. (2014) and Zhou and Tung (2013) where the global temperature pattern is described using MLR by 5 factors: anthropogenic, solar, volcano, ENSO, and AMO. We systematically altered the characterization of the AMO (no AMO or 4 different descriptions, see Fig. 1), and the anthropogenic influence – linear as done in Zhou and Tung (2013) or based on the radiative forcing as done in Chylek et al. (2014) – for a total of 10 runs MLR runs.

We focused on the 1900–2011 period and used Goddard Institute for Space Studies (GISS) global average annual temperature available at http://data.giss.nasa.gov/gistemp/ (Hansen et al., 2010) as well as the combined GISS anthropogenic forcings from Hansen et al. (2011), see http://data.giss.nasa.gov/modelforce/Fe.1880-2011.txt. ENSO was based on average monthly data from http://jisao.washington.edu/data/cti. Solar radiation and volcanic activity were taken from the GISS forcings mentioned above. This set-up is similar to the one used in Chylek et al. (2014). Zhou and Tung (2013) analysed a longer time period (1856–2012) but given the limited spatial coverage of the temperature dataset in the 19th century we refrain from extending our study period to before 1900. Another key difference is that Zhou and Tung (2013) did not use the anthropogenic forcings but a linear trend, just as Foster and Rahmstorf (2011) did. However, the latter study focused on a much shorter time period than the former.

We performed 10 MLR runs, the first 5 runs were based on a linear trend for the anthropogenic factor as in Foster and Rahmstorf (2011) and Zhou and Tung (2013), the second 5 with the anthropogenic radiative forcing for the anthropogenic factor as in Lean and Rind (2008) and Chylek et al. (2014). The linear trend we used had the same overall slope as the anthropogenic radiative forcing time series so that their coefficients in the MLR could be compared. Within these two sets of 5 scenarios we only changed how the AMO was represented; (i) no AMO, (ii) AMO based on the detrended NA SST, (iii) as (ii) but with a 10 year running mean as in Enfield et al. (2001), (iv) as in Van Oldenborgh et al. (2009), and (v) as in Trenberth and Shea (2006). The AMO descriptions of Van Oldenborgh et al. (2009) and Trenberth and Shea (2006) are specifically designed to isolate the AMO from external forcings. The four different AMO characterizations will be referred to as “NA SST”, “Enfield”, “Van Oldenborgh”, and “Trenberth” and are shown in Fig. 1.

MLR methods should be handled with care, see for example Benestad and Schmidt (2009). They could lead to erroneous outcomes when for example explanatory variables co-vary. This has been addressed in the studies we follow up on and here we focus on the importance of the AMO characterization and the shape of the anthropogenic trend.

3 Results

The regression coefficients for the anthropogenic factor (Fig. 2a) varied little between the 10 different runs indicating that the role of anthropogenic forcing is relatively robust in these MLRs. For solar radiation the coefficient is negative when the anthropogenic influence in the MLR is represented by a linear trend while it has a roughly similar or somewhat higher value as the anthropogenic factor when this influence is based on the anthropogenic radiative forcings (Fig. 2b). The coefficients for volcanoes and ENSO (Fig. 2c and d) were rather comparable with most weight given to these factors when running without AMO, least weight when using the NA SST, and intermediate

weight when using one of the other AMO descriptions. The coefficients for volcanoes and ENSO were relatively insensitive to the shape of the anthropogenic factor.

The coefficients for the AMO (Fig. 2e) varied considerably between the 4 characterizations with those based on the NA SST having the highest coefficients. Between those two, using 10 year running mean values (Enfield et al., 2001) resulted in a somewhat higher coefficient than the plain annual detrended NA SST. The coefficients for the more intrinsic AMO characterizations were substantially lower. As shown earlier by Chylek et al. (2014), highest correlations are achieved when using the NA SST as a proxy for AMO (Fig. 2f), with the annual data having a somewhat higher correlation than the 10 year running mean. The other AMO parameterizations also boosted the correlation compared to running without AMO, albeit marginally (Fig. 2f). These correlations are adjusted for the number of explanatory variables, which is 4 for the runs without AMO and 5 when running with AMO.

Finally, the long-term rate of anthropogenic warming for both the 100 and 60 year period varies little between the MLRs and all indicate an acceleration when going from a 100 year to a 60 year period (Fig. 2g and h). These time periods are somewhat arbitrary but results are very similar when investigating a 70 or 50 year period instead of 60 year. Results vary much more for what is the shortest time interval when investigating climate (30 years) as shown in Fig. 2i. These results are approximately inversely related to the weight given to the AMO (Fig. 3) and yield the highest values when excluding the AMO and lower values with AMO. However, the key result here is that also intermediate values are possible; the characterization of the AMO plays an important role.

4 Discussion

The different MLRs pointed out that the choice of AMO and anthropogenic representation substantially impacts the results of these exercises. The weight given to the anthropogenic influence, however, was quantitatively remarkably robust between the scenarios. These two main findings are discussed in more detail below.

There was one crucial difference between the scenarios that were based on a linear anthropogenic trend vs. those based on the anthropogenic forcing. The former indicated a negative impact of solar radiation. When considering an earlier start year (1856) as done in Zhou and Tung (2013) the coefficient becomes positive, but not statistically different from zero. The underlying reason for this small – or even negative – effect is that the warming rate in the 1910–1940 and 1970–2000 periods was relatively similar, and thus best captured by a linear function, leaving no room for the sun to explain part of the signal. The radiative forcing signal, however, has a smaller slope during the early 20th century warming than during the late 20th century warming, thus requiring solar radiation to have an influence because it increased in strength during the early 20th century warming but not during the late warming.

Since (1) the shape of the anthropogenic forcing is relatively well know because of direct atmospheric and firn or ice-core measurements of greenhouse gases, the dominant factor, and (2) because it is almost certainly a statistical artefact that the measured variability in solar radiation has a negative or no influence, we feel it is more justifiable to use the anthropogenic forcing as the pre-defined shape of the anthropogenic influence. A consequence is that part of the recent air temperature plateau can be explained by a lull in solar activity over the past decade, see for example Schmidt et al. (2014) and discussion therein. In the work where a linear trend for the anthropogenic factor was used (Tung and Zhou, 2013; Zhou and Tung, 2013) it is acknowledged that not too much weight should be given to the results for the solar coefficients, indicating again that using the radiative forcing is the preferred way to go forward. These studies also yielded the lowest anthropogenic temperature trend for the past 30 years (0.07 °C decade^{-1}) which is partly an artefact of using a linear trend but also related to using a very early start year. One other reason for not making the linear trend assumption is that this yields lower correlations (Fig. 2f) although we shall see below that this should not be the sole criterion for choosing representations. For the rest of

the discussion we therefore focus on the results derived from using radiative forcing to describe the anthropogenic factor (the open circles in Figs. 2 and 3).

The inverse relation between the weight given to the AMO and the 30 year anthropogenic trend as shown in Fig. 3 begs the question which AMO description is most accurate. But first we iterate on the implications as drawn from the different MLRs. The temperature amplitude of the AMO is about 0.4 °C and the AMO regression coefficient indicates what fraction of that 0.4 °C is maintained in the global temperature record. The NA covers about 10 % of the global earth surface and the bare minimum coefficient should therefore be about 0.1, but probably higher because of impacts of the AMO SST on surrounding land surface and due to teleconnections (Chylek et al., 2009; Knight et al., 2006) and potentially due to positive land surface feedbacks (Della-Marta et al., 2007). Studies that did not include the AMO (Foster and Rahmstorf, 2011; Lean and Rind, 2008) will therefore yield anthropogenic trends that are too high during periods when the AMO transitions from a cool to a warm phase as happened over the past 30–40 years.

The maximum coefficient indicated by the various scenarios is about 0.5, which would indicate strong teleconnections because the AMO effect would be felt over half the earth's surface. Where in between the ~ 0.1 and ~ 0.5 the coefficient should lie is speculation and depends for a large part on our ability to better understand and characterize the AMO. The results are sensitive to whether the AMO peaks higher during the current than the previous cycle (as indicated by the detrended annual and running mean NA SST) or not (as indicated by Van Oldenborgh et al., 2009 and Trenberth and Shea, 2006), see Fig. 1. We argue that using the straight detrended NA SST (Chylek et al., 2014; Zhou and Tung, 2013) is not the preferred approach because it is contaminated by external factors and potentially gives more weight to the AMO at the expense of for example volcanoes and ENSO (Fig. 2), even though it yields the highest correlation. However, when partly accounting for this by using a 10 year running mean the results with regard to the weight given to AMO and thus the anthropogenic temperature trend of the past 30 years do not deviate much from running with annual data. In fact, the AMO coefficient increased somewhat and the coefficients for ENSO and volcanoes were more in line with the other MLRs. Only when using more sophisticated approaches for the AMO did the coefficient drop substantially, and increased the anthropogenic warming trend for the past 30 years.

One other outcome of these MLR analyses is that most of the temperature increase over the past 100 years is of anthropogenic origin, whether the AMO is included or not and whether the anthropogenic shape is linear or follows the forcing estimates. This indicates that there is no combination of natural factors that can better match the observed temperature pattern than one with a large anthropogenic influence.

One piece of information related to this that has not been explored before is that the weight given to the anthropogenic factor as represented by the radiative forcing signal yields information about the transient climate response (TCR). Multiplying the coefficient with the radiative forcing of a doubling of CO_2 ($3.71\,W\,m^{-2}$) yields best estimates between 1.5 and 1.8 °C using the GISS forcings. Adjusting these forcings linearly so that they scale with those from IPCC AR5 (Myhre et al., 2013) yields values between 1.2 and 1.4 °C. The net forcing increased in AR5 mostly because of a lower estimate of the aerosol cooling effect. Two sigma uncertainties around these best estimates are about 0.1 °C but do not take into account uncertainties in the forcing estimates and are thus underestimating the real uncertainty. These TCR values are in line with studies based on energy budget constraints, e.g. Otto et al. (2013). Key advantages of the MLR approach are that we can account for the temporal patterns and that the MLR may better isolate the anthropogenic signal from the natural signal.

Finally, if the AMO influence has as large a coefficient as almost 0.5 as indicated by some of the MLRs, global temperatures may stay close to constant because an upcoming warm to cold shift taking about 30 years (total cooling of about 0.2 °C) compensates part of the $0.1\,°C\,decade^{-1}$ anthropogenic trend corresponding to those AMO descriptions. If its role is smaller (with a coefficient of about 0.25 it will cool about 0.1 °C over the next 30 years), it will still compensate some of the on-going anthropogenic warming (about $0.14\,°C\,decade^{-1}$ corresponding to those AMO descriptions) but cannot offset

it. Clearly, these are just rough indications and they assume that all else is equal, but they do underscore again the need to better understand and characterize the AMO and its impact on climate.

5 Conclusions

Assuming that at least part of the AMO is of natural origin and given that it has a substantial temperature cycle and large footprint, it should be included in MLR studies as an explanatory variable. This will lower the anthropogenic temperature trend for the past 30 years compared to MLR studies neglecting the AMO as shown by Zhou and Tung (2013) and Chylek et al. (2014). However, our results indicate that the degree to which this is the case depends on the choice of AMO description. Using detrended NA SST indicates a strong role for the AMO and thus a relatively low anthropogenic trend but these observations are contaminated by other factors influencing NA SST. More sophisticated AMO descriptions indicate a similar or smaller role for the AMO, and consequently potential higher anthropogenic trends for the past 30 years. Our results thus imply that a better understanding of the AMO is required to increase our confidence in the outcomes of these MLR exercises, especially when considering relatively short periods when fluctuations in multidecadal oscillations such as the AMO do not average out.

The most robust outcome of the different MLRs we ran was the anthropogenic factor which indicated best estimates of transient climate response between 1.2 and 1.4 °C using IPCC AR5 radiative forcing estimates, in line with recent studies based on energy budget constraints. The added benefit from an MLR approach is that it takes the temporal signal into account and may better isolate the anthropogenic factor from natural variability.

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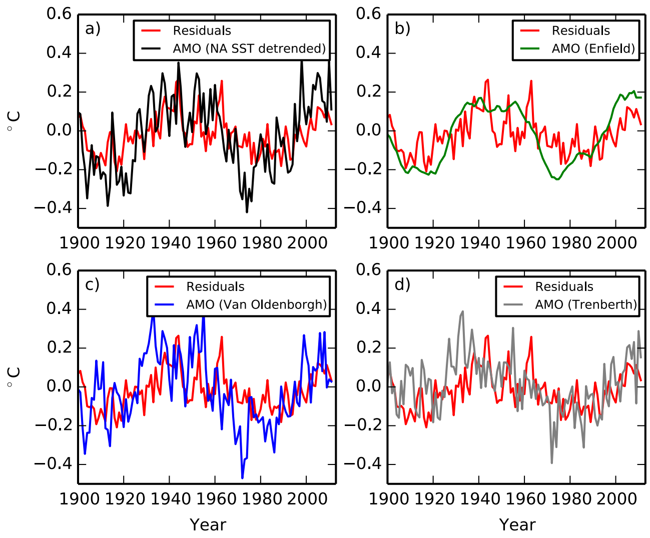

Fig. 1. MLR residuals when explaining global temperature with anthropogenic radiative forcing as well as with solar, volcanoes, and ENSO as explanatory variables plotted in combination with 4 different characterization of the AMO: **(a)** detrended NA SST, **(b)** as **(a)** but using a 10 year running mean (except for 2008 onwards where the running mean for the remaining years was taken) as done in Enfield et al. (2001), **(c)** the characterization of Van Oldenborgh et al. (2009) and **(d)** the one of Trenberth and Shea (2006). The latter two aimed specifically to isolate the intrinsic AMO signal.

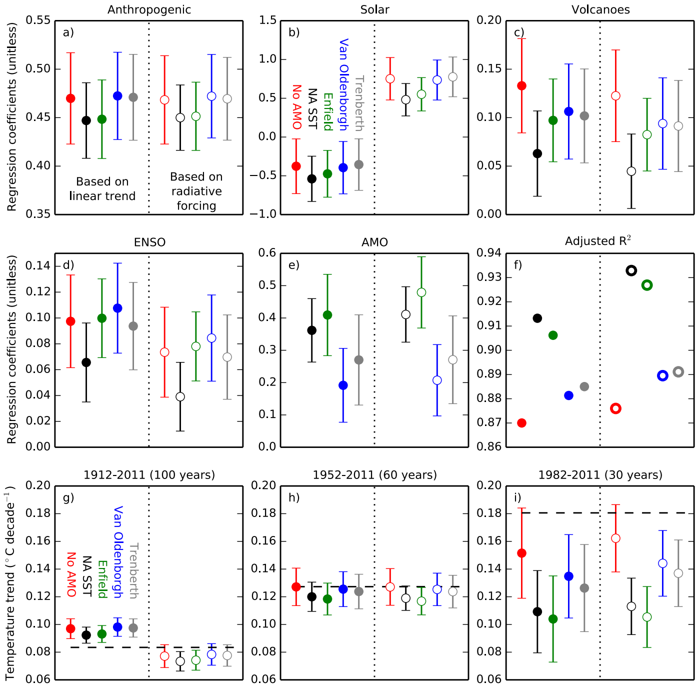

Fig. 2. Regression coefficients **(a–e)**, adjusted correlation coefficient **(f)**, and observed temperature trends (dotted black line) and anthropogenic trends for three different time windows **(g–i)**. Results are shown for 10 different MLR exercises with the first five (closed circles) based on a linear trend for the anthropogenic influence and the second five (open circles) using anthropogenic radiative forcing instead. Within these two sets 5 MLRs were done without AMO and with 4 different AMO descriptions as indicated in **(b)** and **(g)**. Errorbars indicate 2σ values.

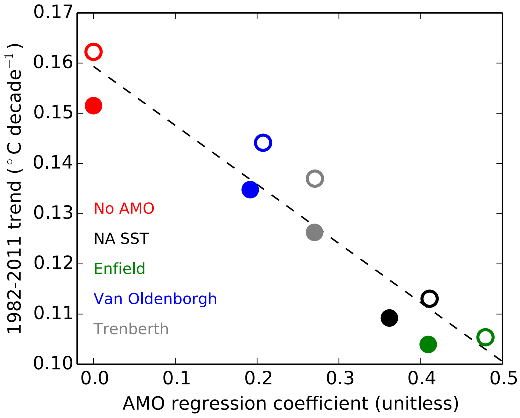

Fig. 3. Relation between the weight given to AMO and the anthropogenic temperature trend over the 1982–2011 period for 10 different MLRs as described in Fig. 2.