Has the climate recently shifted?

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This paper provides an update to an earlier work that showed specific changes in the aggregate time evolution of major Northern Hemispheric atmospheric and oceanic modes of variability serve as a harbinger of climate shifts. Specifically, when the major modes of Northern Hemisphere climate variability are synchronized, or resonate, and the coupling between those modes simultaneously increases, the climate system appears to be thrown into a new state, marked by a break in the global mean temperature trend and in the character of El Niño/Southern Oscillation variability. Here, a new and improved means to quantify the coupling between climate modes confirms that another synchronization of these modes, followed by an increase in coupling occurred in 2001/02. This suggests that a break in the global mean temperature trend from the consistent warming over the 1976/77–2001/02 period may have occurred.

1. Introduction

The subject of decadal to inter-decadal climate variability is of intrinsic importance not only scientifically but also for society as a whole. Interpreting past such variability and making informed projections about potential future variability requires (i) identifying the dynamical processes internal to the climate system that underlie such variability (see e.g. *Mantua et al.* [1997]; *Zhang et al.* [1997]; *Zhang et al.* [2007]; *Knight et al.* [2005]; *Dima and Lohmann* [2007]), and (ii) recognizing the chain of events that mark the onset of large amplitude variability events, i.e., shifts in the climate state. Such shifts mark changes in the qualitative behavior of climate modes of variability, as well as breaks in trends of hemispheric and global mean temperature. The most celebrated of these shifts in the instrumental record occurred in 1976/77. That particular winter ushered in an extended period in which the tropical Pacific Ocean was warmer than normal, with strong El Niño-Southern Oscillation (ENSO) events occurring after that time, contrasting with the weaker ENSO variability in the decades before (*Hoerling et al.* [2004]; *Huang et al.* [2005]). Global mean surface temperature also experienced a trend break, transitioning from cooling in the decades prior to 1976/77 to the strong warming that characterized the remainder of the century.

Extension of this analysis to the entire 20th century as shown in the bottom panel of Figure 1 reveals three climate shifts marked by breaks in the temperature trend with respect to time, superimposed upon an overall warming presumably due to increasing greenhouse gasses. Global mean temperature decreased prior to World War I, increased during the 1920s and 1930s, decreased from the 1940s to 1976/77, and as noted above increased from that point to the end of the century. Insofar as the global mean temperature is controlled by the net top-of-the-atmosphere radiative budget [*IPCC* 2007], such breaks in temperature trends imply discontinuities in that budget. Such discontinuities are difficult to reconcile with the presumed smooth evolution of anthropogenic greenhouse gas and aerosol radiative forcing with respect to time [*Hansen et al.* 2005]. This suggests that an internal reorganization of the climate system may underlie such shifts [*Zhang et al.* 2007].

This paper provides an update to an earlier work that showed a foreshadowing of such climate shifts in the time evolution of major Northern Hemispheric atmospheric and oceanic modes of variability [*Tsonis et al.* 2007]. In that paper, it was hypothesized that certain aspects of the climate system behave in a manner analagous to that of synchronized chaotic dynamical systems [*Bocaletti et al.* 2002]. Specifically, it was shown that when these modes of climate variability are synchronized, and the coupling between those modes simultaneously increases, the climate system becomes unstable and appears to be thrown into a new state. This chain of events is identical to that found in regime transitions in synchronized chaotic dynamical systems [*Pecora et al.* 1997]. This new state is marked by a break in the global mean temperature trend and in the character of ENSO variability. Synchronization followed by an increase in coupling coincided with all the major climate shifts of the 20th century, and was also shown to mark climate shifts in coupled ocean-atmosphere simulations. While in the observations such breaks in temperature trend are clearly superimposed upon a century time-scale warming presumably due to anthropogenic forcing, those breaks result in significant departures from that warming over time periods spanning multiple decades.

Using a new measure of coupling strength, this update shows that these climate modes have recently synchronized, with synchronization peaking in the year 2001/02. This synchronization has been followed by an increase in coupling. This suggests that the climate system may well have shifted again, with a consequent break in the global mean temperature trend from the post 1976/77 warming to a new period (indeterminate length) of roughly constant global mean temperature.

2. Synchronization and coupling revisited

When important climate dynamical modes are synchronized, or alternatively resonate, the climate system appears to be particularly sensitive to the possibility of a shift. Here, we define this synchronization using the root mean square of the cross-correlation between all unique pairs of the four climate modes used by *Tsonis et al.* [2007], which include ENSO, the Pacific Decadal Oscillation, the North Atlantic Oscillation, and the North Pacific Index. Interested readers are referred to *Tsonis et al.* [2007] for more detail into these modes and the rationale for their selection. The top panel in Figure 1 shows that in a statistically rigorous sense such synchronizations only occurred four times (1910-20; 1938-45; 1956-60; and 1976-1981) during the 20th century, and three of those synchronizations (all but 1956-1960) coincided with shifts in the climate state. Thus, synchronization appears to provide a necessary, but not sufficient marker of shifts in climate state.

More generally, the theory of synchronized chaos (*Bocaletti et al.* [2002]; Pecora *et al.* [1997]) suggests that an increase in coupling between modes while those modes are synchronized destabilizes a dynamical system, often leading to a new and different state. Think of a bicycle team engaged in a team time trial. The riders are all synchronized, with their motions carefully planned to maximize the teams overall speed. However, if those riders were coupled together, for example by attaching their bikes together with a rope, the slightest misstep among one of the bikers would be communicated immediately through the team and would lead to a group crash.

Coupling is a property of an individual mode's phase relative to the phases of other modes. When two modes' phases lock, i.e., retain a fixed relationship for a sufficiently long period of time, then regardless of the phase lag between them those modes are considered coupled. Here we define the phase for each mode non-parametetrically, based upon a mode's value at three consecutive annual points. This definition yields six possible phase combinations. A consistent increase in a mode over a three year period is defined as zero phase, while a consistent decrease is defined as a phase of π; intermediate values follow as defined by *Tsonis et al.* [2007; their Figure 2]. We are interested in the trend phases of 0 or π, as these phases indicate strong time evolution. If these modes are indeed strongly coupled, a strong tendency in one mode should be matched in the near term by strong tendencies in the other modes. This can be defined in statistically rigorous terms, as given a random time series these trend phases should occur 1/3 of the time (2/6 of the possible phase combinations). Empirical analysis shows that the phase of these observed climate modes defined in this manner has essentially *no* autocorrelation from year-to-year; coupling as defined here is emphatically *not* describing the persistence of modes.

There are several important details regarding the definition of coupling in terms of trends in mode evolution with respect to time. First, even if the modes are strongly coupled, trend phases among the different modes in general will not occur simultaneously, as those modes could have physically based phase lags relative to each other. Hence, in the definition of coupling it is necessary to define a window over which to search for trend phases. For the situation here, we are interested in inter-annual to decadal changes in the coupling, so a window of 5-7 years in length is appropriate. The results below are not sensitive to the precise length of that window.

In contrast to the definition of coupling used by *Tsonis et al.* [2007], a clear statistical definition of 'strong' and 'weak' coupling is possible simply by calculating the coupling using surrogate data generated from an AR-1 process with the same autocorrelation as the observed mode time series. Moreover, this measure of coupling is more robust in that significantly less time smoothing needs to be applied to capture fluctuations in coupling strength than the measure used by *Tsonis et al.* [2007]. This allows for identification of coupling strength over the recent past.

It is hypothesized that persistent and consistent trends among several climate modes act to kick the climate state, altering the pattern and magnitude of air-sea interaction between the atmosphere and the underlying ocean. The middle panel in Figure 1 shows that these climate mode trend phases indeed behaved anomalously three times during the 20th century, immediately following the synchronization events of the 1910s, 1940s, and 1970s. This combination of the synchronization of these dynamical modes in the climate, followed immediately afterward by significant increase in the fraction of strong trends (coupling) without exception marked shifts in the 20th century climate state. These shifts were accompanied by breaks in the global mean temperature trend with respect to time, presumably associated with either discontinuities in the global radiative budget due to the global reorganization of clouds and water vapor or dramatic changes in the uptake of heat by the deep ocean. Similar behavior has been found in coupled ocean/atmosphere models, indicating such behavior may be a hallmark of terrestrial-like climate systems [*Tsonis et al.* 2007].

Turning to the most recent decade, the top panel of the Figure shows that another synchronization event has recently taken place, with synchronization peaking in 2001/02 The middle panel shows that this event has once again been followed by a significant increase in the frequency of climate mode trend phases with respect to time, i.e., an increase in coupling. Insofar as this sequence of events without fail led to a shift in the climate state during the 20th century as well as in climate model simulations, this strongly suggests that the climate state has recently shifted. If the 20th century past is indeed prologue, such a shift should mark another break in the global mean temperature trend. Figure 2 shows the running 7-year linear least squares fit to seasonal temperature anomalies derived from the HadCRUT3g temperature data over the instrumental time period (post-1950). Over this period, there have been 6 cooling episodes. Three of these are associated with tropical volcanic eruptions (Agung 1963; El Chichon 1982; Pinatubo 1991), while the 1955 and 1973 events coincide with large amplitude La Niña events (deviation $<$ -1.5 standard deviations of the multivariate ENSO index of *Wolter and Timlin* [1998]). Curiously, the most recent and ongoing cooling event has no obvious proximate explanation, as there has been no substantive recent volcanic activity and the ENSO cycle since 2001/2002 has been benign (variability of less than one standard deviation of the multivariate ENSO index). This cooling, which appears unprecedented over the instrumental period, is suggestive of an *internal* shift of climate dynamical processes that as yet remain poorly understood.

There have been other arguments that a shift in the climate occurred around the turn of the 21st century. *Cummins et al.* [2005] have proposed an upper ocean climate index based upon sea surface height (SSH) data from satellite altimetry and other data which show the mid-1970s climate shift from negative to positive and a later change from positive to negative around 1998 which they call a "shift." *Peterson and Schwing* [2003], *Bratcher and Giese* [2002] and *Hartman and Wendler* [2005] also refer to a "shift" in a climate parameter during 1999 to 2002. However, the verification of this shift using the technique here is notable because it appears global and has broad precedents in 20th century climate behavior as well as in climate model simulations.

It has been hypothesized that the planetary radiative budget in recent decades has been out of balance due to radiative forcing by greenhouse gasses and lags in the oceanic response, with absorption exceeding emission by roughly 0.8 Wm^{-2} around the turn of the century [*Hansen et al.* 2005]. Since then, by itself increasing CO_2 concentrations of roughly 20ppm should have further added roughly 0.2 Wm^{-2} to this top-of-the-atmosphere excess of absorption over emission. Assuming a mixed layer ocean depth of 200 m, an anomaly of roughly 1 Wm^{-2} should in principle have been sufficient to drive roughly a 0.25°C increase in global temperature since 2001/02. That such warming has not occurred suggests an internal reorganization of the climate system has offset this presumptive radiative imbalance, either via an anomalously large uptake of heat by the deep ocean or a direct offset of the greenhouse gas forcing by a shift in cloud forcing.

3. Conclusions

If as suggested here, a dynamically driven climate shift has occurred, the duration of similar shifts during the 20th century suggests the new global mean temperature trend may persist for several decades. Of course, it is purely speculative to presume that the global mean temperature will remain near current levels for such an extended period of time. Moreover, we caution that the shifts described here are presumably superimposed upon a long term warming trend due to anthropogenic forcing. However, the nature of these past shifts in climate state suggests the possibility of near constant temperature lasting a decade or more into the future must at least be entertained. The apparent lack of a proximate cause behind the halt in warming post 2001/02 challenges our understanding of the climate system, specifically the physical reasoning and causal links between longer time-scale modes of internal climate variability and the impact of such modes upon global temperature. Fortunately, climate science is rapidly developing the tools to meet this challenge, as in the near future it will be possible to attribute cause and effect in decadal-scale climate variability within the context of a seamless climate forecast system [*Palmer et al.* 2008]. Doing so is vital, as the future evolution of the global mean temperature may hold surprises on both the warm and cold ends of the spectrum due entirely to internal variability that lie well outside the envelope of a steadily increasing global mean temperature.

Finally, it is vital to note that there is no comfort to be gained by having a climate with a significant degree of internal variability, even if it results in a near-term cessation of global warming. It is straightforward to argue that a climate with significant internal variability is a climate that is very sensitive to applied anthropogenic radiative anomalies (c.f. *Roe* [2009]). If the role of internal variability in the climate system is as large as this analysis would seem to suggest, warming over the 21st century may well be larger than that predicted by the current generation of models, given the propensity of those models to underestimate climate internal variability [*Kravtsov and Spannagle* 2008].

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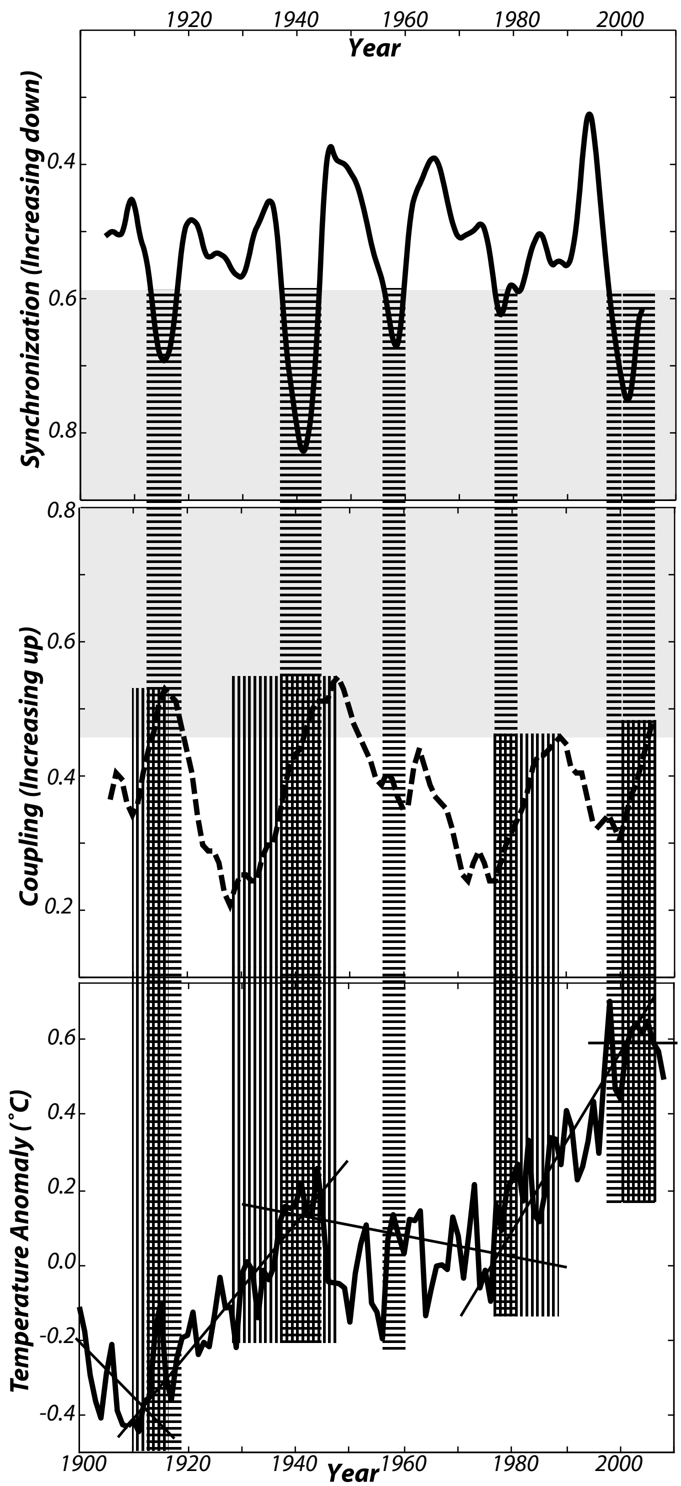
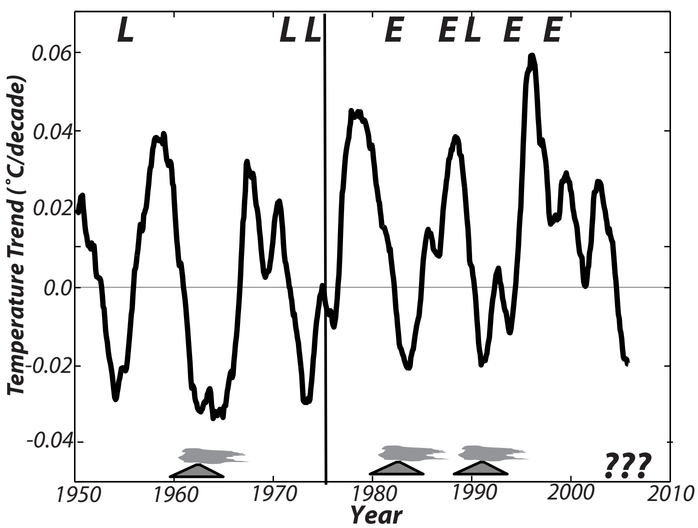
Fig. 1. Top panel: Synchronization as measured by the root-mean-square correlation coefficient between all pairs of modes over a 7-year running window. Note the reversed ordinate; synchronization increases downward in the panel. High synchronization at the $p = 0.95$ level is denoted by shading, tested by generation of surrogate data as described in *Tsonis et al.* (2007). Middle panel: Coupling as measured by the fraction of consistently increasing or decreasing mode time series as described in the text. The shaded region denotes coupling at the $p = 0.95$ level as calculated from the surrogate data used for the confidence intervals in the top panel. Bottom panel: HadCRUT3g global mean temperature over the 20th century, with approximate breaks in temperature indicated. The cross-hatched areas indicated time periods when synchronization is accompanied by increasing coupling.

Fig. 2. Linear least square trends in seasonal global mean temperature over running 7-year periods. Data are taken from the HadCRUT3g temperature records. The Agung (1963), El Chichon (1982) and Pinatubo (1991) volcanic events are indicated on the bottom of the figure, and El Niño (E) and La Niña (L) events that exceed 1.5 standard deviations in magnitude based upon a multivariate ENSO index are indicated on the top.



1920
1940
1960
1980
2000
Year
Synchronization (Increasing down)
0.4
0.6
0.8
Coupling (Increasing up)
0.8
0.6
0.4
0.2
Temperature Anomaly (°C)
0.6
0.4
0.2
0.0
-0.2
-0.4
1900
1920
1940
1960
1980
2000
Year



L
L L
E
E L
E
E
0.06
0.04
0.02
0.0
-0.02
-0.04
Temperature Trend (˚C/decade)
???
1950
1960
1970
1980
1990
2000
2010
Year