Asymmetric seasonal temperature trends

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Current consensus on global climate change predicts warming trends driven by anthropogenic forcing, with maximum temperature changes projected in the Northern Hemisphere (NH) high latitudes during winter. Yet, global temperature trends show little warming over the most recent decade or so. For longer time periods appropriate to the assessment of trends, however, global temperatures have experienced significant warming for all seasons except winter, when cooling trends exist instead across large stretches of eastern North America and northern Eurasia. Hence, the most recent lapse in global warming is a seasonal phenomenon, prevalent only in boreal winter. Additionally, we show that the largest regional contributor to global temperature trends over the past two decades is land surface temperature in the NH extratropics. Therefore, proposed mechanisms explaining the

fluctuations in global annual temperature trends should address this apparent seasonal asymmetry.

1. Introduction

Global surface temperatures are projected to warm due to rapid increases in greenhouse gases (GHGs) and over the entire length of the instrumental record, temperatures have undergone a warming trend [*IPCC*, 2007]. However it has been noted that the global warming trend has slowed and even halted since the late 1990s [e.g., *Easterling and Wehner,* 2009; *Kaufmann et al.,* 2011]. Several studies have offered explanations for the recent cessation in the global temperature trend, including climate variations of the North Atlantic and equatorial Pacific oceans [*Keenlyside et al.,* 2008; *Meehl et al.,* 2011], variations in solar activity [*Lean and Rind,* 2009], changes in stratospheric water vapor [*Solomon et al.,* 2010], and tropospheric aerosols [*Kaufmann et al.,* 2011]. The sudden absence of a warming trend is not particularly unique or even unexpected. Easterling and Wehner [2009], through running decadal trend analysis, show that even the observed record has decadal spans of little to no warming. Even coupled climate model simulations of a future warmer world due to increased GHGs contain periods of little to no warming [*Easterling and Wehner,* 2009; *Meehl et al.,* 2011]. Indeed, large-scale modes of natural variability in the atmosphere and ocean may work to negate radiative warming on decadal timescales.

The aforementioned studies discuss the absence of a warming trend or even a cooling trend in the context of global annual temperatures. Yet, analysis of temperature trends seasonally is not extensively reported, both in the observational record and in coupled climate model simulations. As we will illustrate, recent trends in global surface temperatures are seasonally-dependent; i.e., only Northern Hemisphere (NH) extratropical land surface temperatures during boreal winter display a systematic waning of the warming trend to a near-neutral trend of late. The implications of this finding are important for testing the relative importance of the proposed mechanisms suggested for the cessation of the warming trend and for evaluating how coupled climate models can handle such seasonal asymmetries.

2. Observational Data and Model Output

Observational surface temperature data originate from two sources: (1) The Climate Research Unit land air temperature dataset, version 3 [CRUTEM3; *Brohan et al.,* 2006]; and (2) The National Aeronautics and Space Administration Modern Era Retrospective-Analysis for Research and Applications [NASA MERRA; *Rienecker et al.,* 2011]. The CRUTEM3 dataset, consisting of monthly land station-based temperature anomalies, are on a regular 5° x 5° longitude/latitude grid globally. The data are provided as anomalies, using the 1961-1990 period as the base period, and extend from 1850 to present. NASA MERRA monthly-mean surface temperatures reside on a 1.25° x 1.25° grid globally, covering land and ocean, starting from 1979 to present. Monthly-mean anomalies from MERRA are computed by removing the climatological monthly means (1979-2011) from the raw data.

Coupled-climate model output are provided from the Coupled Model Intercomparison

Project Phase 5 (CMIP5) multi-model ensemble archive, available for download from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) at the Lawrence Livermore National Laboratory (more information on the program is provided online at **http://cmip-pcmdi.llnl.gov/cmip5/**). We used all available ensemble members of the decadal1980 scenario (i.e., the model runs are initialized with conditions as in 1980 and run for 30 years using mainly observed natural and anthropogenic forcing). Six models were available and analyzed for this study (see Table 1), each with multiple realizations. Surface temperature output from the models is interpolated from their native model grids to a common 2.5° by 2.5° longitude/latitude grid for comparison. Surface temperature anomalies are then computed by removing the climatological monthly mean from 1980-2010. Model results are shown as the ensemble-mean of all models and all realizations.

When examining seasonal temperature trends, seasons are defined as follows: December – February (DJF) as boreal winter, March – May (MAM) as boreal spring, June – August (JJA) as boreal summer, and September – November (SON) as boreal fall. To test the robustness of any trends, given that the period 1999-2010 spans twelve years, we computed and tested the significance of multiple periods divisible by six. Therefore we also computed the temperature trend for the following periods: 2005-2010, 1999-2010, 1993-2010 and 1987-2010. For completeness, we also computed the trend and significance for the longer period 1979-2010, which includes the full period that satellite data is assimilated into the reanalysis datasets [*Kalnay et al.,* 1996]. Trends for all periods are shown in degrees Celsius per five years for comparative purposes.

3. Results and Discussion

Figure 1 presents the linear temperature changes from the CRUTEM3 dataset over five periods (1979-2010, 1987-2010, 1993-2010, 1998-2010, and 2005-2010) and four regions: globally (Fig. 1a), the NH extratropics (20-90°N; Fig. 1b), the tropics (20°N-20°S; Fig. 1c) and the Southern Hemisphere (SH) extratropics (20°-90°S; Fig. 1d). Examining the annual temperature trends, we find that the rate of global temperature increase has diminished when looking at more recent periods, and this phenomenon is seen outside of the tropics. Indeed, only the tropics display a significant warming trend for the 1999-2010 interval (Fig. 1c) – elsewhere the trends are not significantly different from zero. The NH extratropics contains large trends (Fig. 1b), as expected from examining land surface records, while the SH extratropical landmasses have much smaller trends (Fig. 1d).

Upon examining temperature trends seasonally, the global temperature record reveals that significant warming occurs in three seasons (boreal spring, summer, and fall) for the four earliest periods (i.e., 1979-2010, 1987-2010, 1993-2010, and 1999-2010). However, boreal winter (DJF) is the glaring exception in the record – only when starting from 1979-2010 is the DJF warming significant. For the following periods, the trend is no longer significant and even turns negative over the last decade. The only sub-region that mirrors this behavior in global temperature trends is the NH extratropics (Fig. 1b).

To check the robustness of this seasonal asymmetry and also examine potential influences of ocean temperatures on the global temperature trend, we repeat the analysis from Fig. 1 but using NASA MERRA surface temperature data (Fig. 2). Inclusion of sea surface temperatures (SSTs) with land temperatures yields similar trend results as from the land-only CRUTEM3 data – i.e., insignificant winter warming trends since the 1980s despite significant warming in the other seasons (Fig. 2a). Global linear temperature trends are also dominated by the trends in the NH extratropics (Figs. 2b and 2e). When examining changes in the trend in NH land and ocean temperatures, we find that SSTs exhibit robust, significant warming annually and seasonally as late as a start in 1993 (Fig. 2e). Land regions show similar robust warming annually and for all seasons but winter, the only season with no statistically significant warming for any period (Fig. 2b). The tropics have no significant trends in land temperatures or SSTs except when going back to 1979 (Figs. 2c and 2f), and trends in the SH ocean and land are somewhat more random and even inconsistent between MERRA and the CRUTEM3 datasets (Figs. 2d and 2g; differences are likely a function of different sampling). Staggering start and end dates by 1-2 years yields similar results for both NASA MERRA and CRUTEM3 (not shown). Hence, we confidently conclude that the cessation of global winter warming since 1987 is mostly attributable to neutral or even cooling temperature trends across the NH extratropical landmasses. We further computed the same trends using an observational ocean dataset [*Smith et al.,* 2008 (shown in Supplementary Fig. S1)] and ERA-Interim [*Dee et al.*, 2011 (not shown)] and though trends differ slightly by region, the absence of winter warming is still tied to NH extratropical land cooling.

Focusing on the NH extratropical land surface temperature trends since 1987, Figure 3 shows both the area-averaged temperature anomaly seasonally (Fig. 3a) and spatially (Figs. 3b-3e). Rapid and significant warming is clearly evident in all seasons but winter, with the boreal fall land surface temperatures warming the most rapidly. For DJF, the linear temperature trend is nearly zero. Of importance is the spatial pattern of the linear temperature trends (Figs. 3b-3e). For boreal summer and fall, except for select areas, most of the NH landmasses are experiencing strong warming trends, at or exceeding 1°C per decade in central and northern Eurasia (Figs. 3d and 3e). Except for pronounced cooling in western and northwestern North America, boreal spring temperatures also are warming strongly (Fig. 3c). However, corresponding to the near-neutral wintertime trend are large regions of significantly strong cooling trends across Europe, northern and central Asia, and parts of central and eastern North America (Fig. 3b). This spatial pattern of temperature trends is reminiscent of the temperature regression pattern associated with the negative phase of the Arctic Oscillation [AO; e.g., *Thompson and Wallace,* 2001]. Indeed, the pattern correlation between the winter temperature trend pattern and the temperature anomaly pattern associated with the negative phase of the AO is 0.85 ($p < 0.01$).

The absence of a warming trend in winter is especially surprising given that coupled climate models project the strongest warming across the NH during boreal winter due to 'winter (or Arctic, polar) amplification' [*Holland and Bitz,* 2003; *Alexeev et al.,* 2005; *Langen and Alexeev,* 2007; *Serreze and Barry,* 2011]. We computed the seasonal temperature trends and anomalies from the decadal1980 runs available from the CMIP5 model archive for the period 1987-2010. Independent of region or season, the models forecast positive temperature trends throughout all time periods, with insignificant warming only over the 2000s (see Supplementary Fig. S2). The model simulated interannual seasonal temperatures are compared with the NASA MERRA seasonal temperature anomalies in Figure 4. The annual ensemble-mean NH extratropical land surface temperatures (solid black line in Fig. 4a) track well with the observed annual NH extratropical land surface temperatures (red line in Fig. 4a), though the ensemble-mean slightly underestimates the total linear trend for the period ($\Delta T_{ENSMEAN}$ = 0.32°C versus ΔT_{OBS} = 0.49°C). For a more complete comparison of the observed temperatures with the model simulated temperatures we include a spaghetti plot of all ensemble members in Figure S3.

The models also simulate closely the seasonal trends for spring, summer and fall. For winter, while there is much more interannual variability in the observed versus simulated temperatures (the observed temperature falls outside the 1σ envelope two thirds of the time, double what is expected), the correspondence between DJF observed and simulated temperature trends remains the weakest of the four. Clearly, the difference in the boreal winter temperature trends represents some poorly resolved or missing forcing that is less influential in the other three seasons. We also note that the models predict robust cooling in all seasons due to the radiative forcing from the volcanic eruption of Mount Pinatubo. The simulated cooling is similar to the observations in all seasons except winter. This suggests that radiative forcing important in spring, summer and fall is likely masked by dynamic forcing associated with wave driving in winter. Ongoing research suggests that the models are deficient in simulating fall snow cover variability and wave forced stratosphere-troposphere coupling, which is contributing to poor model simulations of the AO and NH winter climate trends [e.g. *Hardiman et al.,* 2008; *Cohen et al.,* 2012]. As the leading mode of NH wintertime climate variability, differences in the observed versus simulated AO are likely an important factor. Indeed, when examining the evolution of the AO and associated sea level pressure trends across the NH, we find a divergence in the observed trends – the observations illustrate a trend toward *negative* AO conditions during DJF, while the models actually suggest a slight *positive* trend in the index (Supplementary Fig. S4a). Spatially, observations indicate statistically significant positive trends in sea level pressure (SLP) at high latitudes with statistically significant negative trends in SLP at lower latitudes (i.e., a negative AO pattern), while the models predict no significant SLP trends over the period.

4. Summary and Conclusions

Analysis of monthly and annual temperatures over the past decade shows that the positive global temperature trend has become insignificant and small. Based on previously reported analysis of the observations and modelling studies this is neither inconsistent with a warming planet nor unexpected; and computation of global temperature trends over longer periods does exhibit statistically significant warming. However, upon examining the trends seasonally, more interesting and significant findings are discovered. In examining the NH extratropical landmasses, the biggest contributor to global temperature trends, we find substantial divergence in trends between boreal winter and the other three seasons. A statistically significant warming trend is *absent* across NH landmasses during DJF going back to at least 1987, with either wintertime near-neutral or cooling trends. In contrast, significant warming is found for the other three seasons over the same time period.

Based on current literature and our own examination of the latest coupled climate models, the lack of a significant warming trend in winter spanning nearly three decades is not likely or expected (less than 10% of the ensemble members analyzed in this study predicted no warming in winter). Therefore, we argue that any attribution study on the recent cessation of global warming should explicitly explain the seasonally asymmetric nature of the temperature trend. For example, studies that attribute the recent cooling to diminished shortwave radiation at the surface are at a great disadvantage since their influence is maximized during boreal summer and minimized during boreal winter, opposite to what has been observed.

There are theories that argue for recent cooling that is limited to the winter season. One theory is known as 'warm Arctic cold continents,' where a warmer Arctic and declining Arctic sea ice are contributing to colder winters across the NH continents [*Honda et al.* 2009; *Budikova*, 2009; *Francis et al.,* 2009; *Overland and Wang,* 2010; *Petoukhov and Semenov,* 2010; *Serreze et al*., 2011]. A second theory is that increasing fall Eurasian snow cover that may also be related to a warming Arctic is forcing a negative trend in the winter AO [*Cohen and Barlow,* 2005; *Cohen et al.,* 2009; *Cohen et al.,* 2012]. As Figure 3b illustrates, the observed winter temperature trend spatially resembles the pattern of temperatures associated with the negative phase of the AO. Therefore, the inability of the models to simulate the observed trend in the AO (Fig. S4), may partly explain the poorly simulated DJF temperature trends.

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Figure Legends

FIG. 1. (a) The linear trend in area-averaged global land surface temperature (°C per 5 years) determined from CRUTEM3 for five different periods: 1979-2010 (dark red), 1987-2010 (light blue), 1993-2010 (green), 1999-2010 (orange), and 2005-2010 (pink). Filled bars represent trends that are significant at the 95% significance level. (b) As in (a) but only for the NH (20°N-90°N). (c) As in (a) but for the tropics (20°N-20°S). (d) As in (a) but for the Southern Hemisphere (SH; 20°S-90°S).

FIG. 2. (a) The linear trend in area-averaged global surface temperature (°C per 5 years) over *land and ocean* from the NASA MERRA dataset. Filled bars represent trends that are significant at the 95% significance level. (b)-(d) The linear trend in averaged *land* surface temperature only (°C per 5 years) in the (b) NH (20°N-90°N), (c) tropics (20°N-20°S), and (d) SH (20°S-90°S). Filled bars as in (a). (e)-(g) As in (b)-(d) but for *ocean* surface temperatures.

FIG. 3. (a) Surface temperature anomalies (solid lines; °C) from CRUTEM3 averaged poleward of 20°N from 1988 – 2010 for the four seasons: winter (DJF), spring (MAM), summer (JJA), and fall (SON). Linear trend lines (dashed lines) superimposed for each season, with the magnitude of the trend (°C per 10 years) and statistical significance shown. The spatial pattern of linear trends in surface temperature (°C per 10 years) are shown for: b) winter, c) spring, d) summer and e) fall.

FIG. 4. (a) (red line) Annual land surface temperature anomaly (°C), area-averaged poleward of 20°N, from NASA MERRA from 1987-2010. (black line) The CMIP5 ensemble-mean annual land surface anomaly, area-averaged poleward of 20°N. Gray shading represents ±1σ from the ensemble-mean. (b)-(e) As in (a) but for (b) DJF, (c) MAM, (d) JJA, and (e) SON-averaged NH land surface temperature anomaly.

Table 1. The six coupled climate models from the CMIP5 model archive analyzed for this study. Number of ensemble members for the decadal1980 scenario is also indicated.

Modelling Agency, Country	Model Name	Ensemble Members
Canadian Climate Centre for Modelling and Analysis, Canada	CanCM4	10
Météo-France/Centre National de Recherches Météorologiques, France	CNRM-CM5	10
Hadley Centre for Climate Prediction and Research/Met Office, United Kingdom	HadCM3	10
Center for Climate System Research, Japan	MIROC4h	3
Center for Climate System Research, Japan	MIROC5	6
Meteorological Research Institute, Japan	MRI-CGCM3	3

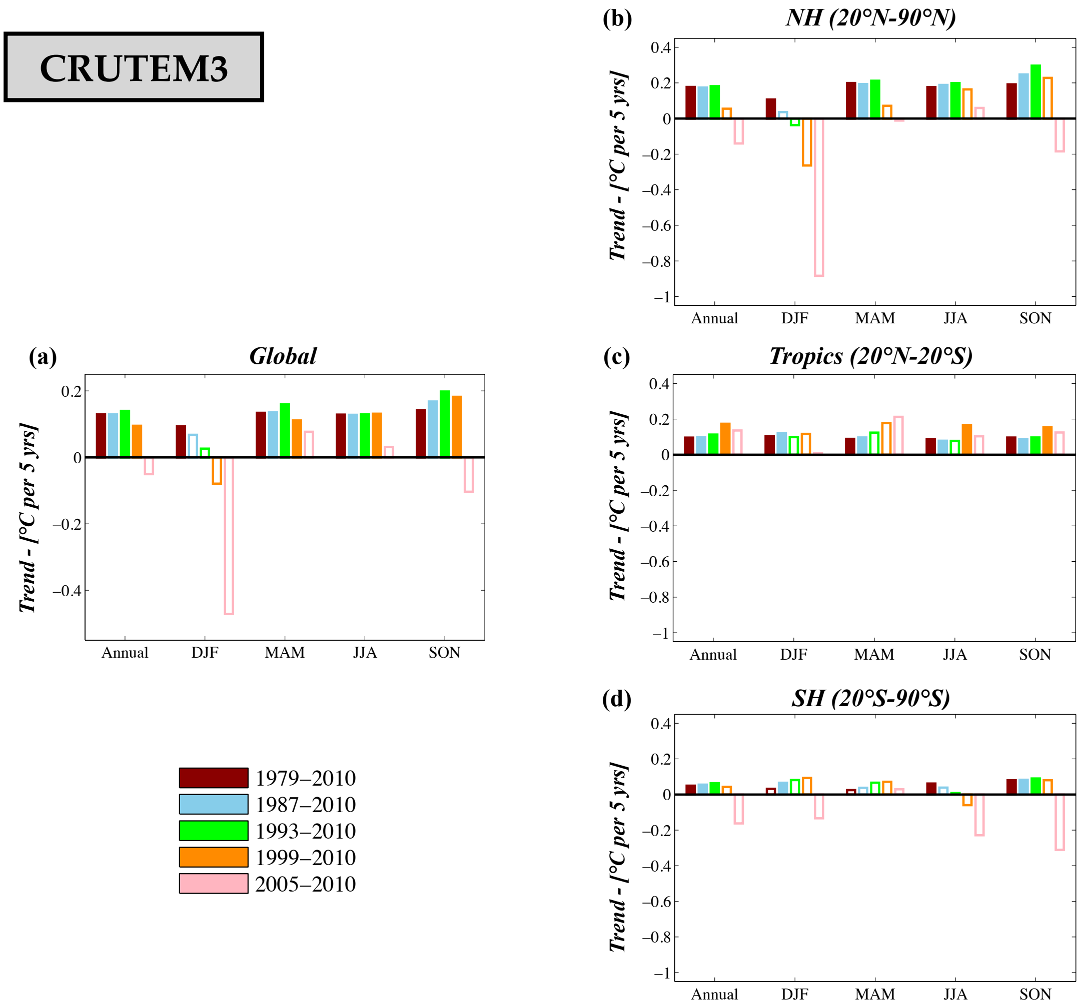
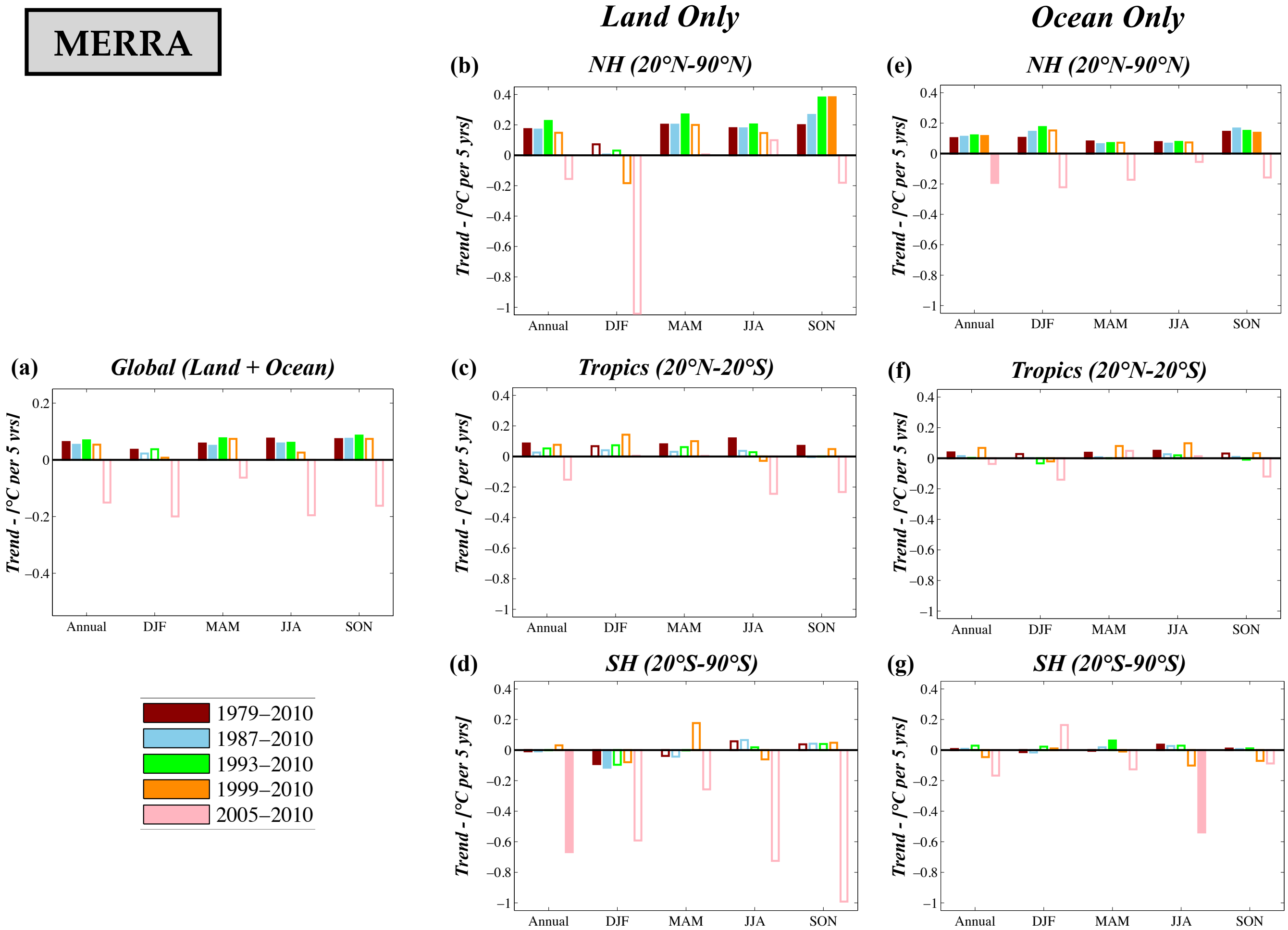
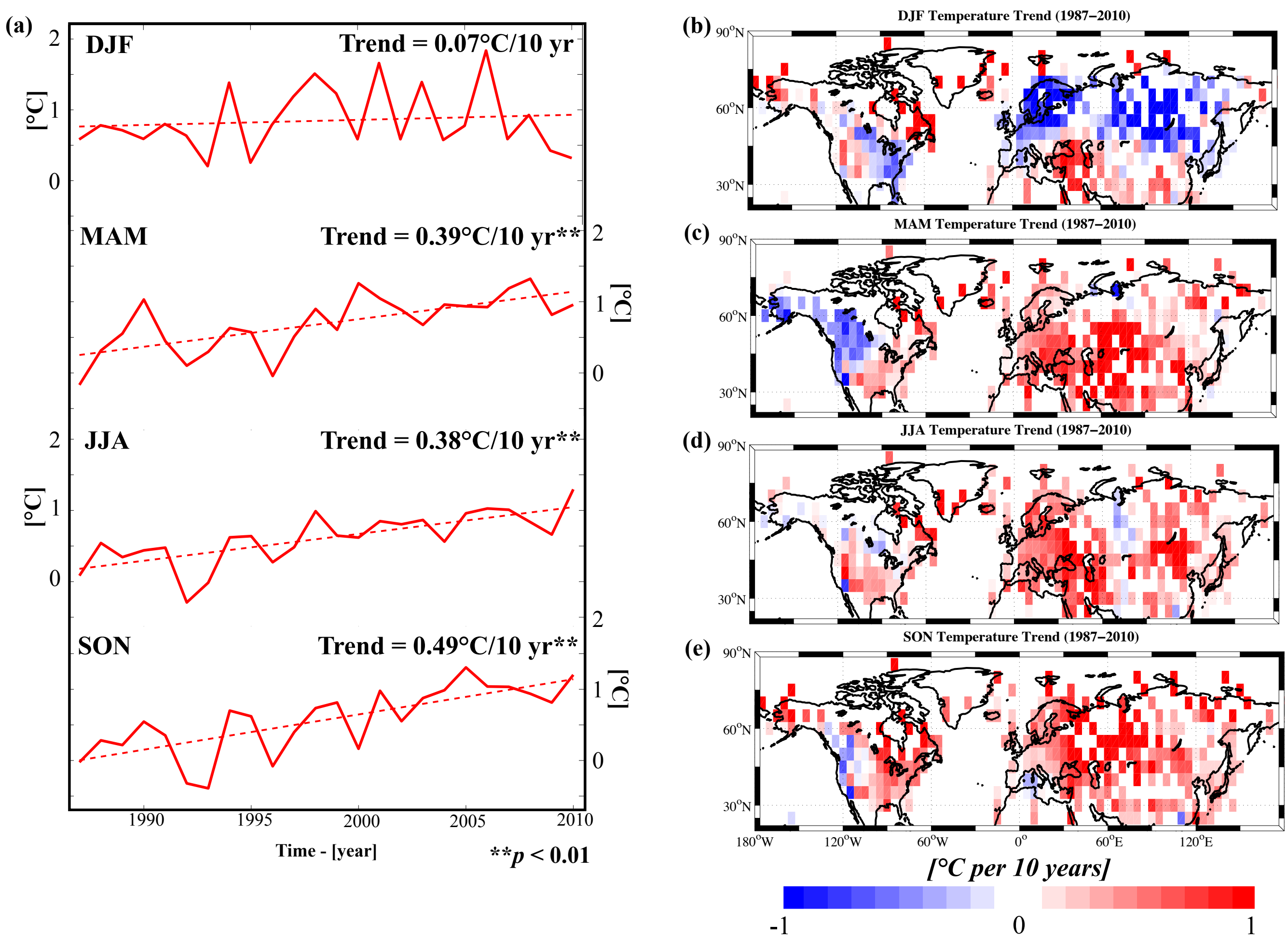

CRUTEM3
(a) Global
(b) NH (20°N-90°N)
(c) Tropics (20°N-20°S)
(d) SH (20°S-90°S)
Trend - [°C per 5 yrs]
Annual
DJF
MAM
JJA
SON
1979–2010
1987–2010
1993–2010
1999–2010
2005–2010

Figure 1



MERRA
Land Only
Ocean Only
(a) Global (Land + Ocean)
(b) NH (20°N-90°N)
(c) Tropics (20°N-20°S)
(d) SH (20°S-90°S)
(e) NH (20°N-90°N)
(f) Tropics (20°N-20°S)
(g) SH (20°S-90°S)
Trend - [°C per 5 yrs]
Annual
DJF
MAM
JJA
SON
1979–2010
1987–2010
1993–2010
1999–2010
2005–2010

Figure 2



(a)
DJF
Trend = 0.07°C/10 yr
MAM
Trend = 0.39°C/10 yr**
JJA
Trend = 0.38°C/10 yr**
SON
Trend = 0.49°C/10 yr**
[°C]
Time - [year]
**p < 0.01
(b)
DJF Temperature Trend (1987–2010)
(c)
MAM Temperature Trend (1987–2010)
(d)
JJA Temperature Trend (1987–2010)
(e)
SON Temperature Trend (1987–2010)
[°C per 10 years]

Figure 3

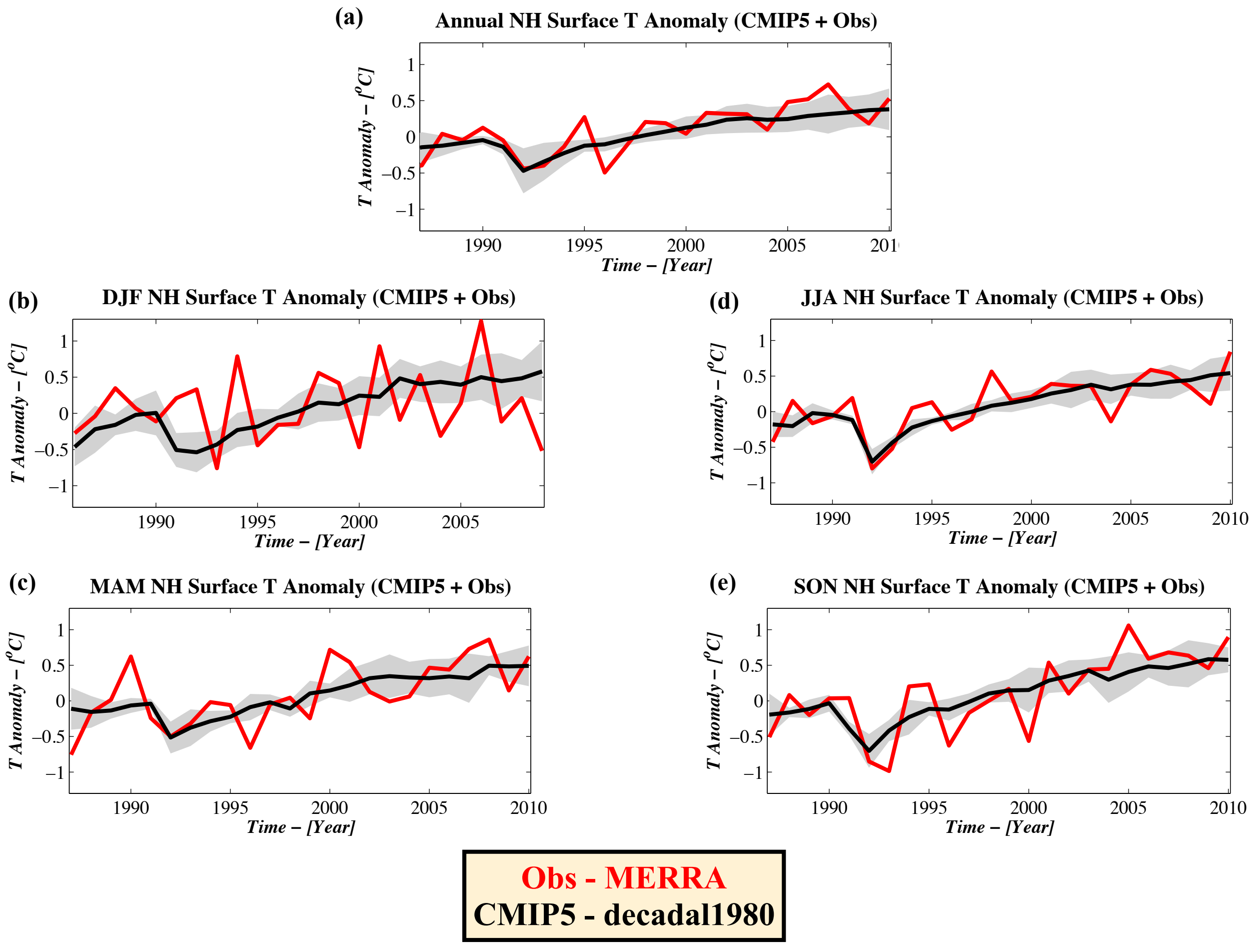

(a)
Annual NH Surface T Anomaly (CMIP5 + Obs)
T Anomaly – [°C]
Time – [Year]
(b)
DJF NH Surface T Anomaly (CMIP5 + Obs)
(c)
MAM NH Surface T Anomaly (CMIP5 + Obs)
(d)
JJA NH Surface T Anomaly (CMIP5 + Obs)
(e)
SON NH Surface T Anomaly (CMIP5 + Obs)
Obs - MERRA
CMIP5 - decadal1980

Figure 4

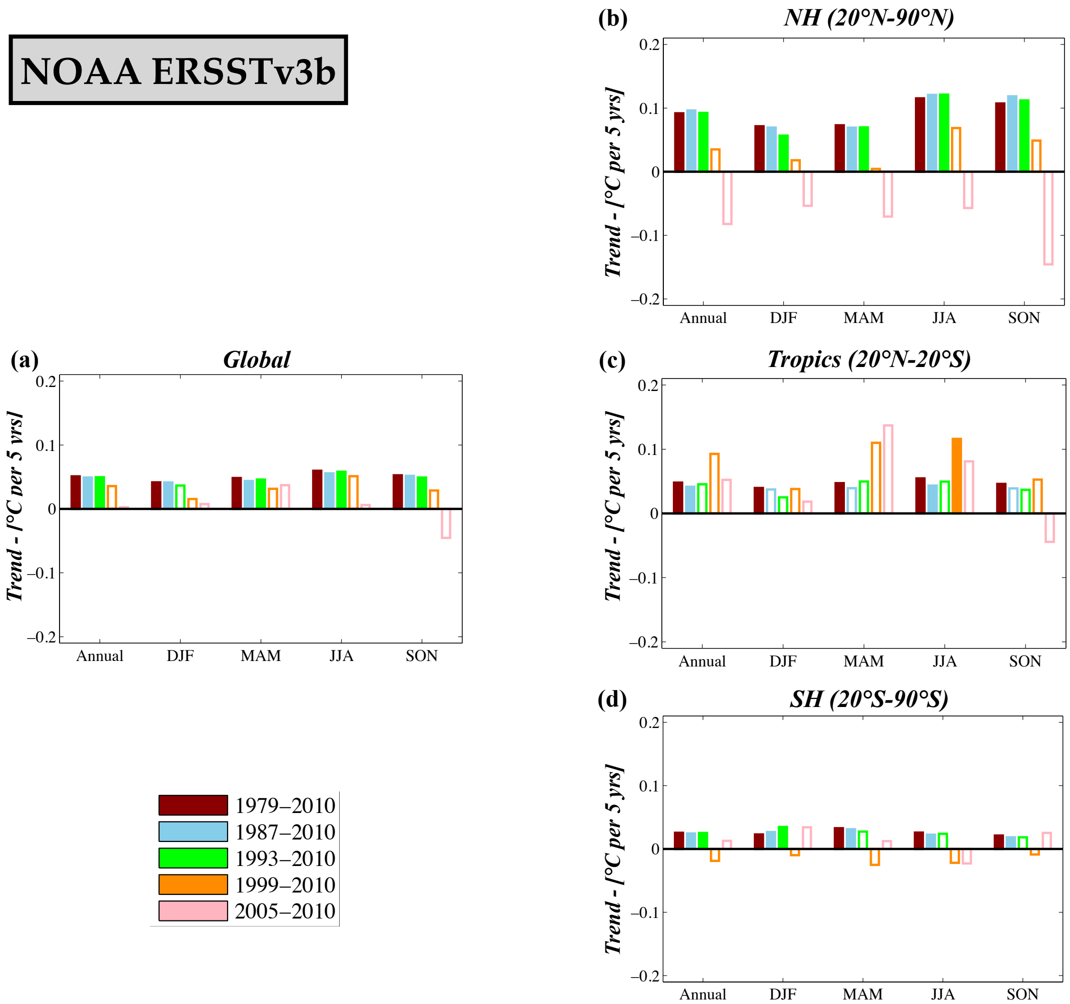


Fig. S1. (a) The linear trend in °C per 5 years area-averaged global ocean surface temperature (°C), determined from NOAA ERSSTv3b for five different periods: 1979-2010 (dark red), 1987-2010 (light blue), 1993-2010 (green), 1999-2010 (orange), and 2005-2010 (pink). Filled bars represent trends that are significant at the 95% significance level. (b) As in (a) but only for the NH (20°N-90°N). (c) As in (a) but for the tropics (20°N-20°S). (d) As in (a) but for the Southern Hemisphere (SH; 20°S-90°S).

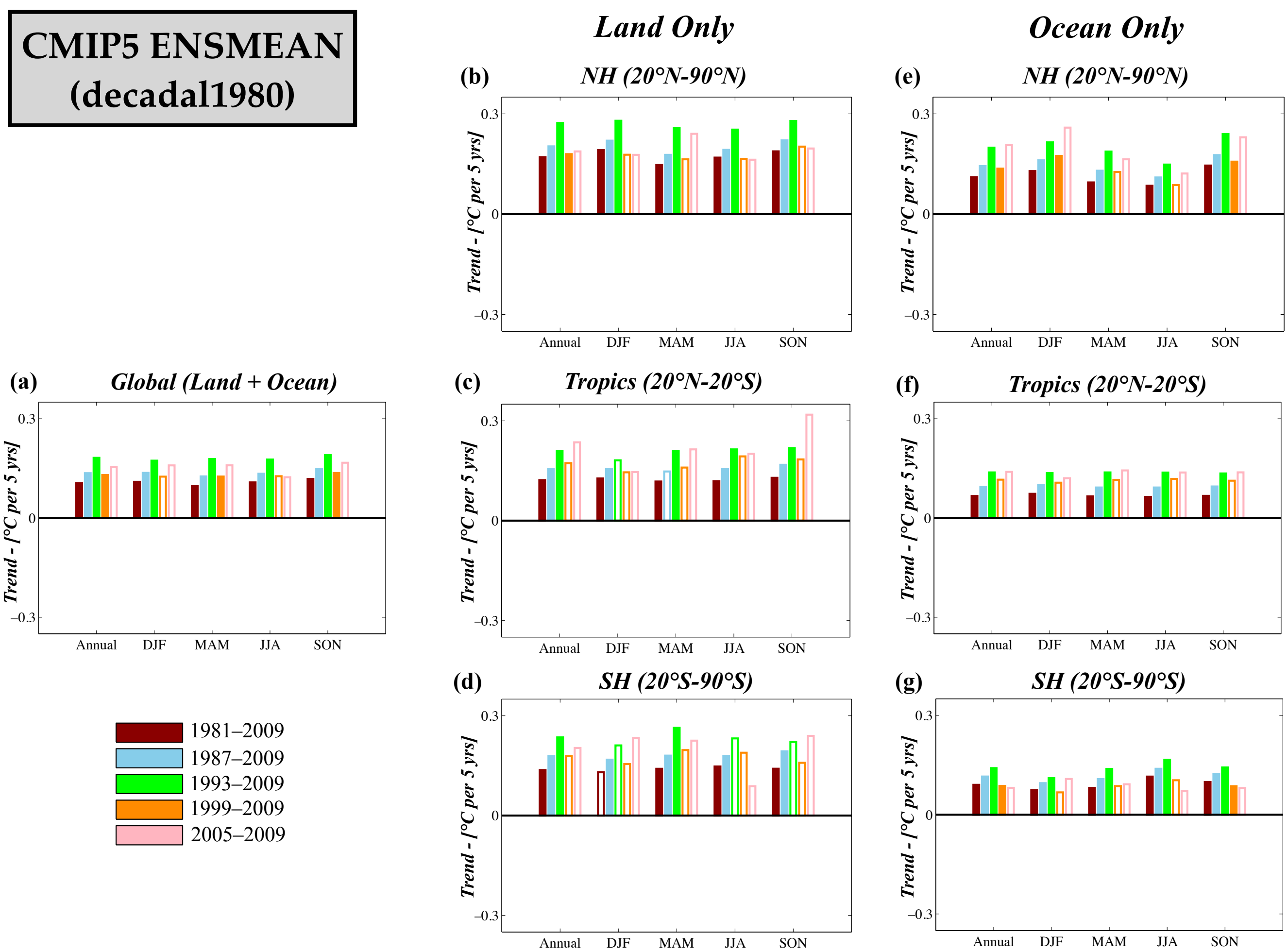


Fig. S2. The linear trend in area-averaged global surface temperature (°C per 5 years) over *land and ocean* from the CMIP5 decadal1980 simulations. Filled bars represent trends that are significant at the 95% significance level. (b)-(d) The linear trend in averaged *land* surface temperature only (°C per 5 years) in the (b) NH (20°N-90°N), (c) the tropics (20°N-20°S), and (d) the SH (20°S-90°S). Filled bars as in (a). (e)-(g) As in (b)-(d) but for *ocean* surface temperatures.

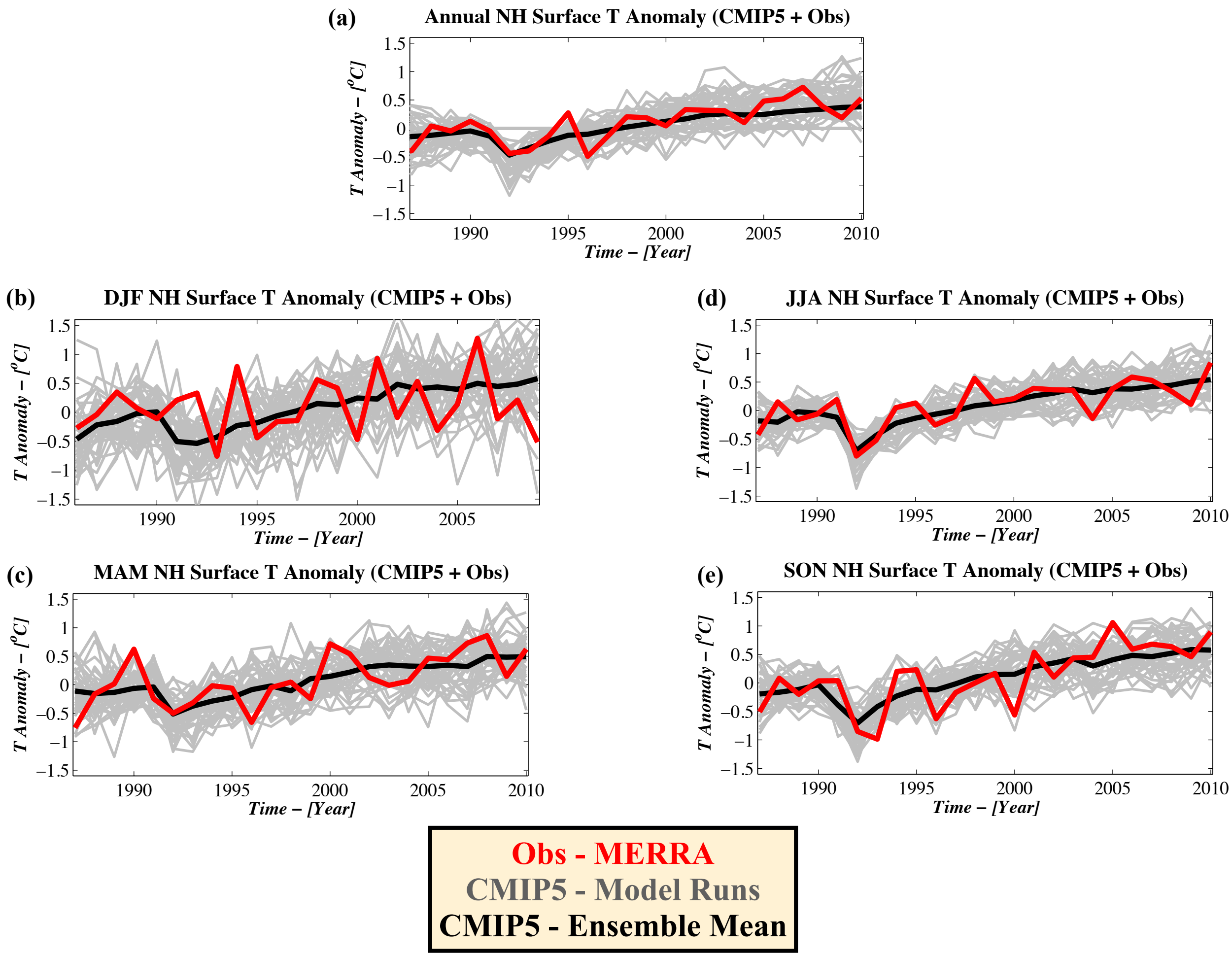


Fig. S3 (a) Annual land surface temperature anomaly (°C), area-averaged poleward of 20°N, from 1987-2010 from NASA MERRA (red), the 42 individual model runs (gray), and the ensemble-mean (black). (b)-(e) As in (a) but for (b) DJF, (c) MAM, (d) JJA, and (e) SON.

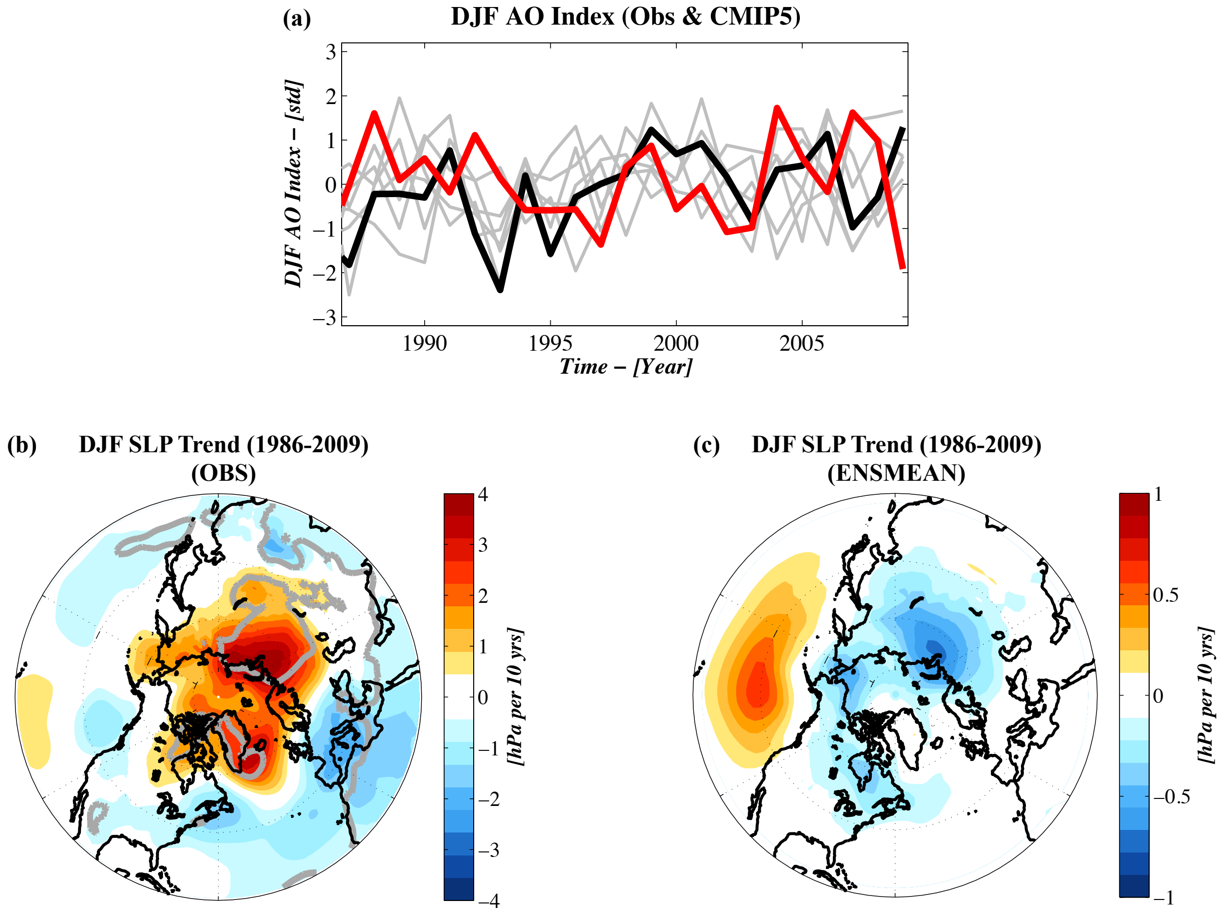


Fig. S4. (a) The standardized DJF average AO index (defined as the difference in sea level pressure between regions between 35-55°N and regions poleward of 65°N) from MERRA (red), the six CMIP5 models (gray), and the ensemble-mean of all models (black) from 1986/87-2009/10. (b) The decadal SLP trend (hPa per 10 years) from MERRA for 1986/87-2009/10. (c) As in (b) but the CMIP5 ensemble-mean decadal trend in SLP. Values that exceed the 95% confidence interval are delineated by gray contour (i.e., none of the values in (c) are significant).