GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L23712, doi:10.1029/2008GL035984, 2008

What is causing the variability in global mean land temperature?

Martin Hoerling,[1] Arun Kumar,[2] Jon Eischeid,[1] and Bhaskar Jha[3]

Received 16 September 2008; revised 30 October 2008; accepted 3 November 2008; published 13 December 2008.

[1] Diagnosis of climate models reveals that most of the observed variability of global mean land temperature during 1880–2007 is caused by variations in global sea surface temperatures (SSTs). Further, most of the variability in global SSTs have themselves resulted from external radiative forcing due to greenhouse gas, aerosol, solar and volcanic variations, especially on multidecadal time scales. Our results indicate that natural variations internal to the Earth's climate system have had a relatively small impact on the low frequency variations in global mean land temperature. It is therefore extremely unlikely that the recent trajectory of terrestrial warming can be overwhelmed (and become colder than normal) as a consequence of natural variability. **Citation:** Hoerling, M., A. Kumar, J. Eischeid, and B. Jha (2008), What is causing the variability in global mean land temperature?, *Geophys. Res. Lett.*, *35*, L23712, doi:10.1029/2008GL035984.

1. Introduction

[2] Global mean land temperature (hereafter, GMLT) is becoming an early warning for Earth's response to anthropogenic forcing. Yet, little is known about the factors responsible for its variability, nor of the extent to which present human-caused warming [*Intergovernmental Panel on Climate Change (IPCC)*, 2007] could become masked by other sources including natural internal variability. A practical, policy relevant question is whether next years' GMLT might be cooler than climatology, or whether another record setting reading is likely to occur. Framed from a climate science perspective, the question is whether sufficient understanding exists of the factors driving the year-to-year variability in global mean land surface temperature. For instance, near-record global terrestrial warmth during 2004 has been attributed to global sea surface temperature (SST) forcing [*Hoerling et al.*, 2006], and a significant role of sea surface temperature forcing has been found in explaining recent multi-decadal continental warming [*Compo and Sardeshmukh*, 2008]. It remains to be determined whether these studies describe a more general behavior occurring within the climate system. With regard to anthropogenic forcing as a cause of GMLT variability, open questions remain about the mechanisms involved—is the variability a direct and local response of terrestrial regions to changes in radiative forcing, or do non-local effects associated with responses in other parts of climate system play important mediating roles (for example, SST changes in response to radiative forcing)?

[3] We examine the role of time varying external radiative forcing and time varying sea surface temperature forcing during the instrumental period of 1880–2007 using a hierarchy of model simulations. Most of the variability in observed global mean land temperatures during the past 128 years is shown to result from SST variations. We also find that the SST variations themselves are mostly the result of external radiative forcing, particularly on multidecadal time scales. Natural internal processes thus exert a relatively small control on the low frequency GMLT variability, leading to the conclusion that it is extremely unlikely that global mean land temperature will cool below normal given the current intensity of anthropogenic forcing.

2. Data and Methods

[4] Global land surface temperature analysis for 1880–2007 is based on the U.K. Hadley Centre's HadCRUT3v [*Brohan et al.*, 2006], NOAA's land/ocean merged data [*Smith and Reynolds*, 2005], and NASA's gridded data [*Hansen et al.*, 2001]. Global monthly SST data is based the UK Meteorological Office's HadISST2 1° gridded analysis [*Rayner et al.*, 2003]. Time series of global mean land temperatures are constructed using an area-weighted averaging of points only over land (excluding Antarctica). Anomalies are computed relative to a 50-yr reference of 1921–1970, a period of relatively stable land temperatures preceding the recent strong warming.

[5] Two configurations of climate model simulations are used to determine causes for the observed variability in global land temperature; atmospheric general circulation models (AMIP), and coupled ocean-atmosphere general circulation models (CMIP). For the former, a total of 5 different models were used, each subjected to specified monthly varying observed global SSTs, but climatological values for the chemical composition of the atmosphere. Multiple realizations were available yielding a maximum ensemble of 83 members during the period of analysis. (The 5 atmospheric models used, the duration of their runs, and their ensemble size are the NCAR Community Climate Model (CCM3) [*Kiehl et al.*, 1998], 1880–2007, 16 member; the GFDL AM2.1 model [*GFDL Global Atmospheric Model Development Team*, 2004], 1880–2004, 10 member; the NASA Seasonal-to-Interannual Prediction Project (NSIPP) model [*Schubert et al.*, 2004], 1901–2007, 22 member, the European Center/Hamburg model (ECHAM4.5) [*Roeckner et al.*, 1996], 1950–2007, 24-member; the Experimental Climate Prediction Center's (ECPC) model [*Kanamitsu et al.*, 2002], 1950–2007, 10 member.) For the CMIP simulations, a total of 22 different models were used, each subjected to specified monthly variations in greenhouse

[1] Earth System Research Laboratory, NOAA, Boulder, Colorado, USA.
[2] Climate Predicton Center, NOAA, Camp Springs, Maryland, USA.
[3] WYLE Information Systems, Gaithersburg, Maryland, USA.

0094-8276/08/2008GL035984$05.00

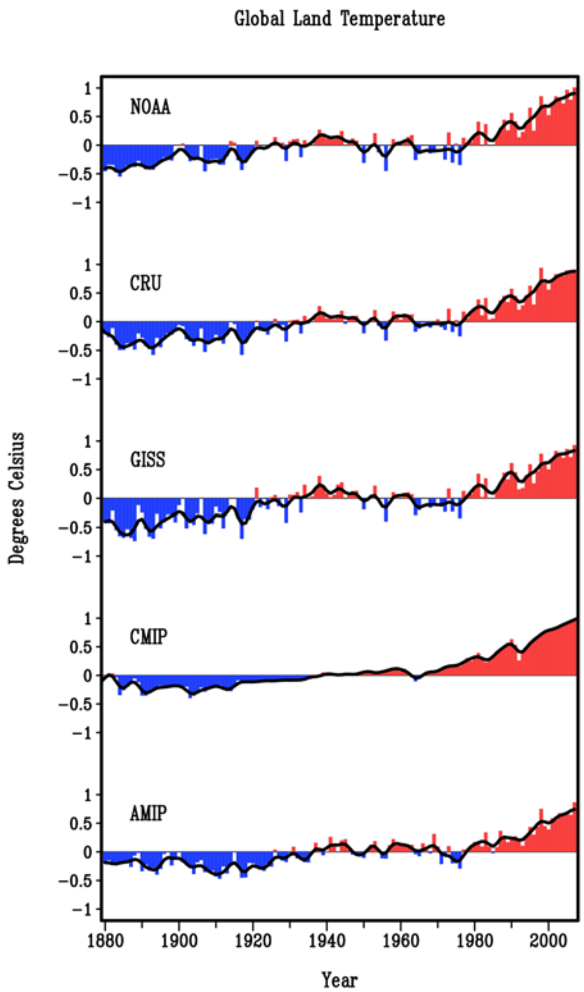

Figure 1. Time series of annual global land temperature departures (°C) during 1880–2007 based on three different observational analyses (NOAA, CRU and NASA), the ensemble of CMIP simulations forced with observed greenhouse gas, aerosol, solar, and volcanic aerosol variability, and the ensemble of AMIP simulations forced with observed global sea surface temperature variability. Reference period is 1921–1970. Bars plot the annual departure, computed relative to a 1921–1970 reference period, and the curve is a 5-point Gaussian filer applied to the annual values.

gases, aerosols, solar irradiance and the radiative effects of volcanic activity for 1880–1999, and with the IPCC Special Emissions Scenario (SRES) A1B [*IPCC*, 2007] for 2000–2007. A maximum ensemble of 48 members was available, with model data accessed from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) archive as part of the Coupled Model Intercomparison Project (CMIP3) [*Meehl et al.*, 2007].

[6] The externally forced (greenhouse gas, aerosol, solar and volcanic) signal in global land temperature variability is estimated by averaging the multi-model CMIP ensemble members, whereas the SST-forced signal is estimated by averaging the multi-model AMIP ensemble members. All anomalies are also computed with respect to the simulated climatology for the period 1921–1970.

3. Principal Causes of Global Mean Land Temperature Variability for 1880–2007

[7] Figure 1 presents observed and simulated time series of annually averaged global mean land temperature departures during 1880–2007. Various observational analyses are shown. Though each is based largely on the same input of available station measurements, differences do arise from methods of interpolation across data sparse regions. The various time series are nonetheless in good agreement—the temporal correlation of the raw annual values among each data set exceeds 0.95 during the 128-yr period. The principal features of variability are the cold epoch during the first half-century, and the recent epoch of strong warming that commenced in the late 1970s. Superimposed on these low frequency states are year-to-year fluctuations. For 1880–2007 as a whole, the standard deviation of annual variations is 0.33°C based on the NOAA analysis. The strong trend in recent decades augments this measure of variability, and a calculation of the standard deviation during 1880–1976 that precedes the emergent warming yields 0.20°C.

[8] The response to time varying external radiative forcing explains many key features of GMLT variability since 1880. The fourth time series in Figure 1 summarizes the variations occurring in the ensemble averaged CMIP simulations. The agreement with observations is evident; correlated at 0.85 with observations (Table 1), most of the observed GMLT variations are caused by external forcing. This is especially true for lower frequency features, including the cold epoch of 1880–1920 and the strong warming after the 1970s. Regarding the simulated cold period, the coupled models are principally responding to aerosol forcing attributable to a sequence of volcanic eruptions including Krakatau (1883), Ritter (1888), Awu (1892), Soufriere (1902), Mount Pele (1902), Santa Maria (1902), and Tall (1911). Regarding the recent warming, the strong agreement between the observations and CMIP simulations reiterates the IPCC Fourth Assessment Report's conclusion that "most of the observed increase in global averaged temperatures since the mid-20th Century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations" [*IPCC*, 2007].

[9] Virtually all features of the global mean land temperature response to time varying external forcing are reproduced in atmospheric model simulations driven by time varying observed SSTs, but employing climatological external forcing. The lower time series in Figure 1 summarizes the fluctuations occurring in the ensemble averaged AMIP simulations. The agreement with both observations and the CMIP results is very strong, with

Table 1. Correlation of Observed and Simulated Annual Global Land Temperature

	1880–2007	1880–1975	1976–2007
OBS v CMIP	0.85	0.46	0.91
OBS v AMIP	0.87	0.62	0.96
CMIP v AMIP	0.86	0.60	0.89

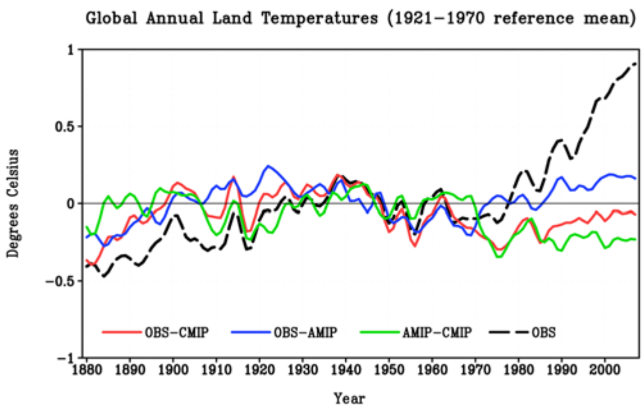

Figure 2. Time series of differences in annual global land temperature departures (°C) during 1880–2007; OBS-CMIP (red), OBS-AMIP (blue), AMIP-CMIP (green). Also shown is the observed time seriesof global land temperature departures (black). Observations are based on the NOAA analysis. The curves are smoothed with a 5-point Gaussian filter to emphasize multi-annual time scales. Reference period is 1921–1970.

temporal correlations of raw annual values during 1880–2007 of 0.87 and 0.86, respectively (Table 1).

[10] The AMIP simulations provide two key new insights on the cause for global mean land temperature variability. First, GMLT variability is essentially a slave to global SST variability. It is remarkable that 75% of the observed globally averaged annual mean land temperature variability in the past 128-years is explained by the response to SST forcing, and furthermore that 92% of the variance in the recent period of strong global warming is so explained. Second, the physical process by which GMLT responds to time varying external forcing occurs mainly through an indirect effect involving the world oceans, rather than through a direct local radiative effect alone. The externally forced response can thus be viewed as occurring via a two-stage process—SSTs respond to the changes in external forcing which in turn drive an atmospheric response that communicates the ocean change to land regions. The time scale for the atmospheric response to the SSTs is less than a month [*Jin and Hoskins*, 1995], whereas the time scale for the SST response to external forcing is much longer and depends on the rate of ocean heat uptake and the slow oceanic equilibration to changes in the radiative forcing.

[11] The time series of differences between observed and simulated global mean land temperature provides further insight on role of various physical processes (Figure 2). The time series are based on the smoothed curves of Figure 1 in order to emphasize more systematic features of the differences. The OBS-CMIP (red curve) and the OBS-AMIP (blue curve) differences are generally less than 0.1°C affirming the strong control exerted by forcing on the observed GMLT variability. Suggested thereby is that atmospheric noise, associated with purely internal variability, is secondary for the variability in global mean land temperature especially at lower frequencies. Such an interpretation is also consistent with the fact that the standard deviation of annual global mean land temperature during 1880–2007 from the CMIP and AMIP ensemble averages, a process that minimizes the contribution of atmospheric internal variability, is 0.32°C and 0.27°C, respectively, which is only slightly lower than the standard deviation of the observed time series. The AMIP-CMIP difference (green curve) also offers a clue on the direct impact of radiative forcing on land temperature, a factor not included in AMIP but implicit in CMIP. An increasing divergence between the simulated responses since the middle of the 20th Century can be discerned, with the AMIP runs consistently colder than CMIP since 1970 consistent with their omission of direct radiative forcing.

4. Ocean Driving of Global Mean Land Temperature Variability for 1880–2007

[12] Figure 3 shows the time series of annual globally averaged SSTs for 1880–2007. Recall that the observed time series (Figure 3 (top)) is identical to the corresponding SST time series in the AMIP simulations for which observed global SSTs were specified, whereas the CMIP

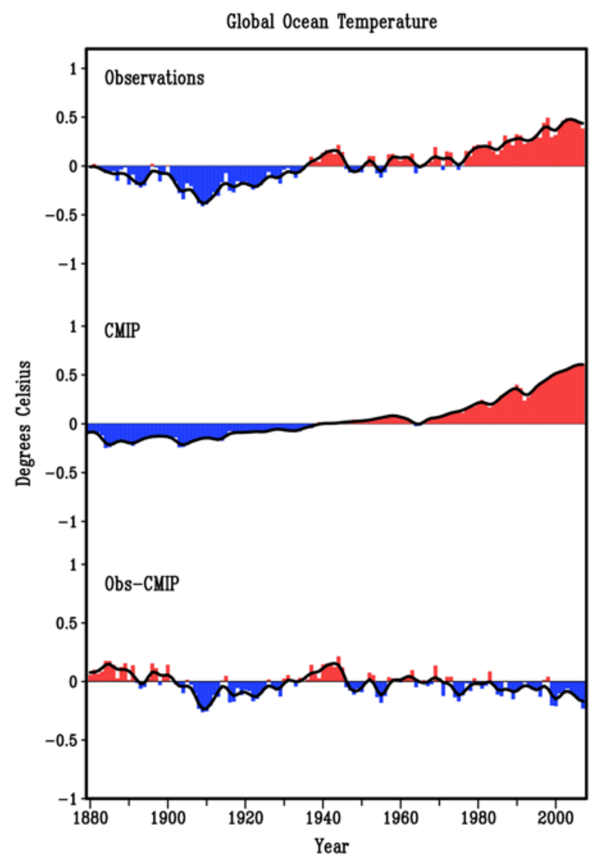

Figure 3. Time series of annual global sea surface temperature departures (°C) during 1880–2007 based on (top) observations, (middle) the ensemble of CMIP simulations forced with observed greenhouse gas, aerosol, solar, and volcanic aerosol variability, and (bottom) the difference (OBS-CMIP). Reference period is 1921–1970. Bars plot the annual departure, computed relative to a 1921–1970 reference period, and the curve is a 5-point Gaussian filer applied to the annual values. Bars in the lower time series are based on the Gaussian filtered differences.

Table 2. Correlation of Observed and Simulated Annual Global Land Temperature and Sea Surface Temperature

	1880–2007	1880–1975	1976–2007
OBS Land v OBS SST	0.81	0.51	0.92
AMIP Land v OBS SST	0.93	0.87	0.94
CMIP Land v CMIP SST	0.99	0.94	0.99
OBS SST v CMIP SST	0.88	0.66	0.88

time series (Figure 3 (middle)) denotes the response of the world oceans to time varying external forcing. The observed SST time series is very similar to that of observed GMLT, with a temporal correlation of 0.81 (Table 2). The results of the AMIP simulations establish that this observed statistical relation is principally one of cause-effect—the SSTs have mainly driven the GMLT variations. Indeed, the correlation between the time series of the AMIP global mean land temperature and specified global SSTs is 0.93.

[13] Much of the variability in global SSTs since 1880 is attributable to changes in external radiative forcing, especially on multidecadal time scales. The 0.88 correlation between CMIP and observed SST time series (Table 2) is largely the result of their common low frequency variations including a protracted cool event related to a sequence of volcanic eruptions in the early century, and the anthropogenic warming trend in recent decades. It is evident from Figure 3, however, that the higher frequency year-to-year global SST variations are not strongly affected by external forcing, aside from abrupt volcanism. Owing to the strong common low frequency components in the observed and CMIP 1880–2007 time series, together with the fact that the interannual fluctuations are of comparatively smaller amplitude, the standard deviation of annual global mean SSTs in the CMIP ensemble mean simulations is only slightly less than in observations. A similar situation was noted with regard to GMLT. A deeper physical explanation can now be rendered of both the protracted cold global land temperature period 1880–1930 and the recent emergent warming (see Figure 1). Both are principally the atmospheric response to externally forced changes in the world oceans—a volcanic induced cooling of SSTs in the early epoch and an anthropogenic induced warming in later decades.

[14] Also shown in Figure 3 is the time series of OBS-CMIP differences in global SSTs. That difference is an estimate of the variability internal to the coupled ocean-atmosphere system, to the extent that the CMIP ensemble is an accurate measure of the externally forced component. Interestingly, a period of warm global SSTs around 1940 (Figure 3 (top)) appears unrelated to external forcing. For this period, the AMIP runs indicate that such ocean warmth elevated global land temperature (see Figure 1), and would thus support the argument that the early 20th Century global warming was in part a large realization of internal coupled ocean-atmosphere variability [*Delworth and Knustson*, 2000; *Kravtsov and Spannagle*, 2008]. During the last several decades, the CMIP global SSTs have been slightly, though consistently, warmer than observations. The CMIP global mean land temperatures have also been slightly higher than observations during that period (see Figure 2), and is physically consistent with the forcing by the warmer oceans in CMIP. It is unclear whether a multidecadal state of internal variability in the world ocean is currently masking some of the greenhouse signal, or whether that response is too strong in the CMIP models.

5. Summary and Discussion

[15] Climate model responses to various forcings were compared to observations in order to determine the causes for variability in global mean land temperature during 1880–2007. It was demonstrated that 76% of the variance in annual global mean land temperatures was caused by SST variations occurring over the world oceans. Most of the global SST variations, especially on multidecadal time scales, were themselves caused by external radiative forcing associated with greenhouse gas, aerosol, volcanic and solar forcing. Furthermore, the comparison of CMIP and AMIP simulations for 1880–2007 demonstrated that the externally forced variability in global mean land temperature occurred mainly via an indirect process involving first the ocean's response and subsequently their atmospheric impact, rather than through a direct local terrestrial response.

[16] It is perhaps not surprising that global sea surface temperatures act as a terrestrial thermostat. A similar relationship has been previously documented to occur over tropical land areas related to ENSO variability [*Kumar et al.*, 2004], and continental warming occurring in recent decades has been shown to be a response largely to worldwide ocean warming [*Hoerling et al.*, 2006; *Compo and Sardeshmukh*, 2008]. An unresolved question of further importance is whether certain regional SST changes are particularly effective in driving global mean land temperature. It has been suggested, for example, that the Atlantic Ocean may be effective in driving global land temperatures, especially on multidecadal time scales [*Zhang et al.*, 2007; *Kravtsov and Spannagle*, 2008]. It is also unclear whether tropical oceans are more important than extratropical oceans, or whether SST variations occurring over the tropical warm pool regions may be especially relevant.

[17] Given global monitoring capabilities and advanced climate modeling tools, can the behavior of the global mean land temperature be anticipated for coming years and decades? What is the likelihood, for instance, that internally generated coupled ocean-atmosphere variations could drive colder global mean land temperatures and temporarily mask the externally forced warming trend? The answer to the question hinges on the expectation for global SSTs. In particular, colder than normal global SSTs would appear to be a necessary condition to cause coolness in terrestrial temperatures. In this regard, it is worth noting that 30 years have passed since global SSTs were last observed to be cooler than normal (1921–1970 climatology). Not coincidentally, an identical period has also passed since global mean land temperatures were also last cooler than normal. If one assumes that the 0.20°C standard deviation of annual global mean land temperature prior to the 1970s was the result of internal variability alone, then in light of the current warming amplitude of 0.8°C, an internally generated cold event of the magnitude of at least four times the standard deviation would be required for global mean temperature to be cooler than 1921–1970 mean. It is expected that a detailed analysis of the sources of variance in the time series of global mean land temperature will

advance our capability to predict and to guide development of prediction systems for the annual and decadal variability.

References

Brohan, P., J. J. Kennedy, I. Harris, S. F. B. Tett, and P. D. Jones (2006), Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850, *J. Geophys. Res.*, *111*, D12106, doi:10.1029/2005JD006548.

Compo, G., and P. Sardeshmukh (2008), Oceanic influences on recent continental warming, *Clim. Dyn.*, doi:10.1007/s00382-008-0448-9.

Delworth, T. L., and T. R. Knustson (2000), Simulation of early 20th century global warming, *Science*, *287*, 2246–2250.

GFDL Global Atmospheric Model Development Team (2004), The new GFDL global atmosphere and land model AM2–LM2: Evaluation with prescribed SST simulations, *J. Clim.*, *17*, 4641–4673.

Hansen, J., R. Ruedy, M. Sato, M. Imhoff, W. Lawrence, D. Easterling, T. Peterson, and T. Karl (2001), A closer look at United States and global surface temperature change, *J. Geophys. Res.*, *106*, 23,947–23,963.

Hoerling, M. P., T. Xu, G. Bates, A. Kumar, and B. Jha (2006), Warm oceans raise land temperatures, *Eos Trans. AGU*, *87*(19), doi:10.1029/2006EO190003.

Intergovernmental Panel on Climate Change (IPCC) (2007), Summary for policymakers, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 1–18, Cambridge Univ. Press, Cambridge, U. K.

Jin, F.-F., and B. J. Hoskins (1995), The direct response to tropical heating in a baroclinic atmosphere, *J. Atmos. Sci.*, *52*, 307–319.

Kanamitsu, M., et al. (2002), NCEP dynamical seasonal forecast system 2000, *Bull. Am. Meteorol. Soc.*, *83*, 1019–1037.

Kiehl, J., J. Hack, G. Bonan, B. Boville, D. Williamson, and P. Rasch (1998), The National Center for Atmospheric Research Community Climate Model: CCM3, *J. Clim.*, *11*, 1131–1149.

Kravtsov, S., and C. Spannagle (2008), Multidecadal climate variability in observed and modeled surface temperatures, *J. Clim.*, *21*, 1104–1121.

Kumar, A., F. Yang, L. Goddard, and S. Schubert (2004), Differing trends in the tropical surface temperatures and precipitation over land and oceans, *J. Clim.*, *17*, 653–664.

Meehl, G., et al. (2007), The WCRP CMP3 multimodel data set: A new era in climate change research, *Bull. Am. Meteorol. Soc.*, *88*, 1384–1394.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.*, *108*(D14), 4407, doi:10.1029/2002JD002670.

Roeckner, E., et al. (1996), The atmospheric general circulation model ECHAM4: Model description and simulation of present-day climate, *Rep. 218*, 90 pp., Max-Planck-Inst. for Meteorol., Hamburg, Germany.

Schubert, S. D., M. J. Suarez, P. J. Pegion, R. D. Koster, and J. T. Bacmeister (2004), On the cause of the 1930s Dust Bowl, *Science*, *33*, 1855–1859.

Smith, T. M., and R. W. Reynolds (2005), A global merged land air and sea surface temperature reconstruction based on historical observations (1880–1997), *J. Clim.*, *18*, 2021–2036.

Zhang, R., T. L. Delworth, and I. M. Held (2007), Can the Atlantic Ocean drive the observed multidecadal variability in Northern Hemisphere mean temperature?, *Geophys. Res. Lett.*, *34*, L02709, doi:10.1029/2006GL028683.

J. Eischeid and M. Hoerling, Earth System Research Laboratory, NOAA, 325 Broadway, Boulder, CO 80305, USA. (martin.hoerling@noaa.gov)

B. Jha, WYLE Information Systems, 656 Quince Orchard Road, Gaithersburg, MD 20878, USA.

A. Kumar, Climate Predicton Center, NOAA, 5200 Auth Road, Room 800, Camp Springs, MD 20746, USA.