Projected Changes in the Seasonal Cycle of Surface Temperature

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When forced with increasing greenhouse gases, global climate models project a delay in the phase and a reduction in the amplitude of the seasonal cycle of surface temperature, expressed as later minimum and maximum annual temperatures and greater warming in winter than summer. All 24 CMIP3 models agree on these changes and, over the 21st century, average a phase delay of 5 days and an amplitude decrease of 5% for the global mean ocean surface temperature. Most of the global mean changes come from the high latitudes, especially over ocean. We provide evidence that the changes are mainly driven by sea ice loss: as sea ice melts during the 21st century, the previously unexposed open ocean increases the effective heat capacity of the surface layer, slowing and damping the temperature response. From the tropics to the midlatitudes, changes in phase and amplitude are smaller and less spatially uniform than near the poles, but they are still robust. These regions experience a small phase delay, but an amplitude increase of the surface temperature cycle, a combination that is inconsistent with changes to the effective heat capacity of the system. We propose that changes in this region are controlled by changes in surface heat fluxes.
1. Introduction

On annual and longer time scales the seasonal cycle is responsible for around 90% of the total surface temperature variance. In this study we focus on potential changes in the seasonality of the surface temperature due to expected increases in greenhouse gases. These are distinct from changes due to the mean temperature increase, even though the latter can also affect the seasonality of climate-sensitive phenomena if they are linked to specific thresholds, such as streamflow timing due to melting snow (Stewart et al. 2005) and plant flowering (Fitter and Fitter 2002). Here we concentrate on changes to the phase and amplitude of the annual cycle in surface temperature (and to a lesser extent, temperature in the upper atmosphere), independent of the annual mean warming. Specifically, we are interested in the geographic pattern of the response in phase and amplitude to greenhouse gases and the mechanisms responsible for these changes.

In the models of the World Climate Research Programme’s (WCRP’s) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al. 2007), the main changes in the seasonality of surface temperature are a robust delay in phase and a robust decrease in amplitude. This means that the models predict peak temperatures to occur later in the year and the difference between annual maximum and minimum to shrink. We illustrate these effects in Figure 1 by plotting the hemispheric, multi-model mean 2 m surface air temperature over ocean for the last two decades of the 20th and 21st centuries with the annual mean removed. By fitting the anomalies to sinusoids we can quantify the changes compared to the late 20th century: the temperature cycle in the late 21st century has a phase delay of 6 days in the NH and 3 days in the SH and an amplitude decrease of 6% in the NH and 3% in the SH.

As we will show in Section 4, the dominant component of the global mean response is a strong phase delay and amplitude reduction over high-latitude ocean. Manabe and Stouffer (1980), Manabe et al. (1992), and Mann and Park (1996) noticed this high-latitude signal in earlier generations of climate models and proposed that it was a consequence of an increase in
effective heat capacity due to sea ice loss. Sufficiently thick sea ice insulates the atmosphere from the ocean and curtails heat storage in the climate system. As the ice thins and melts, the insulation weakens and disappears and the effective heat capacity of the surface increases. Due to this additional thermal inertia, the temperature responds more slowly and with a smaller amplitude than it would were the ice present.

We build on the earlier modeling studies by demonstrating the seasonality changes in the most recent generation of climate models, investigating the spatial patterns of seasonality changes, and providing substantial evidence that sea ice is driving the high-latitude seasonality changes in the models. In order to verify this mechanism, we interpret the CMIP3 results in the context of a simple energy balance model for surface temperature. Using this and other tools we show that the high-latitude phase delay and amplitude reduction are consistent with an increased effective heat capacity and inconsistent with other potential mechanisms including changes in the seasonality of surface heat fluxes or heat transport. Furthermore, we link the effective heat capacity changes to sea ice loss quantitatively.

Previous observational studies in the NH midlatitudes found a phase advance driven by changes over land and an amplitude reduction during the second half of the 20th century (Thomson 1995; Mann and Park 1996; Stine et al. 2009) and have questioned the ability of the CMIP3 models to reproduce the observed phase and amplitude variations. More recent work by the same authors suggest that the small seasonality changes over land might be due to natural variability in atmospheric circulation (Stine and Huybers 2012). The same study also finds a non-statistically significant phase delay and an amplitude reduction in the NH midlatitudinal oceans. Other recent studies of surface temperature over the Arctic Ocean also found evidence of a phase delay and amplitude decrease due to strong late fall and early winter warming during the last 20–30 years (Serreze et al. 2009; Screen and Simmonds 2010). Since the projected changes in seasonality do not become large until well into the 21st century, we do not necessarily expect them to agree with observations for the 20th century. Yet the correspondence between Arctic sea ice loss over the last few decades (Stroeve et al.
2007) and local changes in seasonality suggests that a key mechanism for the simulated late 21st century seasonality changes is also present in nature, irrespective of the inability of models to reproduce observed trends over land.

At lower latitudes there is a smaller, yet still robust change in the temperature seasonality that is different in nature from the high-latitude signal. Although small, these temperature changes might be linked to seasonality changes in the onset and demise of the monsoons (Biasutti and Sobel 2009; Seth et al. 2011), especially given the sensitivity of the Intertropical Convergence Zone to the tropical sea surface temperature distribution (for example, Chiang et al. (2002)). In the tropics and subtropics, the CMIP3 models project a small phase delay and an amplitude increase, the latter being opposite in sign to the high-latitude amplitude response. Because the phase and amplitude changes are of the same sign, these low-latitude changes cannot be primarily driven by a change in effective heat capacity. Instead, some other effect must be the primary cause. We provide evidence that changes in the seasonality of surface flux are linked to the low-latitude temperature phase delay and amplitude increase. The source of the low latitude changes in fluxes is not clear, but it might be linked to wind speed changes as explained in Sobel and Camargo (2011)

The rest of the paper is laid out as follows. In the next section we give background information on the data we analyze from CMIP3 and a reanalysis dataset and explain the methods we use to calculate the phase and amplitude of the annual cycle. In Section 3 we describe the climatological structure of the annual cycle at the surface and aloft as represented by both the CMIP3 multi-model mean and the reanalysis and demonstrate agreement between the two, as both capture the slow, weak surface temperature response to insolation over ocean and the fast, strong response over land. Moreover both datasets show that over sea ice, the temperature response is more land-like than ocean-like. In Section 4 we detail the changes to the annual cycle at the surface and aloft as projected by the models and discuss the differences at high and low latitudes. In Section 5 we look at both of these regions individually and demonstrate that the changes in sea ice account for much of
the high-latitude temperature cycle change, while changes in the seasonality of surface flux explain the seasonal temperature changes. Finally, we summarize our findings in Section 6.

2. Data and Methods

Throughout this study we use the CMIP3 20th century historical simulations (20C3M) and 21st century A1B scenario simulations, where CO$_2$ emissions peak in the middle of the 21st century and decrease thereafter (Meehl et al. 2007). Monthly temperature data is sufficient to characterize the phase and amplitude of the annual cycle. We only use one realization of each model. All 24 models store temperature data at all levels, but only 20 models store sea ice data and 18 store total surface flux data. When data is missing, we take the multi-model mean to be the subset of models with available data. Surface temperature is defined as 2 m air temperature, which is linked to SST over open ocean, though not over sea ice (since SST is constrained to the melting point of sea water). To compare the model results with observations, we use the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 reanalysis data set (Uppala et al. 2005), which covers 1958–2001.

We calculate the phase of the seasonal cycle using two different techniques. The first uses empirical orthogonal functions (EOFs). In this approach we decompose the climatological mean, monthly data into spatial eigenfunctions of the covariance matrix and associated principal component time series (PCs) (Kutzbach 1967). We obtain amplitude and phase information by fitting a sinusoid to the principal component representing the annual cycle, which is always associated with the EOF capturing the highest fraction of the total variance, except within about 5° of the equator. The other method is Fourier transforming the data to obtain the annual harmonic of each field of interest. Both methods are able to resolve phase and amplitude precisely from monthly data. Fourier transforms can be calculated pointwise, but they cannot obtain reliable phase information in the tropics because of the relatively small amplitude of the annual cycle there. EOFs are defined for the entirety of the domain.
of interest, but are dominated by regions of large annual variance. After spatially averaging
area-weighted phases and amplitudes calculated with a Fourier transform, the results are
nearly identical to those calculated using EOFs over the same domain.

Since our analysis is predicated on the temperature cycle being accurately described by a
sinusoid with a period of one year, we will only use locations for which the annual component
explains at least 80% of the total variance. These are roughly the same regions for which
insolation is dominated by the annual harmonic (Trenberth 1983). Surface temperature and
insolation each have over 95% of their total variance described by the annual cycle between
20° and 70°. At higher latitudes only around 85% of the insolation is due to the annual cycle
due to the sunless winters and nightless summers, but the annual cycle is still dominant
enough that we include these regions in our analysis. Over Antarctica, the temperature
cycle has a large semi-annual component due to the “coreless winters” of relatively constant
cold temperatures owing to the large landmass being in longwave radiative balance as well
as to dynamical effects (Loon 1967). In the Arctic, the temperature cycle is surprisingly
annual, with over 95% of the total temperature variance described by the first harmonic.
The strength of the annual harmonic of temperature in the Arctic can be partly attributed
to the seasonal sea ice cycle, which is not discrete, but instead smoothly varies throughout
the year with advancing and retreating ice margins, thickening and thinning sheet ice, melt
pond formation and other effects (Eicken 2008). In the tropics, the second harmonic becomes
prominent since the sun passes overhead two times per year. The variance explained by the
annual insolation and temperature cycle drops sharply into the deep tropics, and within 10°
of the equator less than 85% of the total variance is due to the annual cycle.

The Earth’s axial and apsidal precession also changes the phase of the temperature cycle
towards earlier seasons in the NH and later seasons in the SH (Stine and Huybers 2012).
Only four of the CMIP3 models have a different phase of insolation between the 20th and
21st centuries. We account for any such changes by measuring the temperature phase relative
to the local insolation phase, so that any phase changes in the models are not due to celestial
mechanisms.

3. Climatological Structure

Before analyzing the changes to the annual cycle, we look at the long-term mean of the phase and amplitude at the surface and aloft for both models and the reanalysis. Most models are clustered within about 5 days of the multi-model mean phase and about 15% of the mean amplitude (though in any given year, there is a 15-20 day phase difference and nearly a factor of two difference in amplitude between the most extreme models as in Figure 5 in Section 4). Despite the presence of several models with large biases, the multi-model mean is representative of most models.

a. Surface

The seasonality of incoming diurnal mean solar radiation depends only upon latitude. The phase of annual insolation is a weak function of latitude varying by only a few days between the tropics and poles, but the amplitude of annual insolation increases markedly with latitude from about 50 W m\(^{-2}\) at 10° to around 275 W m\(^{-2}\) at 90° (Trenberth 1983). Since the temperature cycle is primarily governed by the solar cycle, the seasonality of temperature has a pattern that is qualitatively similar to that of insolation, but with substantial departures due to the local effective heat capacity of the surface layer.

Effective heat capacity of the surface is a function of both the material properties and dynamical behavior of the layer adjacent to the atmosphere. We refer to it as effective since it is neither the intensive heat capacity (per unit mass) of some material substance, nor the extensive heat capacity of a fixed mass of that substance. Rather, it is the heat capacity of the layer of material through which heat is transported sufficiently rapidly that it is influenced by the atmosphere on time scales of interest. The mixed-layer ocean has a relatively large heat capacity because turbulent mixing in it is effective in transporting heat downward so
that a thick layer of water is rapidly influenced by air-sea heat exchanged. This causes ocean surface temperature to respond sluggishly and with small amplitude to heat fluxes at the ocean surface. Temperature has a much faster and stronger response to insolation over land than ocean because only a very thin layer of the land responds on annual time scales, since the primary soil heat transfer process is diffusion with a small diffusivity. The effective heat capacity of land depends to some extent on the type of soil and the moisture content, but a typical estimate would be equivalent to a 6 m ocean mixed layer depth (Carson and Moses 1963). For comparison, the heat capacity of a tropospheric air column is roughly equivalent to that of 4 m of ocean.

We plot the ERA-40 reanalysis and CMIP3 multi-model mean surface temperature phase lag from insolation averaged over 1958–2001 in Figure 2(a) and 2(b), respectively. The models show good fidelity to observations in their geographic structure. Phase delays are smaller over the continents, as temperature over land responds more quickly than over ocean, and this effect is propagated downwind (the temperature phase in the NH midlatitudes can be well described by the westward distance from the coast (Stine et al. 2009)). The largest differences between models and observations are mainly over the midlatitude oceans where the models have a larger phase lag than those of observations (Figure 2(c)).

In regions of sea ice (e.g., the high-latitude Arctic and Southern oceans), the phase lag has a response in-between those of land and ocean. Around the maximal winter extent ice margins, the temperature responds slowly - as over the ocean - while closer to the poles the temperature response is more akin to land for both observations and models. This pattern is consistent with the insulating effect of sea ice becoming stronger in regions of more extensive and thicker ice coverage, and being responsible for the rapid polar temperature response due to a reduced effective heat capacity.

A similar pattern holds for the amplitude. Figure 2(d) and 2(e) show the temperature amplitude from the ERA-40 reanalysis and the CMIP3 multi-model mean, respectively. Both show that most of the surface has a relatively weak seasonal cycle with an amplitude under
5°C. The cycle is much stronger over land and sea ice, though. The difference between
models and observations is plotted in Figure 2(f). Differences are mostly small, though the
models are biased towards a larger amplitude in most places.

We provide more evidence that effective heat capacity sets the climatological surface
temperature phase and amplitude and that the ice-covered ocean has a similar heat capacity
to land in Figure 3. In both Figure 3(a) and (b) we plot the percentages of land and sea ice
that comprise each zonal band as a function of latitude. In Figure 3(a) we plot zonal mean
temperature phase, while in Figure 3(b) we plot zonal mean temperature amplitude divided
by insolation amplitude. The phase is strongly anti-correlated with the fraction of land and
sea ice \( r = -0.90 \), while the amplitude is strongly correlated \( r = 0.82 \), as we expect from
the different effective heat capacities of ocean and land or sea ice. If sea ice is not included,
correlations of land fraction drop to \( r = -0.63 \) with phase and \( r = 0.62 \) with amplitude,
indicating that ice-covered ocean has a land-like effective heat capacity.

b. Aloft

The zonal mean temperature phase aloft as a function of latitude and pressure is plotted
in Figure 4(a) and (b) for the ERA-40 reanalysis and the CMIP3 multi-model mean,
respectively. While the two exhibit some differences, they have similar overall structures.
For much of the troposphere, the phase lag stays roughly constant with height above the
boundary layer, presumably reflecting vertical mixing from the surface. Figure 4(c) shows
the difference in phase lag between models and observations. Most locations differ by less
than 5 days.

Figure 4(d) and (e) show the corresponding plots for the amplitude. Both observations
and models have a very different amplitude structure between the NH and SH. The high-
latitude NH has an amplitude that falls off with height, while in the SH the amplitude is
more vertically coherent and less variable overall. One difference between these two regions
is the amount of land. Land comprises most of each latitude band poleward of 45°N while
elsewhere it is mostly ocean (ignoring Antarctica) as in Figure 3. Observations and models agree well on these features as shown in Figure 4(f).

4. Projected Changes

Beginning around the second half of the 20th century and continuing through the 21st century, the models simulate a roughly linear increase in the global mean surface temperature phase lag from insolation and a linear decrease in the amplitude. These global changes are present for each of the 24 CMIP3 models in the time-series of phase (Figure 5(a)) and amplitude (Figure 5(b)). The changes over land are smaller and less robust than those changes over ocean, consistent with the idea that sea ice loss is driving much of the change. The interannual variability of both the phase and amplitude over ocean is smaller than the changes in these quantities over the 21st century.

a. Surface

Where a change in effective heat capacity is the dominant mechanism altering the annual cycle of surface temperature, changes in phase and amplitude are constrained to be of the opposite sign. For example, if the effective heat capacity increases, the phase will shift to later in the year and the amplitude will decrease. On the other hand, in any region where there are changes in phase and amplitude which are not of opposite sign, changes in effective heat capacity are most likely not the primary driver.

The projected annual cycle changes in the 21st century are consistent with an effective heat capacity increase in regions of large climatological sea ice cover. Figure 6(a) and (b) show latitude-longitude maps of the multi-model mean projected temperature phase and amplitude changes between the last two decades of the 21st century and the last two decades of the 20th century. The largest changes are over high-latitude ocean with prominent sea ice, including the entire Arctic Ocean and the Weddell and Ross Seas of Antarctica. Changes
in these regions are robust: at least 75% of models agree with the multi-model mean on the
sign of these changes (as indicated by the stippling).

Near the poles, the phase delay and amplitude decrease are much larger over ocean than
land. For example the delays in Greenland, Northern Canada, and the Antarctic coast are
all smaller than delays over ocean at the same latitude. The same holds true for amplitude,
as we would expect from an effective heat capacity increase over ocean. The largest changes
over high-latitude land are near the coast and fall off farther inland.

The phase delay in the tropics and subtropics is much smaller than at high latitudes,
and there are actually several regions of phase advance. There is no discernible land-sea
contrast in the low and midlatitudes suggesting that the homogenous delay is not solely due
to ocean heat capacity. Contrary to the phase change pattern, amplitude changes in the
subtropics show a clear large-scale change that is in the opposite direction from the high
latitudes: there is an amplitude increase of around 5% equatorward of 45°, most pronounced
over ocean regions. This amplitude increase is not as large as the polar amplitude decrease,
even after weighting by area. Yet this increase is robust among the models, especially in the
NH. In the deep tropics, where the semi-annual harmonic captures a large share of the total
variance, the amplitude of the second harmonic also increases by 15–20%, with the largest
changes in the Western Pacific Ocean. In between the low and high latitude responses
(around 45°-60° in each hemisphere) is a transition zone where the amplitude change is
small. In any individual model, the region of change is smaller, but averaging over all of the
models enlarges it.

b. Aloft

The polar phase and amplitude changes are largest near the surface and weaken aloft,
as shown in Figure 7(a) and (b). This is what we would expect for annual cycle changes
controlled by surface characteristics, and supports the idea that the surface temperature
phase delay and amplitude reduction at the high latitudes are caused by an increased effective
surface heat capacity rather than dynamical changes aloft. The polar changes are likely limited to the lower atmosphere because of the lack of deep vertical mixing due to the strong local atmospheric stability, but we note that while the large surface phase delays are confined to the boundary layer and do not extend above 850 hPa, the amplitude reduction extends to around 600 hPa.

Away from the polar surface, most of the troposphere shows a small phase delay of one to two days in the temperature cycle, of the same sign and similar in strength to the mean phase changes at the midlatitudinal surface. Even though this delay is small, it is robust throughout the high-latitude NH troposphere. In the subtropical midtroposphere, there are amplitude decreases in both hemispheres seemingly independent from changes at the surface. Aside from these regions, the rest of the troposphere has an amplitude increase, which is stronger still in the midlatitude stratosphere (both in relative and absolute magnitude). Donohoe and Battisti (2012) claim that this amplitude increase is due to an increase in absorbed shortwave radiation by the atmosphere in the summer mainly because of increased water vapor. There is an impressive amount of symmetry in the amplitude changes, considering that the climatological amplitude is not that symmetric. The changes are also robust in most locations, with exceptions mostly in regions near where the sign of the multi-model mean change reverses.

5. Mechanisms

In response to increasing CO₂, the CMIP3 models show two different types of seasonal temperature response. At high latitudes poleward of 60°, the CMIP3 models project a large, robust phase delay and amplitude decrease, while at low latitudes equatorward of 45° there is a smaller, less widespread phase delay and an amplitude increase. In a qualitative sense, the changes at high latitudes are consistent with an increase in effective heat capacity caused by reduced sea ice, while the low-latitude changes are not.
To understand these changes in a more quantitative manner, we find it useful to analyze them in terms of a very simple model of the basic energy balance at the surface:

$$C \frac{dT}{dt} = F(t, T(t)), \quad (1)$$

where $C$ is the effective heat capacity, $T$ is the temperature, and $F$ is the net heat flux flux into the surface. Even though $C$ has a seasonal dependence due to changing mixed layer depths, sea ice, soil moisture and other effects, we treat it as a constant for each time period. This is both for the sake of simplicity and because the results of interest prove insensitive to the particulars of a seasonally varying heat capacity, once the annual mean value is specified.\(^1\)

To isolate the factors that can affect the seasonal temperature cycle, we partition the net flux as $F(t, T(t)) = Q(t) - \beta T$ where $Q(t)$ is the seasonal surface flux that is not linearly related to temperature (such as solar radiation) and $\beta$ is a constant. Physically, $-\beta T$ represents longwave flux, turbulent heat fluxes, and heat transports that damp the temperature response to the seasonal flux cycle. The term crudely represents the temperature dependence of the surface flux and heat transports.

After Fourier transforming, we find the following relation for the annual harmonic ($\omega = 2\pi/(1 \text{ year})$) of $T$ and $Q$:

$$i\omega CT = Q - \beta T$$

$$T(\beta + i\omega C) = Q, \quad (2)$$

which yields the following phase and amplitude relations between $T$ and $Q$:

\(^1\)This was verified by numerically solving the temperature equation with a sinusoidally varying $C(t)$ with different phases.
\[ \phi_T - \phi_Q = \arctan \frac{\omega C}{\beta} \]

\[ |T| = \frac{|Q|}{\sqrt{\beta^2 + \omega^2 C^2}}. \]  

(3)

The temperature phase lag is set by the ratio of \( C \) to \( \beta \). In the limiting case of small heat capacity, for which \( \omega C/\beta \to 0 \), the temperature is in phase with \( Q \), while for very large heat capacity, \( \omega C/\beta \to \infty \), and the temperature is in quadrature with \( Q \). The relative amplitude of temperature to seasonal flux is inversely related to both \( C \) and \( \beta \). To understand the effects of changes in \( C \) and \( \beta \) to the temperature seasonality we linearize and decompose the variations to Equation 3 to find their dependences on variations in \( C \) and \( \beta \). The result is:

\[ \Delta \phi_T - \Delta \phi_Q = \frac{\omega C/\beta}{1 + (\omega C/\beta)^2} \left( \frac{\Delta C}{C} - \frac{\Delta \beta}{\beta} \right) \]

\[ \frac{\Delta |T|}{|T|} - \frac{\Delta |Q|}{|Q|} = \frac{-1}{1 + (\omega C/\beta)^2} \left( \left( \frac{\omega C}{\beta} \right)^2 \frac{\Delta C}{C} + \frac{\Delta \beta}{\beta} \right). \]  

(4)

Assuming small variations in \( \beta \) and \( \phi_Q \), an increase in heat capacity will cause a phase delay. Likewise, for small variations in \( \beta \) and \( |Q| \), an increase in \( C \) will lead to a decreased amplitude. Thus we see that heat capacity changes have opposite effects on phase and amplitude and that if phase and amplitude do not change in opposite ways, this implies that effective heat capacity changes are not the dominant effect. We can quantify this: since \( \omega C/\beta \) is around 0.5 in the models, variations in \( C \) are dominant when \( \Delta C/C \gg 4\Delta \beta/\beta \).

We have seen in the previous section that at high latitudes the temperature cycle is slowed and damped (more over ocean than land), which is qualitatively consistent with an increase in effective heat capacity. These seasonality changes occur in the same regions in which sea ice decreases in extent, thins, or becomes less persistent throughout the year. We will show below in more quantitative, greater detail that an effective heat capacity increase due to sea ice loss is most likely driving the phase delay and weakened amplitude of the temperature cycle at high latitudes and in the global mean.
The temperature cycle changes are different in the tropics and subtropics. We have already made the case that since phase and amplitude both increase in these regions, these temperature cycle changes must be forced at least in part by something other than changes in effective heat capacity. We provide evidence that this may be a consequence of a fractional increase in $\beta$ that is nearly an order of magnitude larger than the local fractional reduction in effective heat capacity.

The dividing line between these two regions meanders longitudinally, but is approximately between $45^\circ$–$60^\circ$. While sea ice extent varies with time, longitude, and hemisphere, the extent of late 20th century sea ice is approximately around $60^\circ$, marking the top of the transition zone. Below we focus on the high and low latitudes separately due to the different nature of their temperature annual cycle changes.

a. High latitudes

Before demonstrating that the high-latitude phase delay and amplitude decrease are due to sea ice loss we demonstrate that they are not directly due to changes in the surface flux cycle. For the flux to be responsible for the high-latitude seasonality changes to temperature, seasonal surface flux would need to delay and weaken. In fact, the reverse happens, as shown in Figure 8(a) and (b).

There is little change in the phase of surface flux at high latitudes. In fact, the phase is actually advancing over some high-latitude ocean regions, indicating that the high-latitude temperature phase delay is not being driven by changes in the surface flux phase. The surface flux amplitude, on the other hand, does show robust changes in the high latitudes. These changes, however, are of the opposite sign to the temperature amplitude changes. Over high-latitude ocean in both hemispheres, the surface flux amplitude increases by around 50% in both hemispheres. The increase is confined to ocean and is in the same region as the reduction in the amplitude of surface temperature. Since the phase and amplitude changes of surface flux are of the opposite sign to the temperature changes, they cannot be responsible
for the latter.

In terms of our energy balance model, Figure 8(a) and (b) show the seasonality changes to 

\[ F = Q - \beta T \]

The seasonality changes to \( Q(t) \) are similar to \( F(t) \) at high latitudes. Whether we take \( Q(t) \) to be the net shortwave flux at the surface or at the top of the atmosphere, we find the same small phase advance and large amplitude increase in the high latitudes (not shown). In Equation 4, this means that \( \Delta \phi_Q \) is a small negative number and that \( \Delta |Q|/|Q| \) is a large positive number. Hence we can rule out seasonal changes of \( Q \) as responsible for driving the high-latitude seasonal temperature changes.

The surface flux amplitude changes at high latitudes in Figure 8(b) are consistent with sea ice loss (Screen and Simmonds 2010). Climatologically, the ice margin is not only the region of greatest upward turbulent heat flux during the winter, but also where the total surface flux amplitude is greatest. As the ice edge shifts poleward during the 21st century, the consequence to the surface flux is an increase in amplitude in the polar ocean and a decrease in amplitude in the sub-polar ocean (Deser et al. 2010). In the polar ocean, the albedo is also reduced, which increases the downward shortwave radiation at the surface during the summer, contributing to an increased surface flux amplitude at high latitudes.

In the multi-model mean, the surface temperature has a phase delay and amplitude decrease at high latitudes, consistent with an effective heat capacity increase. We also look for this consistency on an individual model basis. For example, do models with large phase delays also tend to have large amplitude decreases? We address this question in Figure 9. On the y-axis we plot \( \Delta \phi = \Delta \phi_T - \Delta \phi_Q \), the change in the phase of the surface temperature relative to the change in phase of seasonal surface flux and on the x-axis we plot \( \Delta A = \Delta (|T|/|Q|) \), the change in the ratio of amplitudes of surface temperature to seasonal surface flux. The phase and amplitude changes are averaged over the NH and SH oceanic polar caps for each model. We find correlations between the phase and amplitude changes for both polar caps: \( r = -0.67 \) in the NH and \( r = -0.79 \) in the SH. Results are similar if we plot \( \Delta \phi_T \) against \( \Delta |T| \), though the correlations rise to \( r = -0.79 \) in the NH and fall to...
There is only one model where $\Delta \phi$ and $\Delta A$ have the same sign, and both phase and amplitude changes in that model are small.

If the $\phi$ and $A$ changes were entirely due to an effective heat capacity change we would expect the changes to be linearly related with slope $-\beta \sqrt{1 + (\beta/\omega C)^2}$, represented by the dotted line in Figure 9; we use the multi-model mean of the above quantity to compute the theoretical slope. The theoretical slope (-0.08) is much flatter than the slope of the best fit line (-0.40) in the NH, while for the SH the slopes are more similar (-0.16 theoretically and -0.26 for the best-fit line). We do not completely understand why the theoretical and best-fit slopes differ so much in the NH. An obvious possibility is that our very simple, zero-dimensional, two-parameter model is inadequate to capture the GCM behavior at this quantitative level; another is that the multi-model mean is not the most appropriate estimate of $\beta$ to use to compute the theoretical slope. Nonetheless, that the changes in phase and amplitude are negatively correlated qualitatively supports the hypothesis that heat capacity changes control the seasonality changes. A change in $\beta$ alone would produce a positive correlation, and surface flux amplitude changes alone would not be expected to change the phase to the extent that the response is linear.

To further understand whether seasonality changes are due to $C$ or $\beta$, we calculate the changes to effective heat capacity in the context of our energy balance model. Solving Equation 3 for $C$ and $\beta$ in terms of phase and amplitude gives the following.

$$C = \frac{\sin \phi}{\omega A}$$

$$\beta = \frac{\cos \phi}{A}$$

Since we calculate $A$ and $\phi$ directly via Fourier transform, Equation 5 gives expressions for the $C$ and $\beta$ changes for the CMIP3 models in the context of this simple temperature model.

In our calculations we take $Q$ to be the net shortwave flux at the surface, but the results are nearly the same if we take it to be the net shortwave flux at the top of the atmosphere.
For both the surface temperature and the net surface shortwave flux we calculate the average phase and amplitude over ocean poleward of 60° for each hemisphere for the last two decades of the 20th and 21st centuries. From these values we find \( C \) and \( \beta \) and plot the changes in Figure 10(a).

As in previous plots for the high latitudes, there is a robust phase delay and amplitude reduction among the models. Changes to \( C \) show a robust increase among the models in both hemispheres; nearly every single model predicts an increase in effective heat capacity. The multi-model mean increases are 82% and 43% for the NH and SH, respectively. Changes to \( \beta \) are smaller, but no less robust. The multi-model mean increase is 16% for the NH and 9% for the SH. We interpret the \( \beta \) changes mathematically as an increased damping in the system, and physically as the turbulent and longwave fluxes and heat transports - in some combination - becoming more effective at returning the surface temperature to equilibrium.

Which of the processes involved is most responsible for this change, and how the change is ultimately forced by greenhouse gas increases is not yet clear and will require further study.

Despite the robust increase in \( \beta \), the proportionally larger increase in \( C \) has the greater influence on the changes in the seasonality of temperature at high latitudes. From Equation 4, phase delays are proportional to \( \Delta C/C - \Delta \beta/\beta \), indicating that if \( \beta \) did not change, the phase delay would be even larger. Amplitude changes are proportional to \( -\Delta \beta/\beta - (\omega C/\beta)^2 \Delta C/C \), where \( (\omega C/\beta)^2 \) is a proportionality factor averaging 0.4 for the NH and 0.7 for the SH in the 20th century. Since \( \beta \) and \( C \) both increase in the 21st century, both are responsible for a decreased amplitude. However, when we calculate the multi-model mean of \( (\omega C/\beta)^2(\Delta C/C)(\Delta \beta/\beta)^{-1} \) we find that the contribution from the heat capacity change term is two to three times larger than that from the \( \beta \) term.

Sea ice loss was postulated to be the reason for high latitude changes in seasonality by earlier authors (Manabe and Stouffer 1980; Manabe et al. 1992; Mann and Park 1996). The explanation goes as follows: sea ice acts as a partition between the atmosphere and ocean by shutting off radiative transfer and turbulent heat fluxes between the two domains. The
only coupling is by conduction through the sea ice. As sea ice melts, the insulating effect
wanes and the ocean and atmosphere can more freely exchange heat, raising the effective
heat capacity of the surface. Any external addition of heat, such as from solar radiation,
will more easily be shared between the atmosphere and ocean if there is less sea ice. Sea ice
loss is robust in the models: sea ice area diminishes in every model at a roughly linear rate
during the 21st century (Figure 11). The NH suffers a larger ice loss than the SH, which
may partly account for why the amplitude and phase changes are larger in the NH.

If all of the effective heat capacity increase were due to sea ice loss, then $\Delta C/C$ would
be roughly proportional to the fractional change in open ocean area. We calculate the latter
quantity for each model and in Figure 12 plot it against the fractional change in effective
heat capacity for each model as calculated from Equation 5.

The two calculations of effective heat capacity correlate well with each other, indicating
that sea ice loss is probably the dominant mechanism for the effective heat capacity change.
While the correlations are strong, the models do exhibit a bias: the two effective heat capacity
calculations aren’t randomly distributed about the one-to-one line, but instead the effective
heat capacity change is larger when calculated from Equation 5. This could be due to the
limitations of relating effective heat capacity increase to ice area alone. For example, simply
measuring the open ocean increase does not take into account sea ice thinning, which would
increase the effective heat capacity relative to a thick sea ice layer. Regardless, sea ice area
loss appears to account for most of the effective heat capacity increase which is driving the
delayed and weakened annual temperature cycle in the high latitudes.

Another way to quantify the relationship between temperature annual cycle changes and
sea ice changes is to correlate the two across models in the ensemble. We focus on high-
latitude (poleward of $60^\circ$) annual cycle changes to air temperature over ocean in order to
determine if models with large sea ice loss tend to have large phase delays and weak annual
cycles. We find that correlations of temperature phase delay with annual sea ice area change
are significant for the NH ($r = -0.67$), but not for the SH ($r = -0.35$) at the 95% level
Correlations between amplitude change and sea ice area change are $r = 0.51$ for the NH and $r = 0.46$ for the SH and are significant for both hemispheres (Figure 13(b)). The correlations do not significantly change if we weight the area loss with a factor to account for the reduction of ice thickness.

**b. Low Latitudes**

While sea ice loss seems to explain the high-latitude phase and amplitude changes of the annual temperature cycle, it does not directly explain the changes at low latitudes. Equatorward of roughly 45° the models expect a slight phase delay and an increased amplitude. One possible explanation for this behavior is that the high-latitude seasonality changes are transported equatorward, for example, by midlatitude eddies. There are two reasons this is unlikely. For one, the amplitude increases at low latitudes, while it decreases near the poles. The other reason is that models that have large delays in the high latitudes do not tend to have large delays in the subtropics. The only region-to-region phase correlations that appear significant are between the extratropics and subtropics in the Northern Hemisphere ($r = 0.59$). But the amplitude correlations are small between these two regions ($r = 0.17$), suggesting that the delay in the low latitudes is not simply communicated from higher latitudes.

An alternate explanation is that the temperature seasonality changes are a result of surface flux seasonality changes. While the phase and amplitude of surface flux changes are opposite in sign to those of the temperature changes at high latitudes, this is not the case at low latitudes as shown in Figure 8. Both the phase of surface temperature and surface flux show a small delay of less than 5 days from 45°S–45°N. The amplitude changes of temperature and surface flux are even more similar. From 45°S–45°N both temperature and surface flux amplitude show broad increases of around 5%.

There is also a strong spatial correlation between the temperature and flux changes. Robust phase delays occur in the same places such as the Eastern Pacific and the NH subtropical
Atlantic. The temperature and flux also both have especially large amplitude increases in the Eastern Pacific and Eastern Atlantic. We create a measure of spatial correlation in Figure 14 by plotting the multi-model mean seasonality changes for temperature and flux against one another for all subtropical ocean grid boxes between $15^\circ$–$30^\circ$ in both hemispheres, not including locations where the annual cycle is small. There are strong correlations of $r = 0.67$ for the phases and $r = 0.78$ for the amplitudes, indicating that the surface flux changes are spatially correlated with the surface temperature changes.

We can understand these changes in the context of our energy balance model. While the seasonal cycle of total flux, $F$, delays and strengthens in the subtropics in Figure 8, the same cannot be said of the temperature-independent component of the flux, $Q$. There is almost no change in the phase or amplitude of the net shortwave radiation at the surface (not shown). Since $F = Q - \beta T$, this suggests that changes in $\beta$ are responsible for the changes in total surface flux.

To find the explicit changes to $C$ and $\beta$, we use the same procedure as for the high latitudes by calculating $C$ and $\beta$ from $A$ and $\phi$ with Equation 5 and plot these results in Figure 10(b). The phase delay is around 2.8 days in the NH and 1.6 days in the SH, while the amplitude increase is around 3–4% for both the NH and SH. While small, these changes are robust in the models: the vast majority have the same sign as the mean change. Unlike in the high latitudes, we find a small decrease in the subtropical heat capacity around 2–3% in both hemispheres. This might be a consequence of a reduction in tropical ocean mixed layer depth (Philip and Oldenborgh 2006). The larger changes are in $\beta$, which decreases by 20% in the NH and 12% in the SH. Since $\Delta \phi \propto \Delta C/C - \Delta \beta/\beta$, we can attribute the subtropical phase delay primarily to the $\beta$ decrease. Likewise, since $\Delta A/A \propto -\Delta \beta/\beta - (\omega C/\beta)^2 \Delta C/C$, and $\omega C/\beta < 1$, the amplitude increase is also primarily due to the $\beta$ decrease.

The reduction in $\beta$ indicates that 21st century temperature in the subtropics becomes more weakly damped. Physically, a weakened $\beta$ means that the combination of turbulent and latent fluxes and heat transports become less effective at returning the surface temperature
to equilibrium. A reduced $\beta$ does not necessarily imply a weakened surface flux amplitude because the total surface flux $F = Q - \beta T$ also depends on the phase relationship between $T$ and $Q$. For the low latitudes, the surface flux amplitude increases despite the reduction in $\beta$. Sobel and Camargo (2011) presented evidence that the surface flux amplitude increases are driven by changes in the seasonal cycle of surface winds, with subtropical winds increasing in the winter hemisphere and decreasing in the summer hemisphere. At a fixed subtropical location, these changes in wind speed change sign over the year and thus will not be described well by a simple change in an otherwise constant coefficient $\beta$. Further, because surface air humidity (the other state variable that enters bulk formulae for the surface latent heat flux, besides wind speed and SST) can adjust so quickly to other factors, it may be appropriate to view these wind speed changes as an external forcing on the surface fluxes, rather than a change in a damping coefficient in an SST equation. These considerations suggest that the simple model we have proposed to interpret the high-latitude seasonality changes projected by the models may be inadequate to capture the low-latitude changes. Further work is required to determine the exact roles of the surface wind and other factors in the surface energy budget. It is clear, however, that there is a link between the net surface heat flux and the seasonal temperature cycle at low latitudes, unlike at high latitudes where the effective heat capacity governs the changes in seasonality.

6. Conclusion

In this study we analyzed the changes to the seasonality of surface temperature in response to an increase in greenhouse gases during the 21st century as represented by CMIP3 models. We found large, robust, global changes to the annual cycle of surface temperature: a phase delay and an amplitude reduction. By analyzing these changes geographically, we found that the phase delay and amplitude decrease are strongest at high latitudes and drive the global response. These polar changes are consistent with an effective heat capacity in-
crease of the surface layer due to sea ice loss. At low latitudes there is a small phase delay and an amplitude increase, which we linked to changes in the seasonality of the surface heat flux.

CMIP3 climate models accurately represent the typical phase and amplitude of the annual cycle aloft and at the surface as represented by the ERA-40 reanalysis. Geographic variations in models and observations are spatially consistent and can be traced to different surface effective heat capacities: temperature over ocean responds slowly and weakly, while temperature over land and sea ice responds rapidly and strongly.

At high latitudes the temperature cycle delays and weakens in response to greenhouse gases in the CMIP3 models. We provided evidence that sea ice loss is driving these changes. By fitting CMIP3 data to a parameterized surface energy balance model, we found that an increase in effective heat capacity primarily accounts for the phase delay and amplitude increase at high latitudes. We also demonstrated that the increase in effective heat capacity for each model was consistent with the increase in open-ocean fraction, indicating that sea ice loss is driving the effective heat capacity and seasonality changes at high latitudes. We provided further evidence of this mechanism by showing strong correlations between sea ice loss and phase and amplitude changes among the models at the high latitudes in each hemisphere.

The projected delayed and weakened temperature cycle in the high-latitudinal NH is a manifestation of Arctic Amplification, the accelerated annual mean warming in the Arctic Ocean relative to the rest of the globe robustly predicted by 21st century climate simulations. Arctic Amplification has a seasonal component to it as well, with models predicting little warming in summer and substantial warming during the late fall and early winter (Serreze and Francis 2006). This warming structure is consistent with the changes in the annual harmonic of phase and amplitude. While the models predict the surface annual cycle changes to grow over the course of the 21st century, recent studies have already found early signs of changes in the Arctic Ocean. Among four different data sets, Serreze et al. (2009) and
Screen and Simmonds (2010) found evidence of a delayed and weakened temperature cycle in the Arctic Ocean, consistent with rapid sea ice loss over this time period and providing support for future changes expected by the CMIP3 models.

We suggest that the high-latitude seasonal temperature changes are credible. Not only are they robust among the models, but they are also linked to a robust response in the models: sea ice loss. While there has been some disagreement between models and observations of temperature phase changes over midlatitude NH land during the 20th century (Stine et al. 2009), substantial sea ice loss is already occurring in the Arctic. Furthermore, trends of an Arctic temperature phase delay and amplitude decrease have been observed during the last 30 years.

Changes in the temperature cycle at low latitudes are different in nature than those at high latitudes. While still robust, they have a small phase delay and a small amplitude increase. Because the changes in phase and amplitude are both positive, they are not consistent with an increase in effective heat capacity. However, they are consistent with a delayed and strengthened surface flux cycle that we traced to a decrease in damping of surface temperature by turbulent and longwave heat fluxes in our energy balance model. We also found a strong spatial correlation between seasonality changes in surface flux and surface temperature in the subtropics. Sobel and Camargo (2011) describe a link between changes in the amplitude of the seasonal cycle in SST and those in surface wind speed and describe the latter as a consequence of the expansion of the Hadley cell. While we do not understand the mechanism responsible for the phase changes in the net surface flux, it is worth further effort to do so. Projected phase delays of surface temperature in the tropics appear to be associated with similar phase delays in the onset and demise dates of monsoons (Biasutti and Sobel 2009).

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