Greenhouse Warming and Changes in the Seasonal Cycle of Temperature: Model Versus Observations

Michael E. Mann and Jeffrey Park

Department of Geology and Geophysics, Yale University, New Haven, Connecticut

Abstract. Thomson [1995] argues that an enhanced greenhouse effect may be altering the seasonal cycle in temperature. We compare trends in the amplitude and phase of the seasonal cycle in observational temperature data in the northern hemisphere with the response of two general circulation models to increased CO_2 concentrations. Sizeable amplitude decreases are observed in both models and observations. Significant phase delays (ie, later seasonal transitions) are found in the simulations, opposite to the phase advances isolated in the observations. The retreat of winter sea ice in high-latitude regions appears to explain the models' response to CO_2 increase. Much of the variability in the observational data is not predicted by the models.

Introduction

Thomson [1995] showed that shifts in the phase of the annual cycle in temperature during the 20th century are correlated with atmospheric CO_2 concentrations, and argued for an anthropogenic cause. Similar phase changes have been observed in the seasonal cycle of temperature in particular regions [*Davis*, 1972; *Thompson*, 1995] as well as shifts in the seasonality of precipitation [*Bradley*, 1976; *Rajagopolan and Lall*, 1995], streamflow [*Lins and Michaels*, 1994; *Dettinger and Cayan*, 1995], and Southern Hemisphere winds and sea-level pressure [*Hurrell and Van Loon*, 1994]. Potential physical connections with greenhouse forcing have been suggested [*Lins and Michaels*, 1994], complementing the statistical correlation found by *Thomson* [1995].

If observed changes in seasonality are consistent with an enhanced greenhouse effect, the observed trends in the seasonal cycle should resemble the predicted response of present-generation climate models to enhanced greenhouse conditions. Here, we compare trends in the seasonal cycle of temperature in the northern hemisphere with those predicted by simulations of 1) the Geophysical Fluid Dynamics Lab (GFDL) coupled ocean-atmosphere model, and 2) the NCAR Community Climate Model (CCM1) general circulation/slab ocean model.

Northern hemisphere average trends

We approximate the seasonal cycle in temperature by its fundamental annual component $A(t)\cos(2\pi t + \theta(t))$, where

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t is time in years and the phase $\theta(t)$ and amplitude $A(t)$ can vary with time. This simple statistical model is motivated by the fact that surface temperature seasonality is determined, within a phase lag, by the yearly cycle of insolation at the top of the atmosphere in most locations. The harmonics of the annual cycle are important, however, in the tropics and in the polar latitudes of the southern hemisphere [see e.g., *Trenberth*, 1983] and provide essential information about relationships with specific seasons (e.g., the onset of "spring" [*Davis*, 1972]). The departures of certain seasonal features (e.g., convective mixing in the high-latitude ocean, the termination of the monsoons, or sea ice and snowcover processes) from a simple annual cycle suggest that our analysis provides only a first-order estimate of more general changes in the structure of the seasonal cycle.

Using the estimated Northern Hemisphere (NH) average monthly temperature series of Jones et al ["J&W", 1986–updated in *Jones*, 1994] with seasonal climatology intact, we estimated the variation in $\phi(t)$ and $A(t)$ of the annual cycle over the interval 1854-1990 through complex demodulation (Figure 1). We used three Slepian data tapers and a 10 year moving interval or "projection filter" to obtain low-variance estimates of the trends in $A(t)$ and $\phi(t)$. Through this method, phase shifts of less than one day can be resolved in monthly data [see *Thomson*, 1995]. The calculated trends were robust as we varied the length of the moving window from 5 to 20 years. The highly variable spatial sampling (growing from $\sim 20\%$ to near-complete areal coverage during the interval under examination) may bias estimates of small changes in hemisphere-averaged quantities. To test for such bias, we analyzed alternative "frozen grid" estimates of the NH average series using gridded land air and sea surface temperature data [*Jones and Briffa*, 1992]. These series were calculated from both 1) a "sparse" sampling of all nearly-continuous gridpoint series from 1890 to 1989 [see e.g., *Mann and Park*, 1994] providing 33% coverage, and 2) a "dense" sampling from 1899 to 1989 providing 53% areal coverage (shown in Figure 2). The gross trends in the annual cycle phase and amplitude (Figure 1) appear insensitive to the sampling of large-scale averages (see Table 1), though an unavoidable bias due to data sparseness at latitudes poleward of 70°N may exist. The baseline annual cycle varies with the mixture of land, ocean, and high-latitude grid points due to important regional variations in phase and amplitude.

Trends towards an advanced phase (ie, earlier seasonal transitions) to be significant at better than 2.5σ in each of the three data schemes (Table 1) based on jacknife uncertainties, taking serial correlation into account. Such significance does not alone indicate a causal connection with greenhouse-related warming, as it could result, for example, from the enhanced century-scale *natural* variability that is evident in both observations [*Mann and Park*, 1994; *Schlesinger and Ramankutty*, 1994; *Mann et al* 1995*b*] and modeling studies [*Delworth et al*, 1994]. If an opposing trend towards delayed phase due to orbital precession is adopted as a null hypothesis [*Thomson*, 1995], the above trends become more significant. However, because this effect is still subject to controversy [e.g., *Karl et al* 1995] we have adopted the more conservative null hypothesis.

A significant decreasing trend in $A(t)$ is also found for each data-weighting scheme (Figure 1b). A break in the slope between 1884 and 1895 is significant at the $p = 0.01$ level. Lean et al [1995] suggest an increasing trend in solar irradiance beginning in the early 20th century. This trend could counteract an even greater decrease in $A(t)$ that might arise from global warming and associated ice albedo feedback, potentially explaining the break in slope. A connection between decreasing $A(t)$ and decreased winter ice cover is suggested by the model responses to greenhouse forcing.

We analyzed for comparison both (i) the change in the CCM1 climatological annual cycle between 330 ppm and 460 ppm CO_2 level equilibrations [see *Oglesby and Saltzman*, 1992; *Marshall et al*, 1995] and (ii) 100-year simulations of the GFDL coupled model [e.g., *Manabe et al*, 1991] with (a) a gradual (1%/year) CO_2 increase and (b) with fixed present-day CO_2. Both models exhibit a significant annual cycle response to greenhouse forcing (Table 1). Decreased amplitude of the annual cycle under CO_2-enhanced conditions is consistent with the observations. The trend in phase for the models, however, is opposite to that observed, exhibiting a delay, rather than an advance, of the seasons. The magnitude and significance of the trends in the enhanced-greenhouse GFDL simulation diminishes if high and low-latitude regions, poorly sampled by the observational data, are excluded (Figure 1a), but no latitude band exhibits the phase *advance* found in the the observations. The control GFDL simulation, like the observations, exhibits a marginally significant advance in phase (Table 1), perhaps associated with organized century-scale variability [*Delworth et al*, 1994].

Spatial patterns

To reconstruct the spatial patterns of the climatological annual cycle, we used a multivariate generalization [*Mann and Park*, 1994; *Mann et al*, 1995*ab*] of the complex demodulation procedure used by *Thomson* [1995]. The climatological seasonal cycle in the control GFDL simulation resembles quite closely that for the "dense" observational temperature sampling (Figure 2). It should, however, be noted that this is partly due to seasonally-specific flux corrections that are imposed in the model on at the ocean surface [*Manabe et al*, 1991]. These climatological flux corrections, furthermore, may suppress the tendency for the annual cycle in the model to depart from its baseline state. The annual cycle over continents is delayed by ~ 1 month relative to the insolation cycle, due to the thermal capacity of land, continental snow cover, and other climatic factors – see *Trenberth* [1983] for an overview. The greater thermal capacity of the oceans leads to a greater delay (typically, 2 months) and a smaller annual cycle amplitude. Land areas strongly influenced by the oceans experience a more maritime annual cycle. Winter sea ice insulates the ocean surface from the mixed layer, exposing some oceanic regions to cold continental outbreaks. This can lead to a more "continental" seasonal cycle in the high-latitude oceans. Changes in the annual cycle could thus arise from many influences. The climatological annual cycle of the CCM1 (not shown) reproduces the observations less well. CCM1 predicts an oceanic phase lag that is typically ~ 1 month too large because the slab ocean is a poor approximation to the true mixed layer.

To determine the spatial pattern of annual cycle trends in the GFDL simulations, we used the multivariate procedure described above to isolate the average annual cycle in successive 10-year intervals. We regressed the long-term trends in $\theta(t)$ and $A(t)$ on a gridpoint-by-gridpoint basis, calculating jacknife uncertainties from the decadal averages. The spatial pattern of the CCM1 response (not shown) was estimated by differencing the 460 ppm and 330 ppm equilibrium climatologies.

The dominant response in both the CCM1 and GFDL models to increased CO_2 is one of substantial phase delays and amplitude decreases in high latitude oceanic regions. We interpret phase trend as arising from decreased winter sea ice cover and greater exposure of the surface to the ocean's mixed layer and its delayed thermal cycle. The amplitude trend is consistent with a strong positive ice-albedo feedback from reduced winter ice-cover. The close similarity of the primary response in these two very different model experiments suggests a consistent dynamical mechanism. Nonetheless, a more spatially-complex trend pattern in the GFDL coupled model (Figure 3) suggests other potential regional effects. Marginally significant phase advances, for example, are found in south central and eastern Asia. In the western U.S. the phase advance and amplitude increase suggests decreased maritime influence. The significance of these features, however, is comparable to those observed in the control experiment, suggesting that they may be associated with the model's natural century-scale variability rather than with a greenhouse response, or perhaps with some combination of these effects.

Observed amplitude trends (Figure 4) are $-2.4°C < \delta A < +1.0°C$. Phase advances and delays of $3°$–$7°$ (i.e. 3 to 7 days) are common. The largest δA is along the western margins of Greenland, where significant winter warming has occurred during the last century [*Jones and Briffa*, 1992]. Here, we also find the most significant trend towards a delayed (∼8 days) annual cycle in the northern hemisphere consistent with the model-predicted signature of greenhouse-related decreases in high-latitude sea ice. In contrast, the phase of the annual cycle has advanced along the eastern margins of Greenland, where a long-term winter cooling trend is observed [*Jones and Briffa*, 1992]. This cooling appears to be associated with organized century-scale variability in the North Atlantic [see *Mann and Park*, 1994; *Schlesinger and Ramankutty*, 1994; *Mann et al*, 1995*b*] which could explain why the signature of greenhouse forcing is masked in this region. The annual cycle amplitude decreases in this location because winter cooling is offset by even greater summer cooling. A broad region of significant trends in annual cycle phase and amplitude is found in the extreme southwestern U.S. and offshore in the subtropical Pacific. This may be related to secular changes in the El Nino/Southern Oscillation (ENSO) and associated changes in patterns of summer coastal upwelling [e.g. *Trenberth and Hurrell*, 1994; *Graham*, 1995].

A combination of phase advances and amplitude decreases over mid-latitude continental interiors is consistent with an earlier snowmelt and runoff [*Lins and Michaels*, 1994; *Dettinger and Cayan*, 1995; *Groisman et al*, 1994] that may be related to greenhouse warming [*Lins and Michaels*, 1994; *Groisman et al*, 1994]. Few other locations in the Northern Hemisphere exhibit a consistent, readily interpretable annual cycle response. The constructive addition of trends in continental-interior regions is primarily responsible for the average ∼1 day phase advance for the Northern Hemisphere.

Discussion

Both observations and model responses to greenhouse forcing show a trend towards decreased amplitude of the seasonal cycle in NH-average temperatures. The simulations suggest that these amplitude decreases may result from ice-albedo feedback. It is here, however, that the agreement ends; the observed and model-predicted trends in the phase of the seasonal cycle show little similarity.

If, as the models predict, the dominant influence on annual-cycle amplitude $A(t)$ and phase $\phi(t)$ stems from high-latitude sea-ice decreases, the signature of greenhouse warming is scarcely evident in the observational data, which lack widespread high-latitude sampling. The trend in Western Greenland, the highest-latitude region in the observations, does nonetheless resemble model predictions. It is possible that observed trends in phase, largely influenced by mid-latitude continental interiors, do not arise from greenhouse warming, but rather from natural variability. Such a notion is reinforced by the fact that marginally-significant trends are found in the control GFDL annual cycle, presumably due to organized century-scale internal variability.

If, on the other hand, the observed variation in the seasonal cycle truly represents a "fingerprint" of greenhouse warming, the GFDL and CCM1 models do not appear capable of capturing the detailed responses of the seasonal cycle to greenhouse forcing. In particular, if the phase advances that result from the behavior in continental interiors are not only statistically (as *Thomson* [1995] suggests), but in fact, causally related to greenhouse forcing, the predicted behavior of the models in these regions would appear to be flawed. Deficiencies in certain aspects of the models (e.g., land surface parameterizations) could plausibly be at fault in such a scenario. The absence of an ENSO of realistic amplitude is also a potential shortcoming of model-predicted changes in seasonality, as some of the observed trends appear to show connections with ENSO.

It is possible, probably likely, that the observed trends in the seasonal cycle represent a combination of internal variability, enhanced greenhouse effects and external forcings. Various alternative scenarios are difficult to resolve, owing to limitations in the observational data and potential shortcomings in the models' descriptions of certain climate processes. The latter limitation may largely be overcome in newer generation climate models. Discrepancies between the observed and model-predicted trends must be resolved before a compelling connection can be drawn between 20th century changes in the behavior of the annual cycle in temperature, and anthropogenic forcing of the climate.

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M. E. Mann, Department of Geology and Geophysics, Kline Geology Laboratory, P.O. Box 208109, New Haven, CT 06520-8109.

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Figure 1. (a) Phase of annual cycle in Northern Hemisphere average temperature for observations and model simulations. Best-fit linear trends (Table 1) are shown. For the observational data, results for both the "J&W" expanding grid, and sparse and dense "frozen-grid" estimates (see text) are indicated. For the longer J&W series, a break in slope near 1900, marks a transition from decreasing to increasing phase (latter portion shown with thicker curve). Time axis for the model defined by the actual year corresponding to the initial prescribed CO_2 level. For the CCM1 (equilibrium) experiment, only the net change has meaning. For graphical purposes, a timescale is prescribed by assuming the same 1 %/year increase as in the GFDL experiment. (b) Amplitude of the annual cycle. Decreasing trends of varying magnitude are found for both model and observed data. Best-fit linear trends are shown (Table 1), with a break in slope again evident in the observations between 1890 and 1900.

Figure 2. Phase and amplitude of the "baseline" annual cycle in temperature for (a) observation and (b) control GFDL simulation. A phase of 0° (rightward pointing arrow) indicates a minimum temperature that coincides with minimum insolation (Dec. 22nd) in the Northern Hemisphere. A 30° counter-clockwise rotation indicates a 1-month phase delay of minimum temperature relative to the insolation minimum.

Table 1. Linear Trends in Phase and Amplitude of Northern Hemisphere Average Annual Temperature Cycle for Model and Observations.

SERIES	$\Delta\phi(^o)$	signif.	ΔA	signif.
OBSERV (J&W: 1854-1904)	-1.4	$> 5.5\sigma$	-0.55	$> 6\sigma$
OBSERV (J&W: 1899-1989)	0.79	$> 4.5\sigma$	-0.13	$> 4\sigma$
OBSERV (SPARSE)	0.71	$> 3\sigma$	-0.12	$> 3\sigma$
OBSERV (DENSE)	0.83	$> 3.5\sigma$	-0.10	$> 2.5\sigma$
GFDL (CO_2 increase)	-1.7	$> 7.5\sigma$	-0.48	$> 16\sigma$
" (20-70^o)	-1.2	$> 4\sigma$	-0.50	$> 10\sigma$
" (20-50^o)	-0.2	$< \sigma$	-0.04	$< \sigma$
GFDL (control)	0.5	$> 1.5\sigma$	+0.02	$< \sigma$
CCM1 (460ppm-330ppm)	-5.6		-1.05	

Figure 3. The linear trend of the annual cycle for the enhanced-greenhouse GFDL simulation (a) phase and (b) amplitude. Size of arrows scales the average amplitude of the annual cycle, while the direction indicates relative delay or advance of the annual cycle. A rightward arrow indicates no change in phase. Clockwise and counter-clockwise rotation indicates phase advances and delays, respectively. Significance of trends is indicated in terms of the ratio of the phase shift to its jackknife uncertainty estimate. Boldface symbols/darkest shading indicate nonzero phase and amplitude shifts at the 2-σ level, thin black symbols/medium shading indicate nonzero shifts at the 1-σ level, and grey symbols/no shading indicate shifts within 1-σ of zero.

Figure 4. The linear trend in (a) phase and (b) amplitude of the annual cycle for the "dense" observational network of gridded land air and sea surface temperature data from 1899-1990 discussed in the text. Significance of trends indicated as in Figure 3.