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Key Points:
- Loss of sea ice over the next three decades will amplify Arctic climate change
- Carbon mitigation can slow down changes to late-century Arctic temperatures

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Future Arctic climate changes: Adaptation and mitigation time scales

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Abstract The climate in the Arctic is changing faster than in midlatitudes. This is shown by increased temperatures, loss of summer sea ice, earlier snow melt, impacts on ecosystems, and increased economic access. Arctic sea ice volume has decreased by 75% since the 1980s. Long-lasting global anthropogenic forcing from carbon dioxide has increased over the previous decades and is anticipated to increase over the next decades. Temperature increases in response to greenhouse gases are amplified in the Arctic through feedback processes associated with shifts in albedo, ocean and land heat storage, and near-surface longwave radiation fluxes. Thus, for the next few decades out to 2040, continuing environmental changes in the Arctic are very likely, and the appropriate response is to plan for adaptation to these changes. For example, it is very likely that the Arctic Ocean will become seasonally nearly sea ice free before 2050 and possibly within a decade or two, which in turn will further increase Arctic temperatures, economic access, and ecological shifts. Mitigation becomes an important option to reduce potential Arctic impacts in the second half of the 21st century. Using the most recent set of climate model projections (CMIP5), multimodel mean temperature projections show an Arctic-wide end of century increase of +13°C in late fall and +5°C in late spring for a business-as-usual emission scenario (RCP8.5) in contrast to +7°C in late fall and +3°C in late spring if civilization follows a mitigation scenario (RCP4.5). Such temperature increases demonstrate the heightened sensitivity of the Arctic to greenhouse gas forcing.

1. Introduction

Duarte et al. [2012] and *Jeffries et al*. [2013] note a large number of recent abrupt climate changes in the Arctic, and *Post et al*. [2013] show emerging ecological consequences of sea ice decline. Among these are a 75% loss of sea ice volume since the 1980s [*Schweiger et al*., 2011; *Overland and Wang*, 2013] and earlier loss of late spring snow cover extent during 2008–2012 on high-latitude land areas [*Derksen and Brown*, 2012]. Both snow and ice losses represent a shift in surface albedo that results in increased ocean and land heat retention. Global warming has produced a larger effect in the Arctic than it has in midlatitudes (Figure 1), a pattern known as Arctic amplification [*Serreze et al*., 2009] that was predicted in model simulations beginning in 1980 [*Manabe and Stouffer*, 1980; *Holland and Bitz*, 2003; *Bracegirdle and Stephenson*, 2013]. Arctic air temperatures increased in all seasons during the period 2001–2012 compared to 1971–2000, with the greatest warming in autumn and winter. Mean annual temperature in the Arctic is now more than 1.5°C higher than the 1971–2000 average, more than double the warming at lower latitudes during the same period. Figure 2a shows that the record of minimum sea ice extent (white area) in September 2012 was reduced by nearly 50% in area compared to its climatological extent (pink line). Figure 2b shows the reduction in September sea ice volume between 1979 and 2012, calculated from a sea ice data assimilation model (the Pan-Arctic Ice-Ocean Modeling and Assimilation System, PIOMAS), which is occurring at a relatively faster rate than sea ice extent owing to the influence of thinning sea ice.

Arctic amplification is a response to sea ice-temperature positive feedbacks [*Mahlstein and Knutti*, 2012]. Such interactions include the loss of sea ice with direct albedo reduction and additional heat storage in sea ice-free areas [*Serreze et al*., 2009; *Screen and Simmonds*, 2010]. Secondary, large relative contributions to Arctic warming are from additional downwelling longwave radiation reaching the surface that has its origin from the additional heat and water vapor given to the lower atmosphere over newly sea ice-free areas [*Bintanja and van der Linden*, 2013; *Ghatak and Miller*, 2013]. The combined effects of multiple feedbacks explain much of the enhanced recent and suggested future Arctic warming, including its seasonality. We begin by investigating the next 30 years that are dominated by further sea ice loss in summer, which we refer to as the adaptation time scale. The choice of path followed for additional greenhouse gas emissions is the primary determinant of potential air temperature increases near the end of the 21st century, which we refer to as the mitigation time scale.

2. The Near-Term (<2040) Adaptation Time Scale

The previous decade saw an increase of 27% of global emissions of carbon dioxide (CO_2), with concentration values passing 400 ppm at several observation sites during 2013 [*Monastersky*, 2013]. Given the current rate of population and urbanization increase and the current status of global political activity on global warming, it is reasonable to project a continuing CO_2 rise over the next two decades. Modest external forcing from global warming combines with Arctic amplification—the emergence of strong sea ice-temperature positive feedbacks—to increase the likelihood of future Arctic warming and sea ice decline [*Serreze and Barry*, 2011].

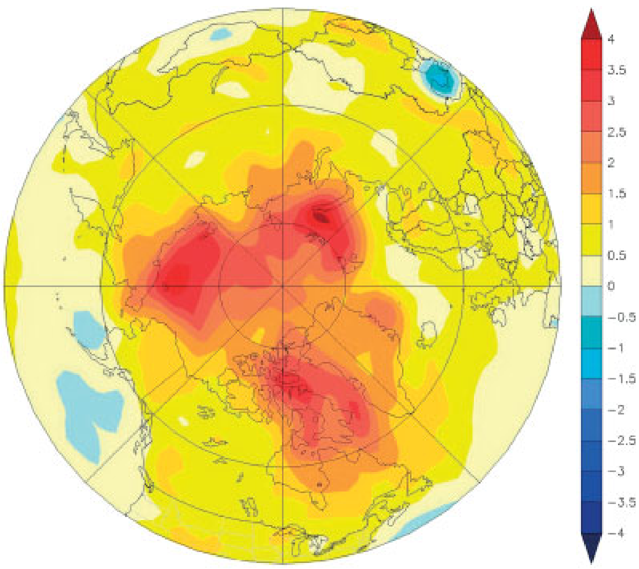

Figure 1. The difference in recent annual averaged Arctic temperatures (2001–2012) from a baseline period of 1971–2000. Data are from NCEP/NCAR reanalyis.

Global climate models (GCMs) are major tools available to provide climate projections based on physical laws. Recently, results from more than 30 models have been made available to the wider scientific community through the archive at the Program for Climate Model Diagnosis and Intercomparison (PCMDI). This constitutes the fifth phase of the Coupled Model Intercomparison Project (CMIP5) that followed an earlier CMIP3. All models show loss of sea ice as greenhouse gas concentrations increase and a faster rate of temperature increase in the Arctic than at lower latitudes. However, there are major difficulties in using the results from these models for quantitative projections in sea ice loss relative to the real-world changes as shown in Figure 2. The first difficulty is the wide spread of different model hindcast and forecast results; they vary by model, location, variable, internal chaotic variability, and evaluation metric. The second difficulty is that 80% of 56 CMIP5 ensemble member trends for 1979–2011 are smaller than observed. The observed trend lies outside the 2 standard deviation bound of the models' trends [*Stroeve et al*., 2012 and their Figure 3]. *Overland and Wang* [2013] conclude that recent data and expert opinion should be considered over CMIP5 GCM results to advance the very likely timing for a future with nearly sea ice-free conditions to the first half of the 21st century, with a possibility of a nearly complete loss within a decade or two.

The lack of confidence in CMIP5 projections of the timing for Arctic sea ice loss relative to recent data also brings into question near-term CMIP5 projections for Arctic air temperatures (<2040) because of the strong sea ice-temperature positive feedbacks. The combination of continued external forcing by anthropogenic greenhouse gases, the residence time of CO_2 in the atmosphere, and the continuing contributions of Arctic amplification support the conclusion that *major Arctic changes are locked into the climate system over the next decades* and that one should consider adaptation as a priority for human response to the changes.

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3. Surface Temperatures at the Mitigation Time Scale (2080–2100)

CMIP5 projections are subject to three main types of uncertainty: model differences, internal variability, and choice of emission scenario [*Overland et al*., 2011; *Hodson et al*., 2012]. Model variations are due to different formulations and parameterization of physical processes; internal variability arises from the chaotic nature of the earth's climate system and leads to different results for similar initial conditions of the models. Near-term projections are dominated by these two types of uncertainties. Longer-term projections are dominated by the choice of the future emission pathway. Coincident with the development of CMIP5, four representative concentration pathways (RCPs) were developed to span a range of potential radiative forcing values for the year 2100, ranging from 2.6 to 8.5 W/m^2 (Figure 3) [*van Vuuren et al*., 2011]. RCPs and emission scenarios are plausible descriptions of how the future may evolve based on the scientific literature on socioeconomic change, technological change, energy and land use, and emissions of greenhouse gases and air pollutants. RCP8.5 represents a rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 equivalent) by 2100. RCP4.5 represents stabilization near 2060 to 4.5 W/m^2 (~650 ppm CO_2 equivalent). The RCP2.6 scenario requires a 70% reduction of emissions relative to present levels by 2050, a scenario that is highly unlikely in view of the current trajectory of emissions and the absence of progress toward mitigation measures. We refer to the RCP8.5 and RCP4.5 future scenarios as business-as-usual and mitigation.

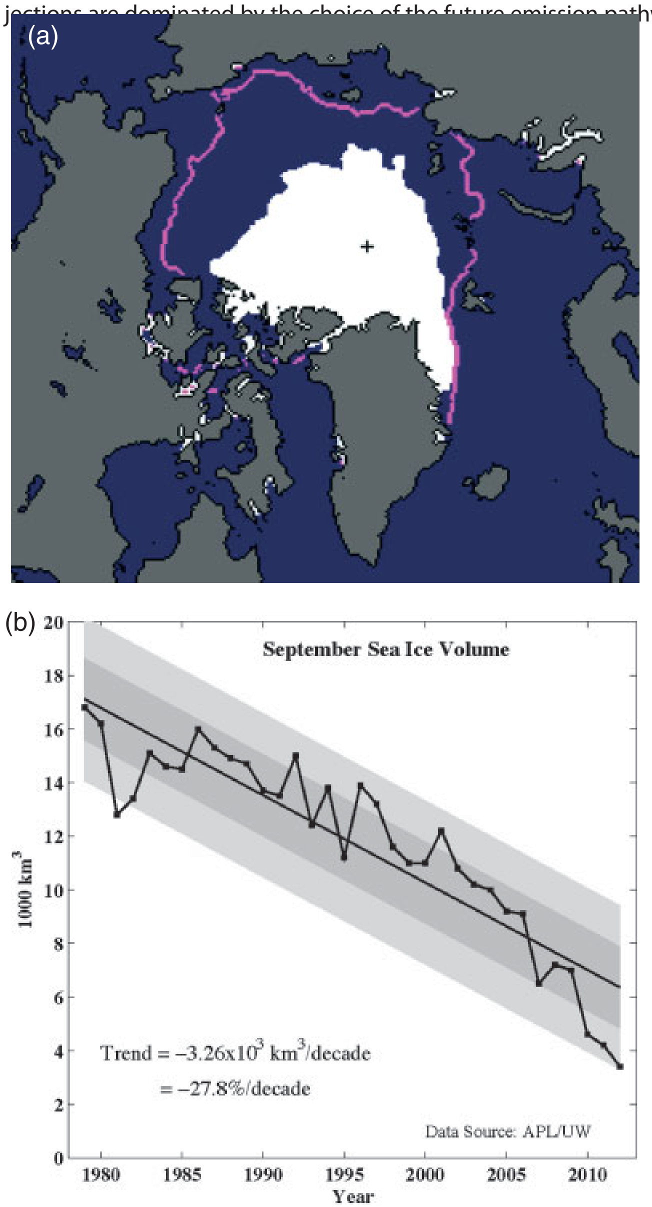

Figure 2. (a) Arctic sea ice extent for September 2012 (white region). Climatological sea ice extent for September is shown by pink outline (From NSIDC). (b) Trend in loss of Arctic sea ice volume calculated from a sea ice data assimilation model (From *Overland and Wang* [2013] based on values from the PIOMAS project at the University of Washington). Dark and light shading indicate 1 and 2 standard deviations.

Figure 4 [updated from *Stroeve et al*., 2012] shows that the Arctic continues to lose summer sea ice in GCMs based on all scenarios except the implausible RCP2.6. The business-as-usual (RCP8.5) scenario leads to the most rapid rate of ice loss. However, as noted earlier, the observed rate of sea ice loss over the past few decades lies outside the range of model simulations of the same period. Strategies for adjusting the model projections include bias correction and/or the selection of subsets of models that are more successful in capturing the sea coverage of the past few decades [*Massonnet et al*., 2012; *Wang and Overland*, 2012; *Liu et al*., 2013]. However, it is unclear whether comparing the fastest sea ice loss rates from a set of model ensemble members with extrapolation from observed conditions is valid, given the potential slow mean responses of the models.

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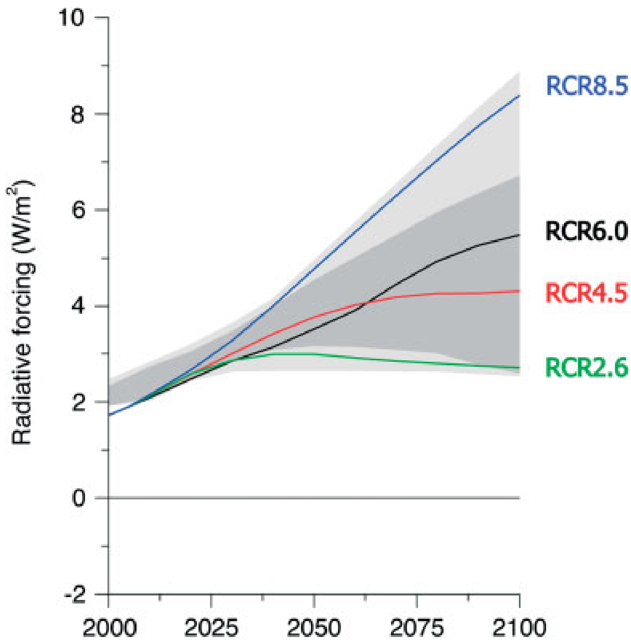

Figure 3. Four future climate scenarios based on amount of global radiative forcing at the end of the century [after *van Vuuren et al.*, 2011].

Figure 5 shows a comparison of the linear trend in annual surface temperature observations versus the set of 36 CMIP5 models during 1966–2005. Averaging over all models and months should highlight the climate sensitivity (temperature change per CO_2 increase), as it averages out the across-model differences and much of the internal variability. Indeed, we find a reasonable consistency between the two fields, especially in Arctic amplification of the warming and the tendency for greater warming over land than ocean in middle latitudes. Because the observed pattern represents only one realization in contrast to the 36 realizations averaged into the model composite, the observed pattern is more spatially complex.

As noted in the previous section, we have concern about CMIP5 air temperature projections near 2040 because of the uncertainty in sea ice extents. However, by 2080, most CMIP5 projection results have caught up with the real world in transitioning to a sea ice-free summer. Thus, beyond 2080, we consider that we are primarily comparing the effects of different emission/radiative forcing on a seasonally sea ice-free Arctic.

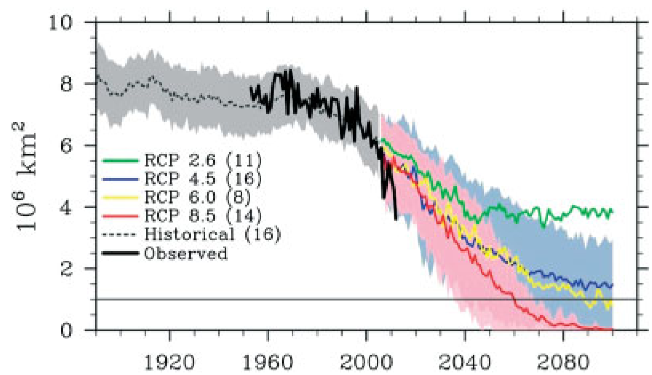

Figure 4. Model simulations of Arctic sea ice extent for September, 1900–2100, based on observed concentrations of heat-trapping gases and particles (through 2005) and four emissions scenarios. Colored lines for RCP scenarios are model averages (CMIP5) and lighter shades of the line colors denote ranges among models for each scenario. Dotted gray line and gray shading denote average and range of the historical simulations through 2005. The thick black line shows observed data for 1953–2012. The simulated September ice losses under all scenarios lag behind the observed loss of the past decade (Figure source: adapted from *Stroeve et al*. [2012]).

Because we are investigating one of the two planetary regions with the largest range of seasonal radiative forcing and sea ice, it is important to detail the results for each month individually [*Deser et al*., 2010; *Bintanja and van der Linden*, 2013]. Figure 6 shows the mean model projections of surface temperatures for the Northern Hemisphere during 1950–2100 by month for business-as-usual (RCP8.5) in red and the mitigation scenario (RCP4.5) in blue. At the end of the century the mitigation scenario tops out at approximately +3.0°C increase for September through January relative to a 1981–2005 baseline period and a slightly lower value for the remainder of the year. The warming in the business-as-usual (RCP8.5) scenario reaches approximately +6.0°C in November through January, with values closer to 5°C in the other months.

The seasonality in the Arctic (60°N–90°N) is larger than the Northern Hemisphere (Figure 7 versus Figure 6). For spring and early summer (April through July) the mitigation scenario is in the range of a +2–3°C temperature increase over the 1981–2005 baseline; this increases in the fall owing to the lack of sea ice to a +7°C change in November and December. For the business-as-usual, temperatures continue to rise through the second half of the 21st century. The May-June-July temperature increases are near +5°C,

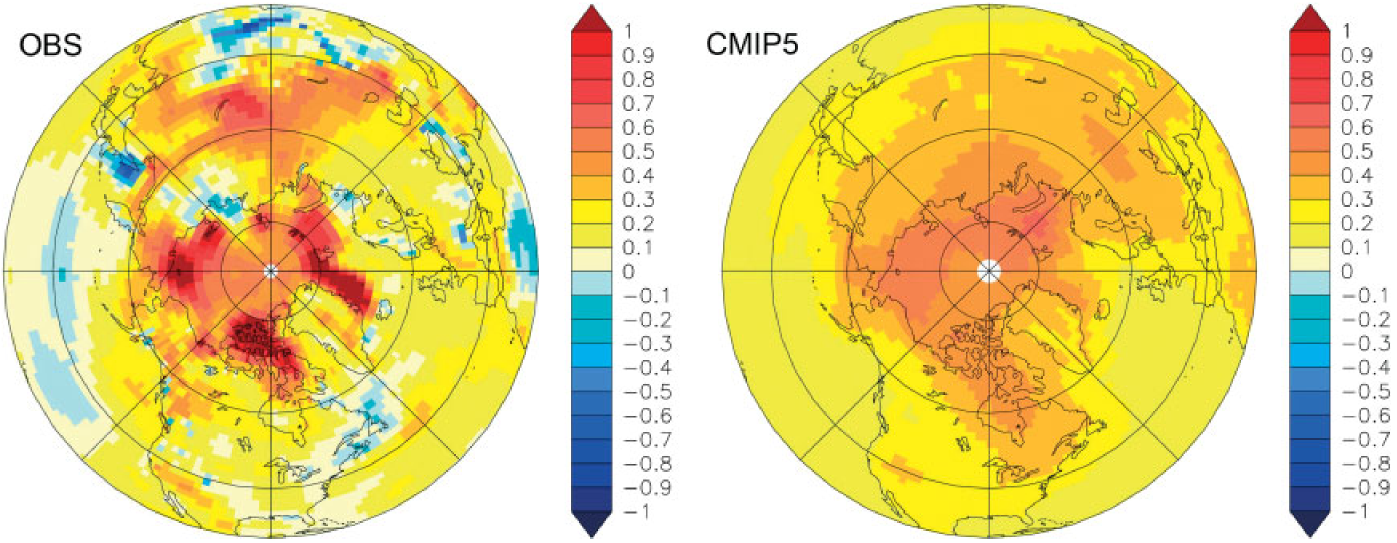

Figure 5. Linear trend of annual mean surface air temperature for 1966–2005 period based on NCEP/NCAR reanalysis (left) and ensemble mean of 36 CMIP5 models (one member each). Units are °C/decade.

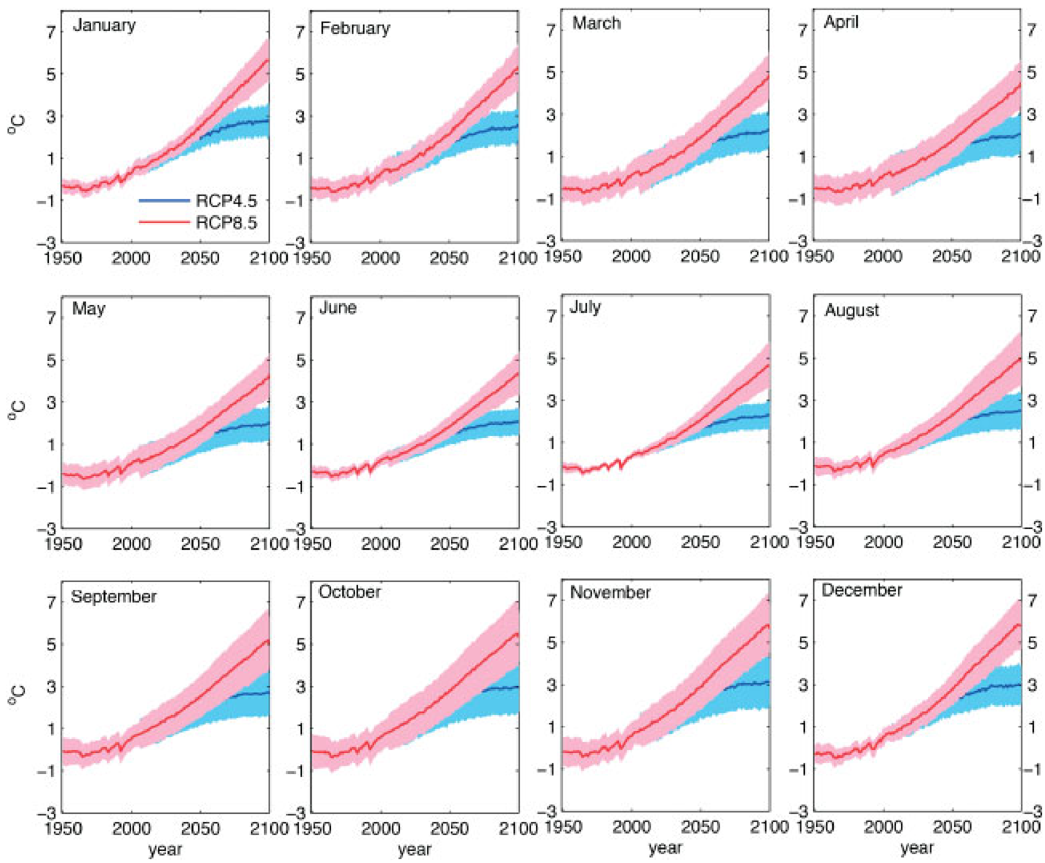

Figure 6. Northern Hemisphere monthly temperature anomalies averaged over 36 ensemble members from 36 models. The red line is the ensemble mean under RCP8.5, and the blue line is for RCP4.5. The shaded area outlines 1 standard deviation from the ensemble mean. The temperature anomalies are calculated relative to 1981–2005 period mean.

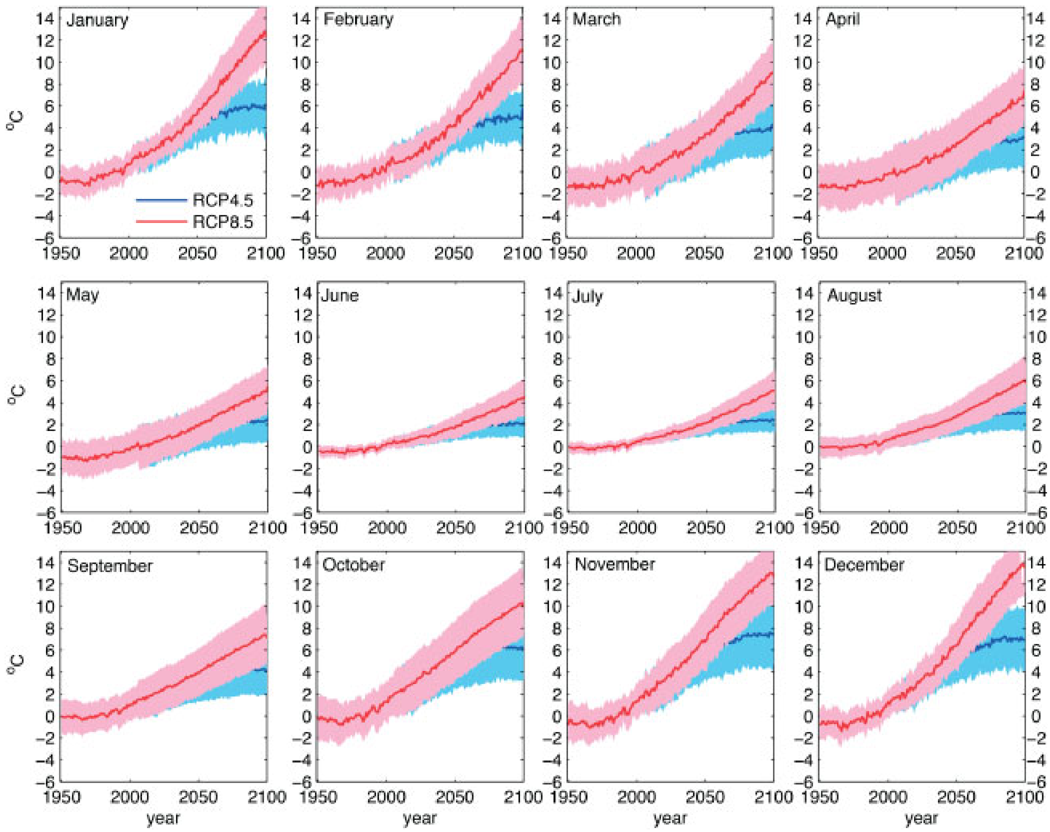

Figure 7. Similar to Figure 6, but averaged over the Arctic domain (60°N–90°N).

and the November-December-January temperatures top out at a +13°C increase relative to the 1981–2005 baseline, a further indication of the Arctic's heightened sensitivity to greenhouse gas forcing.

In comparison to previous studies, *Bitz et al*. [2012] show that two models, CCSM3 and HADGEM1, had greater temperature increases for 2040–2059 minus 1980–1999 compared to the mean of the set of models from the previous CMIP3 results; they attribute this difference to improved sea ice physics in these two models. Because their dates are around the variable timing of sea ice loss in different models, their difference in temperature increases supports our contention that it is difficult to obtain stable temperature projection results at mid-century. On the other hand, two recent studies that look at temperatures from single models at the end of the century find results similar to our CMIP5 composite temperature increases [*Koenigk et al*., 2012; *Vavrus et al*., 2012].

4. Conclusions

On the basis of two radiative forcing scenarios (mitigation and business-as-usual) in the CMIP5 collection of GCMs we note a large difference in surface air temperatures in the Arctic at the end of the 21st century, *which makes a strong case to begin mitigation activities for greenhouse gases*. The RCP4.5 scenario, which stabilizes CO_2 concentrations by mid-century [*Thomson et al*., 2011], is a plausible target if decisive actions are begun. We consider that our estimates of future Arctic temperature increases are realistic as we are highlighting the radiative components of the model projections by averaging spatially and over a large number of models.

For the decadal scale out to 2040, we have low confidence in quantitative projections of the collection of CMIP5 models on the timing of Arctic-wide sea ice loss. There are a number of reasons for this, primarily the spread in the results, which in turn may depend not only on natural variability but also on the models' different formulations of sea ice physics, treatment of clouds, radiation, and atmospheric and ocean dynamics [*Karlsson and Svensson*, 2013; *Overland and Wang*, 2013]. There is a wide gap in projected timing of future sea ice loss between model results, and inferred from observed sea ice loss (Figures 2 and 4) and physical reasoning based on Arctic amplification from recent thinning of sea ice. This leaves us with no reliable quantitative estimates for changes in the Arctic over the next few decades. However, based on continued increases in external forcing from greenhouse gases, current Arctic conditions, and Arctic amplification feedbacks, we can say that *it is very likely that the Arctic climate will continue to show major changes over the next decades*, and that society should consider planning to adapt to changing conditions. Such changes include several additional months of open water in the Arctic Ocean, ever earlier snow melt, further loss of permafrost, increased economic access, and dramatic impacts on ecological systems [*Jeffries et al*., 2013].

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