

1 **Impact of the Atlantic Multidecadal Oscillation (AMO) on** 2 **deriving anthropogenic warming rates from the instrumental** 3 **temperature record**

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9 10 **Abstract**

11 The instrumental surface air temperature record has been used in several statistical
12 studies to assess the relative role of natural and anthropogenic drivers of climate change. The
13 results of those studies varied considerably, with anthropogenic temperature trends over the
14 past 25-30 years suggested to range from 0.07 to 0.20°C decade⁻¹. In this short
15 communication we assess the origin of these differences and highlight the inverse relation
16 between the temperature trend of the past 30 years and the weight given to the Atlantic
17 Multidecadal Oscillation (AMO) as an explanatory factor in the multiple linear regression
18 (MLR) tool that is usually employed. We highlight that robust MLR outcomes require a better
19 understanding of the AMO in general and more specifically its characterization. Our results
20 indicate that both the high- and low end of the anthropogenic trend over the past 30 years
21 found in previous studies are unlikely and that a transient climate response of 1.6 (1.0-3.3) °C
22 best captures the historic instrumental temperature record.

23

24 **1 Introduction**

25 The surface air temperature of the earth is influenced by a large number of natural and
26 anthropogenic factors (Bindoff et al., 2013). The relative role of these has been the subject of
27 much debate, both in the scientific community and in the public domain. Climate models
28 rooted in physics are the preferred tool to perform attribution studies and project future
29 climate, but have difficulty in predicting variability related to natural processes such as the El

1 Niño Southern Oscillation (ENSO). Simple statistical models have therefore also been used to
2 explain the evolution of the temperature record (Foster and Rahmstorf, 2011; Lean and Rind,
3 2008; Santer et al., 2001; Tung and Zhou, 2013)

4 Most of these studies used a multiple linear regression (MLR) where a dependent
5 variable (in this case temperature) is explained by a number of explanatory variables using co-
6 variations in the dependent and explanatory variables. One recent outcome highlighted by
7 Zhou and Tung (2013) and Chylek et al. (2014) is that the residuals of an MLR exercise using
8 anthropogenic forcing, solar radiation, volcanic activity, and ENSO as explanatory variables
9 correlates strongly with the Atlantic Multidecadal Oscillation (AMO), see Fig. 1. Including
10 the AMO in a MLR therefore increases the correlation with observed global temperature. The
11 AMO is in a warming mode since about 1980 so it “competes” with anthropogenic forcings to
12 explain the warming since then (Delsole et al., 2011). The implications are that, depending on
13 whether or not the AMO was included, the calculated anthropogenic warming rate of the
14 recent 25-30 year period varied considerably between $0.07 \text{ K decade}^{-1}$ (Zhou and Tung, 2013)
15 and $0.20 \text{ K decade}^{-1}$ (Lean and Rind, 2008), although the time periods considered do not
16 overlap completely.

17 The term AMO was introduced by Kerr (2000) but the oscillation was identified earlier
18 (Bjerknes, 1964; Schlesinger and Ramankutty, 1994). Variability in AMO has been traced
19 back in the instrumental record to over 350 years ago (Tung and Zhou, 2013) and using
20 different types of proxy data up to 8,000 years ago (Chylek et al., 2012; Delworth and Mann,
21 2000; Knudsen et al., 2011). However, Booth et al. (2012) argued that since 1860 the AMO
22 was for a large part related to changes in aerosol loads driven mostly by anthropogenic
23 emissions. These two lines of thought (natural versus anthropogenic) are difficult to reconcile
24 but given the multiple lines of evidence showing a natural component and doubts on whether
25 aerosols are indeed driving the AMO (Zhang et al., 2012) we assume here that the AMO
26 represents a natural oscillation.

27 The uncertain nature of this oceanic oscillation and its teleconnections makes it difficult
28 to characterize the AMO for use in MLR studies. In its simplest form the AMO is based on
29 the North Atlantic sea surface temperature (NA SST) but linearly detrended to compensate for
30 anthropogenic warming. This is also the characterization used in the MLR studies of Zhou
31 and Tung (2013) and Chylek et al. (2014). However, the NA SST itself is influenced by short-
32 term variability such as volcanic activity and ENSO. Enfield et al. (2001) therefore proposed

1 to use a 10-year running mean of the detrended NA SST. Going one step further and also
2 aiming to account for non-linearities in detrending the NA SST, Van Oldenborgh et al. (2009)
3 computed an AMO index based on the averaged SST in the North Atlantic minus the
4 regression of this SST on global mean temperature. This approach supersedes that of
5 Trenberth and Shea (2006) which includes more influence of the tropical regions. These four
6 AMO characterizations are shown in Fig. 1. This short communication aims to identify how
7 important these different characterizations of the AMO as well as the shape of the
8 anthropogenic influence are for the outcomes of MLR studies and derived estimates of the
9 transient climate response (TCR).

10

11 **2 Data and Methods**

12 We repeated the analyses of Chylek et al. (2014) and Zhou and Tung (2013) where the
13 global temperature pattern is described using MLR by 5 factors: anthropogenic, solar,
14 volcano, ENSO, and AMO (Fig. 1). We systematically altered the characterization of the
15 AMO (no AMO or 4 different descriptions, Fig. 1e, f), and the anthropogenic influence -linear
16 as done in Zhou and Tung (2013) or based on the radiative forcing as done in Chylek et al.
17 (2014)- for a total of 10 runs MLR runs.

18 We focused on the 1900-2011 period and used the Intergovernmental Panel on Climate
19 Change (IPCC) fifth assessment report (AR5) radiative forcing estimates (Myhre et al., 2013).
20 Net IPCC AR5 forcing estimates are higher and have a somewhat different pattern than the
21 Goddard Institute for Space Studies (GISS) anthropogenic forcings from Hansen et al. (2011,
22 <http://data.giss.nasa.gov/modelforce/Fe.1880-2011.txt>) used in Chylek et al. (2014) and in the
23 discussion version of this paper (Fig. 1b). The increase in net forcing is mostly due to reduced
24 (less negative) estimates of the aerosol forcings. Our main analyses relied on GISS global
25 average annual temperature (GISTEMP) available at
26 <http://data.giss.nasa.gov/gistemp/Temperature> (Hansen et al., 2010). We tested the sensitivity
27 of our results to using global average temperature estimates of 1) the blended Met Office
28 Hadley Centre and the Climatic Research Unit at the University of East Anglia HadCRUT4
29 (Morice et al., 2012) and 2) the Berkeley Earth Surface Temperature Study (Rohde et al.,
30 2013), see Fig. 1a. One key difference between the temperature datasets is that HadCRUT4
31 does not extrapolate beyond station data in the rapidly warming Arctic region and its trend is
32 thus somewhat lower than the other two datasets which do extrapolate here (Fig. 1a).

1 ENSO was based on Kaplan et al. (1998) available from
2 <http://climexp.knmi.nl/data/inino5.dat>. All oceanic factors (AMO and ENSO) were based on
3 annual means with a 6-month delay that was chosen because it yielded highest correlations.
4 Solar radiation and volcanic activity were taken from the IPCC AR5 forcings mentioned
5 above. This set-up is similar to the one used in Chylek et al. (2014), except that we thus used
6 an updated radiative forcing dataset and a more frequently used ENSO parameterization.
7 Zhou and Tung (2013) analysed a longer time period (1856-2012) but given the limited
8 spatial coverage of the temperature dataset in the 19th century we refrain from extending our
9 study period to before 1900. Another key difference compared to Chylek et al. (2013) is that
10 Zhou and Tung (2013) did not use the anthropogenic forcings but a linear trend, just as Foster
11 and Rahmstorf (2011) did. However, the latter study focused on a much shorter time period
12 than the former.

13 We performed 10 MLR runs on an annual time step over 1900-2011, the first 5 runs
14 were based on a linear trend for the anthropogenic factor as in Foster and Rahmstorf (2011)
15 and Zhou and Tung (2013), the second 5 with the anthropogenic radiative forcing for the
16 anthropogenic factor as in Lean and Rind (2008) and Chylek et al. (2014) but with updated
17 data. The linear trend we used had the same overall slope as the anthropogenic radiative
18 forcing time series so that their coefficients in the MLR could be compared. Within these two
19 sets of 5 scenarios we only changed how the AMO was represented; i) no AMO, ii) AMO
20 based on the detrended NA SST, iii) as ii) but with a 10-year running mean as in Enfield et al.
21 (2001), iv) as in Van Oldenborgh et al. (2009), and v) as in Trenberth and Shea (2006). The
22 AMO descriptions of Van Oldenborgh et al. (2009) and Trenberth and Shea (2006) are
23 specifically designed to isolate the AMO signal from external factors. The four different
24 AMO characterizations will be referred to as 'NA SST', 'Enfield', 'Van Oldenborgh', and
25 'Trenberth' and are shown in Fig. 1e and f.

26 We used the outcomes of the MLR exercises (always for the whole 1900-2011 study
27 period) to estimate the anthropogenic temperature trend over the past 30, 60, and 100 years.
28 These were established by fitting a linear trend to the observed temperature with natural
29 factors subtracted. The latter were based on the MLR regression coefficient multiplied by the
30 observed pattern for each of the four factors analysed here (solar, volcanic, ENSO, and
31 AMO). Finally, to estimate the transient climate response (TCR) the MLR regression
32 coefficients for the anthropogenic forcing estimates were multiplied by 3.71 W m^{-2} (the

1 radiative forcing of a CO₂ doubling). To estimate its uncertainty we carried out a Monte Carlo
2 simulation accounting for uncertainties in the radiative forcing estimates based on Myhre et
3 al. (2013), uncertainty in the MLR regression coefficient, and uncertainties from and between
4 the temperature time series. Because the GISTEMP dataset has no uncertainty estimates we
5 used those from the relatively similar Berkeley temperature dataset. Uncertainties reported
6 throughout this paper are 5th and 95th percentiles.

7

8 **3 Results**

9 The regression coefficients for the anthropogenic factor (Fig. 2a) varied little between
10 the 10 different runs indicating that the role of anthropogenic forcing is relatively robust in
11 these MLRs. For solar radiation the coefficient was negative when the anthropogenic
12 influence in the MLR was represented by a linear trend while it had a roughly similar (which
13 was expected) or somewhat higher value than the anthropogenic factor when this influence
14 was based on the anthropogenic radiative forcings (Fig. 2b). The variability in coefficients for
15 volcanic and ENSO influences (Fig 2c, d) were rather comparable with most weight given to
16 these factors when running without AMO, least weight when using the NA SST, and
17 intermediate weight when using one of the other AMO descriptions. The coefficients for
18 volcanoes and ENSO were relatively insensitive to the shape of the anthropogenic factor.

19 The coefficients for the AMO (Fig. 2e) varied considerably between the 4
20 characterizations with those based on the NA SST having the highest coefficients. Between
21 these two, using 10 year running mean values (Enfield et al., 2001) resulted in a somewhat
22 higher coefficient than the plain annual detrended NA SST. The coefficients for the more
23 intrinsic AMO characterizations were lower, especially when the anthropogenic factor was
24 represented by the anthropogenic forcing instead of a linear trend. As shown earlier by
25 Chylek et al. (2014), highest coefficient of determination are achieved when using the NA
26 SST as a proxy for AMO (Fig. 2f), with the annual data having a marginally higher
27 coefficient of determination than the 10 year running mean. The other AMO
28 parameterizations also boosted the correlation compared to running without AMO, but to a
29 smaller degree. These coefficients of determination were adjusted for the number of
30 explanatory variables, which was 4 for the runs without AMO and 5 when running with
31 AMO.

32 Finally, the long-term rate of anthropogenic warming for both the 100 and 60 year

1 period varied little between the MLRs and all indicated an acceleration when going from a
2 100 year to a 60 year period (Fig. 2g, h). These time periods are somewhat arbitrary but
3 results were very similar when investigating a 70 or 50 year period instead of 60 year.
4 Results varied much more for what is the shortest time interval when investigating climate (30
5 years) as shown in Fig. 2i. These results were inversely related to the weight given to the
6 AMO (shown in Fig. 3 for the anthropogenic radiative forcing based estimates) and yielded
7 the highest values when excluding the AMO and lower values with AMO. However, the key
8 result here is that also intermediate values are possible; the characterization of the AMO as
9 well as the temperature dataset used played an important role (Fig. 3). According to our
10 results, anthropogenic temperature trends for the past 30 years were between about 0.11 and
11 0.17°C per decade (Fig. 2i, range of values based on using radiative forcing as anthropogenic
12 influence and including AMO). The anthropogenic trends calculated this way show a similar
13 pattern as and agree within their uncertainties with the trends we had expected from
14 multiplying the coefficients found for the anthropogenic forcing (Fig. 2a) with the change in
15 forcing over the 1982-2011 period (1.01 W m^{-2}), shown light coloured in Fig. 2i. However,
16 the difference is larger than expected for the NA SST and Enfield AMO descriptions,
17 potentially reflecting non-linearities or temporal variability in the role of the natural forcings
18 highlighting uncertainties in these approaches.

19 To some degree, the way the AMO characterization influences the 30-year
20 anthropogenic warming rate was also seen in the TCR values we derived from multiplying the
21 coefficients given to the anthropogenic factor with the radiative forcing of a CO₂ doubling
22 (Table 1). Including AMO in general lowered the TCR, but to a much smaller degree than for
23 the 30-year anthropogenic warming rate discussed above. This is because of the longer time
24 period considered (1900-2011) and thus smaller relative impact of multidecadal oscillations.
25 Differences in temperature datasets had a larger impact on the calculated TCR's than the
26 different AMO description with in general GISTEMP and Berkeley being higher than results
27 based on HadCRUT4. When randomly choosing the temperature dataset and AMO
28 description (excluding running without AMO) in the Monte Carlo simulation TCR was found
29 to be 1.6 (1.0-3.3) °C (Table 1).

30

31 **4 Discussion**

32 The different MLRs pointed out that the choice of AMO and anthropogenic

1 representation substantially impacts the results of these exercises. The weight given to the
2 anthropogenic influence and thus TCR, however, was quantitatively remarkably robust
3 between the scenarios. These two main findings are discussed in more detail below.

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

15 Since 1) the shape of the anthropogenic forcing is known to be not linear (while large
16 uncertainties exist in the aerosol forcing the dominant greenhouse gas forcing is well known
17 and increased exponentially) and 2) because it is almost certainly a statistical artefact that the
18 measured variability in solar radiation has a negative or no influence, we feel it is more
19 justifiable to use the anthropogenic forcing as the pre-defined shape of the anthropogenic
20 influence. A consequence is that part of the recent air temperature plateau can be explained by
21 a lull in solar activity over the past decade, see for example Schmidt et al. (2014) and
22 discussion therein. Our work also highlights the role of ENSO and stagnating AMO in this. In
23 the work where a linear trend for the anthropogenic factor was used (Tung and Zhou, 2013;
24 Zhou and Tung, 2013) it is acknowledged that not too much weight should be given to the
25 results for the solar coefficients, indicating again that using the radiative forcing is the
26 preferred way to go forward. Studies using a linear trend for the anthropogenic forcing
27 yielded the lowest anthropogenic temperature trend for the past 30 years ($0.07^{\circ}\text{C decade}^{-1}$)
28 which is partly an artefact of using a linear trend but also related to using a very early start
29 year. One other reason for not making the linear trend assumption is that this yields lower
30 correlations (Fig. 2f) although we shall see below that this should not be the sole criterion for
31 choosing representations. For the rest of the discussion we therefore focus on the results
32 derived from using radiative forcing to describe the anthropogenic factor (the open circles in

1 Fig. 2).

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

14 The maximum coefficient indicated by the various scenarios is about 0.5 (Fig. 3), which
15 would indicate strong teleconnections because the AMO effect would be felt over half the
16 earth's surface, for example as a result of modifying cloud patterns. Where in between the
17 ~ 0.1 and ~ 0.5 the coefficient should lie is speculation and depends for a large part on our
18 ability to better understand and characterize the AMO and its teleconnections. The results are
19 sensitive to whether the AMO peaks higher during the current than the previous cycle (as
20 indicated by the detrended annual and running mean NA SST) or not (as indicated by Van
21 Oldenborgh et al. (2009) and Trenberth and Shea (2006)), see Fig. 1e,f. We argue that using
22 the straight detrended NA SST (Chylek et al., 2014; Zhou and Tung, 2013) is not the
23 preferred approach because it is contaminated by external factors and potentially gives more
24 weight to the AMO at the expense of for example volcanoes and ENSO (Fig. 2), even though
25 it yields the highest correlation. However, when partly accounting for this by using a 10 year
26 running mean the results with regard to the weight given to AMO and thus the anthropogenic
27 temperature trend of the past 30 years do not deviate much from running with annual data. In
28 fact, the AMO coefficient increased somewhat and the coefficients for ENSO and volcanoes
29 were more in line with the other MLRs, although still lower. Only when using more
30 sophisticated approaches for the AMO did the coefficient drop substantially, and increased
31 the calculated anthropogenic warming trend for the past 30 years.

32 One other outcome of these MLR analyses is that most of the temperature increase over

1 the past 100 years was of anthropogenic origin, whether the AMO was included or not and
2 whether the anthropogenic shape was linear or followed the forcing estimates. This indicates
3 there is no combination of natural factors considered here that could better match the
4 observed temperature pattern than one with a large anthropogenic influence. This translates to
5 relatively stable TCR values that differed more from changing temperature dataset than due to
6 differences in AMO characterization (Table 3). Our values were somewhat higher but well
7 within the uncertainty range of recent studies based on energy budget constraints, e.g., Otto et
8 al. (2013), but lower than more sophisticated attribution studies also accounting for the spatial
9 variability (e.g., Stott et al., 2006). Key advantages of the MLR approach over energy budget
10 studies are that we can account for the temporal patterns and that the MLR may better isolate
11 the anthropogenic signal from the natural signal.

12

13 **5 Conclusions**

14 Assuming that at least part of the AMO is of natural origin and given that it has a substantial
15 temperature cycle and large footprint, it should be included in MLR studies as an explanatory
16 variable. This will lower the anthropogenic temperature trend for the past 30 years compared
17 to MLR studies neglecting the AMO as shown by Zhou and Tung (2013) and Chylek et al.
18 (2014). However, our results indicate that the degree to which this is the case depends on the
19 choice of AMO description. Using detrended NA SST indicates a strong role for the AMO
20 and thus a relatively low anthropogenic warming trend for the past 30 years but these
21 observations are contaminated by other factors influencing NA SST. More sophisticated
22 AMO descriptions indicate a similar or smaller role for the AMO, and consequently potential
23 higher anthropogenic warming trends for the past 30 years. Our results thus imply that a better
24 understanding of the AMO is required to increase our confidence in the outcomes of these
25 MLR exercises, especially when considering relatively short periods when fluctuations in
26 multidecadal oscillations such as the AMO do not average out.

27 The most robust outcome of the different MLRs we ran was the anthropogenic factor which
28 indicated a transient climate response (TCR) of 1.6 (1.0-3.3) °C, with the uncertainty range
29 reflecting uncertainties in AMO characterization as well as the temperature and radiative
30 forcing datasets used. These values are somewhat higher but well within the uncertainty range
31 of recent studies based on energy budget constraints. The added benefit from an MLR

1 approach is that it takes the temporal signal into account and may better isolate the
2 anthropogenic factor from natural variability.

3

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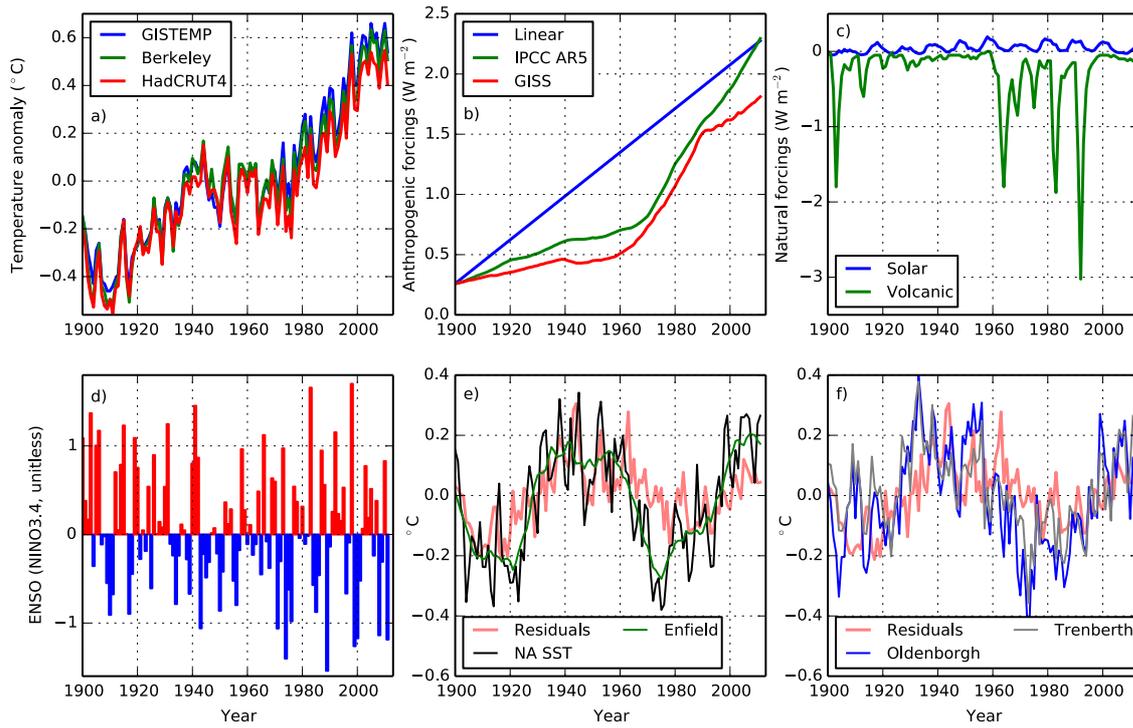
1 Table 1. Transient climate response (TCR, in °C) including 5th and 95th percentiles based on
 2 Monte Carlo simulations taking into account uncertainties in radiative forcing, temperature
 3 data, and the radiative forcing regression coefficient.

AMO description	Temperature dataset			
	GISTEMP	HadCRUT4	Berkeley	All
No AMO	1.76 (1.16-3.55)	1.57 (1.03-3.18)	1.67 (1.10-3.38)	1.67 (1.09-3.37)
NA SST	1.66 (1.09-3.34)	1.46 (0.96-2.95)	1.55 (1.02-3.13)	1.56 (1.01-3.16)
Enfield	1.64 (1.08-3.32)	1.43 (0.94-2.89)	1.52 (1.00-3.08)	1.53 (0.99-3.11)
Van Oldenborgh	1.75 (1.16-3.55)	1.57 (1.03-3.17)	1.67 (1.10-3.37)	1.66 (1.09-3.36)
Trenberth	1.76 (1.16-3.56)	1.58 (1.04-3.20)	1.68 (1.11-3.38)	1.67 (1.09-3.39)
All ¹	1.70 (1.12-3.44)	1.51 (0.98-3.06)	1.61 (1.05-3.26)	1.61 (1.04-3.26)

4 ¹. Running with no AMO excluded

5

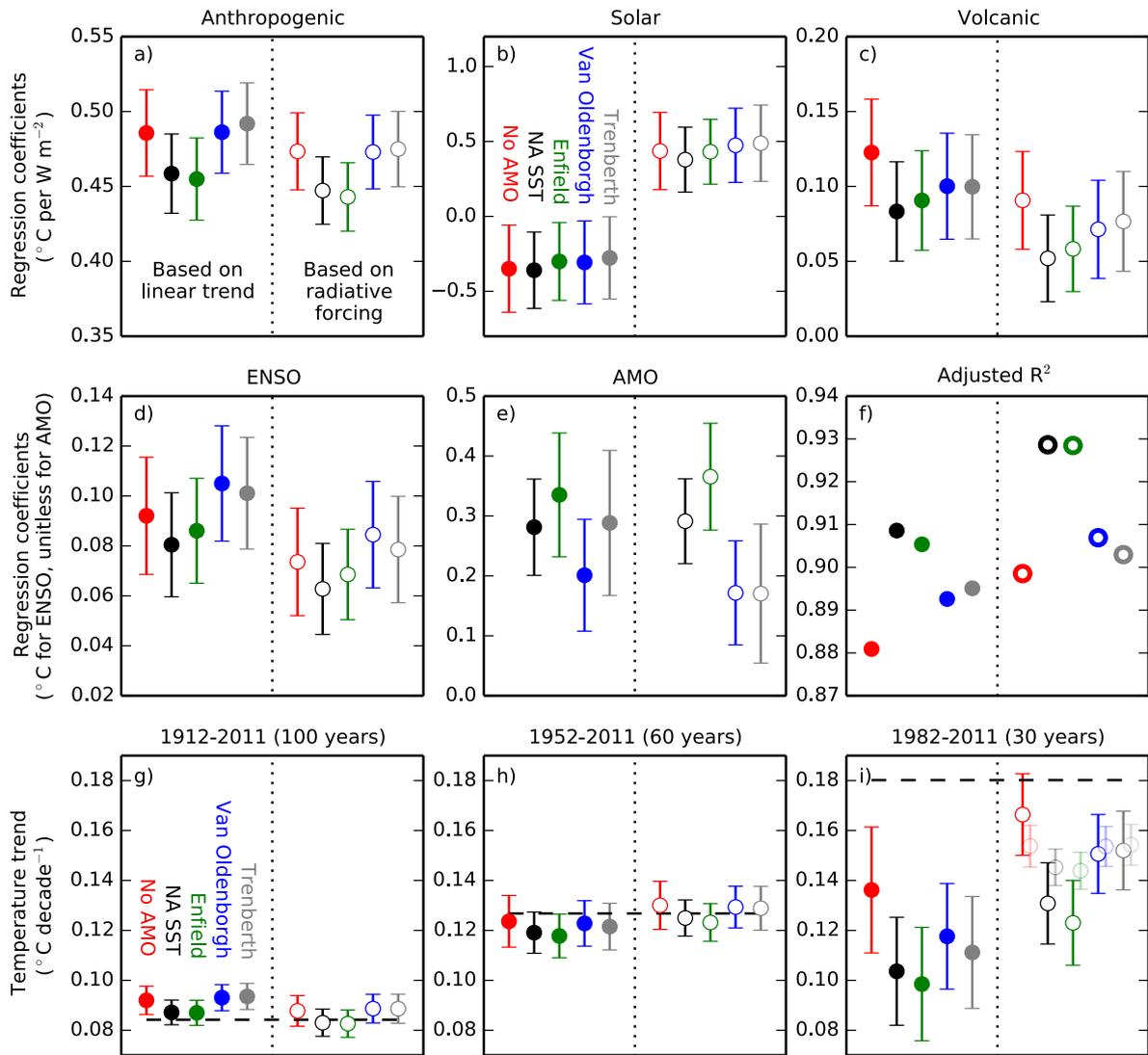
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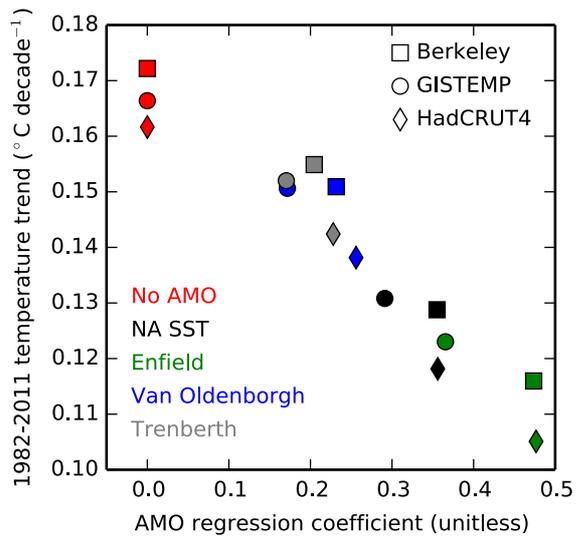
3 Figure 1. Input datasets used in this study, a) three different temperature datasets, b)
4 anthropogenic forcing, c) natural forcings, d) ENSO, e) AMO characterizations based only on
5 NA SST, and f) AMO characterizations aiming to isolate the intrinsic AMO signal. Also
6 shown in e) and f) are MLR residuals when explaining GISTEMP temperature with GISS
7 anthropogenic radiative forcing as well as with solar, volcanoes, and ENSO as explanatory
8 variables.

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 2 Figure 2. Regression coefficients (a-e) and adjusted coefficient of determination (f) for MLR
 3 exercises over the 1900-2011 period using GISTEMP temperature data as well as calculated
 4 anthropogenic trends and observed temperature trends (dotted black lines) for three different
 5 time windows (g-i). Light colored bars in i) are calculated anthropogenic temperate trends
 6 based on the regression coefficients shown in panel a) and the change in forcing. Results are
 7 shown for 10 different MLR exercises with the first five (closed circles) based on a linear
 8 trend for the anthropogenic influence and the second five (open circles) using IPCC AR5
 9 anthropogenic radiative forcing instead. Within these two sets 5 MLRs were done, one
 10 without AMO and 4 with different AMO descriptions as indicated in b) and g). Errorbars
 11 indicate 5th and 95th percentiles without taking uncertainties in input datasets into account.

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2 Figure 3. Relation between the weight given to the AMO in the MLR and the derived
 3 anthropogenic temperature trend over 1982-2011 for 3 different temperature datasets and 5
 4 different AMO characterizations.

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