Arctic climate change in numerical experiments with abrupt CO_2 increase

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Abstract

Over the last several decades, the Arctic has warmed faster than any other region on Earth. While many recent studies have focused on the effects of atmospheric CO_2 doubling within the next century, IPCC business-as-usual future warming scenarios suggest that on longer time scales, CO_2 levels will increase appreciably more than two-fold. Thus, it is important that we understand the ways in which changes in the Arctic climate as a result of higher levels of CO_2 will impact the dynamics of both the regional and global climate systems over the long-term. In this study, we use the Community Earth System Model (CESM) to investigate the nature of the spatial and temporal patterns that govern the Arctic as well as global system response to abrupt CO_2 increases of 2x, 4x, 8x, and 16x relative to a pre-industrial baseline simulation, over a period of 200 years. Investigating such a broad range of climate forcing allows us to highlight the key mechanisms and timescales of sea ice loss. We find that the resultant warming leads to a loss of permanent sea ice by the end of the $4xCO_2$ simulation, and that complete sea ice depletion occurs in the $16xCO_2$ simulation. We identify a strong correlation between atmospheric CO_2 increases, melting sea ice, and general Arctic ocean freshening: We find that the amplitude of the seasonal sea surface salinity cycle in the Arctic is larger at the outset of each simulation than at the close. The combined warming and freshening of the Arctic ocean induce a weakening in the Atlantic Meridional Overturning Circulation (AMOC) of 44%, 63%, 66%, and 69% from the control model run in the $2xCO_2$, $4xCO_2$, $8xCO_2$, and $16xCO_2$ simulations, respectively. These changes are accompanied by an intensification in the hydrological cycle, with shifts in global convective and large-scale precipitation levels and increases in precipitation in the Arctic. Finally, we discuss briefly the modeled changes in column aerosol optical depth over the circumpolar region.

Introduction

The Arctic plays a critical role in the Earth's climate system, and it is warming at rates as much as double the global average in part as a result of positive ice-albedo and water vapor feedbacks, which together act to enhance the effects of climate change (Symon et al., 2004). This process, known as polar amplification, has accelerated sea ice melting over the last several decades, one of the most important indicators of warming in the region (Parkinson & Cavalieri, 2008). Loss of Arctic sea ice has been demonstrated in observations by reductions in total sea ice extent, in ice thickness, and in the shortening of the duration of the ice season (Vihma, 2014). Since 1980, Arctic sea ice volume has decreased by 75% (Overland et al., 2013), and climate models in the IPCC AR5 report have projected that significant areas of the Arctic will be free of ice in the summertime by as early as mid-century under the high-warming scenario. Warming in the Arctic has not only regional but global implications: Sea ice depletion affects the global climate system via factors including the release of methane and decreases in surface reflectivity caused by loss of ice cover (Screen and Simmonds, 2010). The climate change that is expected over the next several decades in the Arctic region will affect world energy security by allowing for easier resource exploration, development, and removal.

Previous experiments have indicated that Arctic sea ice decline can cause large-scale changes in atmospheric as well as ocean overturning circulation, and may also affect mid-latitude weather patterns (e.g. Overland & Wang, 2010; Screen et al., 2013). Net precipitation over the Arctic Ocean has increased since 1958 (Peterson et al., 2006), and there has been growing scientific interest in the response of the Arctic hydrologic cycle to climate change (Kopec et al., 2016). Climate modeling studies have identified increases in the transport of subtropical moisture to the Arctic and increased local evaporation as potential mechanisms for the intensification in Arctic precipitation (e.g. Bengtsson et al., 2011; Bintanja et al., 2014). Sea ice regulates evaporation and precipitation, although the relationship between these remains poorly quantified (Kopec et al., 2016). Globally, changes in Arctic sea ice can affect the latitudinal position of the Intertropical Convergence Zone (ITCZ), which in turn has effects on rainfall patterns (e.g. Chiang & Bitz, 2005). Moreover, Arctic sea ice loss has been shown to weaken the Atlantic meridional overturning circulation (AMOC) by generating positive buoyancy anomalies in the Arctic (Sun et al., 2018). In particular, in an Arctic sea ice climate model perturbation experiment, Liu et al. (2018) found that the climate response to Arctic sea ice decline varies across different periods after the imposed changes, with a northward displacement of the ITCZ over shorter timescales and a weakening in AMOC over longer timescales that leads ultimately to a southward reversal in the position of the ITCZ.

Changes in salinity stratification as a result of warming can also affect the vertical circulation of the ocean, especially in high-latitudes as in the Arctic Ocean. In the polar regions, ocean density is far more sensitive to changes in salinity than to changes in temperature. Previous studies have projected that Arctic fresh water will continue to increase, with the decline in sea ice likely to cause increases in vertical mixing during ice-free periods (Davis et al., 2016). Increased freshwater discharge from the Arctic Ocean are responsible for salinity anomalies in the North Atlantic, and more generally for the cooling and freshening of the deep North Atlantic water over the last several decades (Aagarad and Carmack, 1989). The freshening of the Arctic Ocean may also be a key driver in the weakening of AMOC.

Recent research on anthropogenic climate change has tended to emphasize CO_2 doubling within the next century. However, IPCC future emissions scenarios indicate that on longer time scales, CO_2 levels will far more than double given current emissions trends. The goal of my senior thesis in Geology & Geophysics is to investigate the nature of the spatial and temporal patterns that govern the Arctic as well as global system response to abrupt increases in carbon dioxide (CO_2) of different magnitudes over 200 years, using the

Community Earth System Model (CESM). To do so, I examine changes in Arctic sea ice area and thickness, surface air temperature, sea surface temperature, sea surface salinity, precipitation, and AMOC strength across four CESM simulations in which atmospheric CO_2 is increased abruptly two-fold (2xCO_2), four-fold (4xCO_2), eight-fold (8xCO_2), and 16-fold (16xCO_2) from the pre-industrial level of approximately 285 ppm CO_2. Increasing CO_2 abruptly as opposed to linearly over many years allows a rough estimation of the equilibrium global response to such changes.

Beyond climate, melting sea ice from the Arctic will have profound implications for the way of life of vulnerable indigenous populations of the Arctic, many of whom have relied on the presence of sea ice for hunting and fishing. In addition, a sufficient reduction in sea ice in the summertime may open important shipping routes such as the Northwest Passage and Northern Sea Route, increasing traffic and the potential for accidents in the region. As warming creates more conditions that are more hospitable to navigation, fossil fuel development and extraction will also increase. These changes will make the Arctic a geopolitically important region as interactions and potential for competition and even for conflict between states increase.

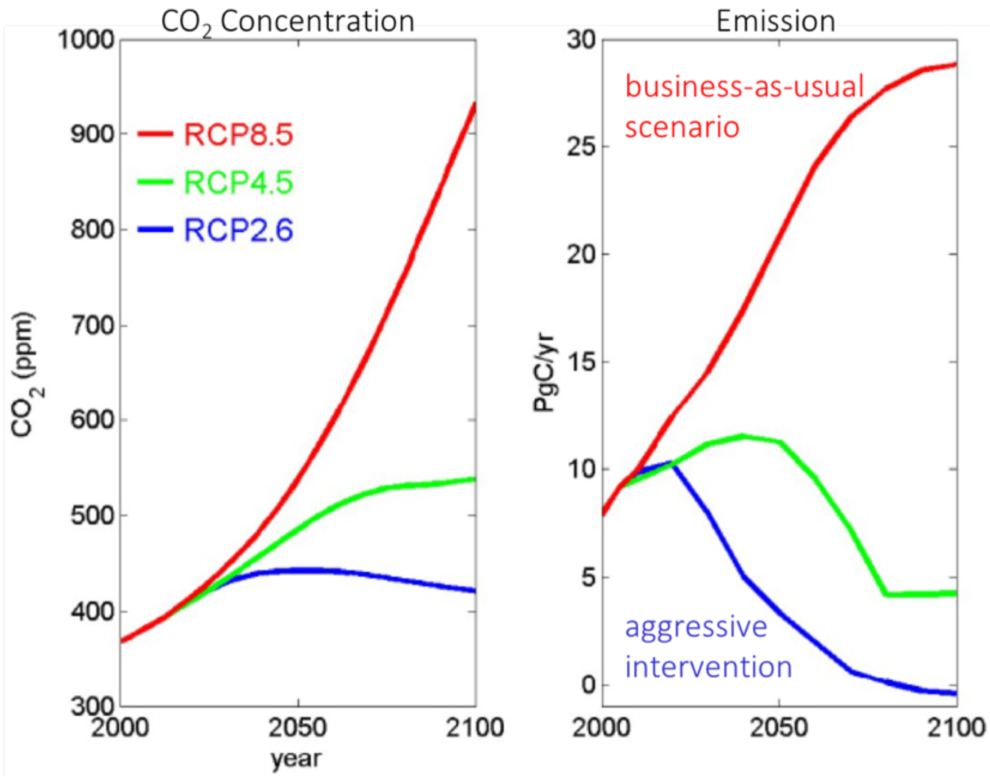

Figure 1. IPCC future climate forcing scenarios.

CESM Model Description

We use NCAR's Community Earth System Model (CESM) version 1.0.6, a fully coupled global climate model, to conduct our numerical experiments. For the purposes of this study, we are interested in output from the model atmosphere (CAM), ocean (POP), and sea ice components (CICE). The model atmosphere has 25 layers and is based in part on a spectral element dynamical core, which allows for higher flexibility with cubed sphere and curved elements of Earth model geometries (Neale et al., 2010). Global spectral atmospheric models decompose flow into spherical harmonic components, and affords an equivalent horizontal and vertical resolution of 4 degrees latitude and longitude. Meanwhile, the model ocean has 4 degrees longitude vertical resolution and 2 degrees latitude horizontal resolution (Smith et al., 2010). This resolution increases near the equator and at the poles in order to better capture Kelvin waves, the radius of deformation of which is on the scale of several hundred kilometers at the equator and less than 10 kilometers at the poles. Where the model lacks in resolution, it makes up in efficiency: Using CESM, we may run a greater number of experiments at longer durations in a shorter amount of time.

Experimental Setup

We conduct model experiments using CESM in which we abruptly raise atmospheric CO_2 concentration to 2 × (~570 ppm), 4 × (~1140 ppm), 8 × (~2280 ppm) and 16 × (~4560 ppm) pre-industrial levels of 285 ppm. The preindustrial control simulation is one in which the Earth's climate has reached a steady state, while abrupt CO_2 increase experiments are forced by an instantaneous doubling, quadrupling, and so on, of CO_2 from preindustrial levels, which are then held fixed for 800 years. In my thesis, I will focus on the first 200 of these.

Results

Global and Arctic Sea Ice Thickness, Area, and Volume Time Series

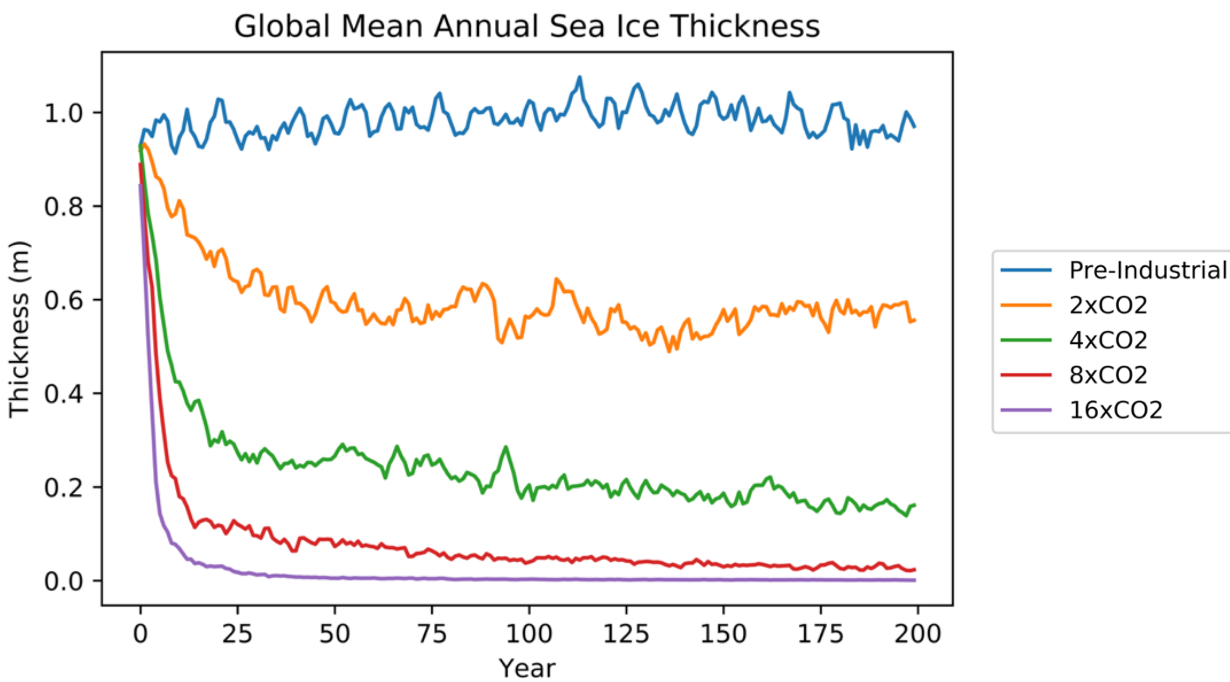

Figure 2. Global mean annual sea ice thickness (m) over 200 years.

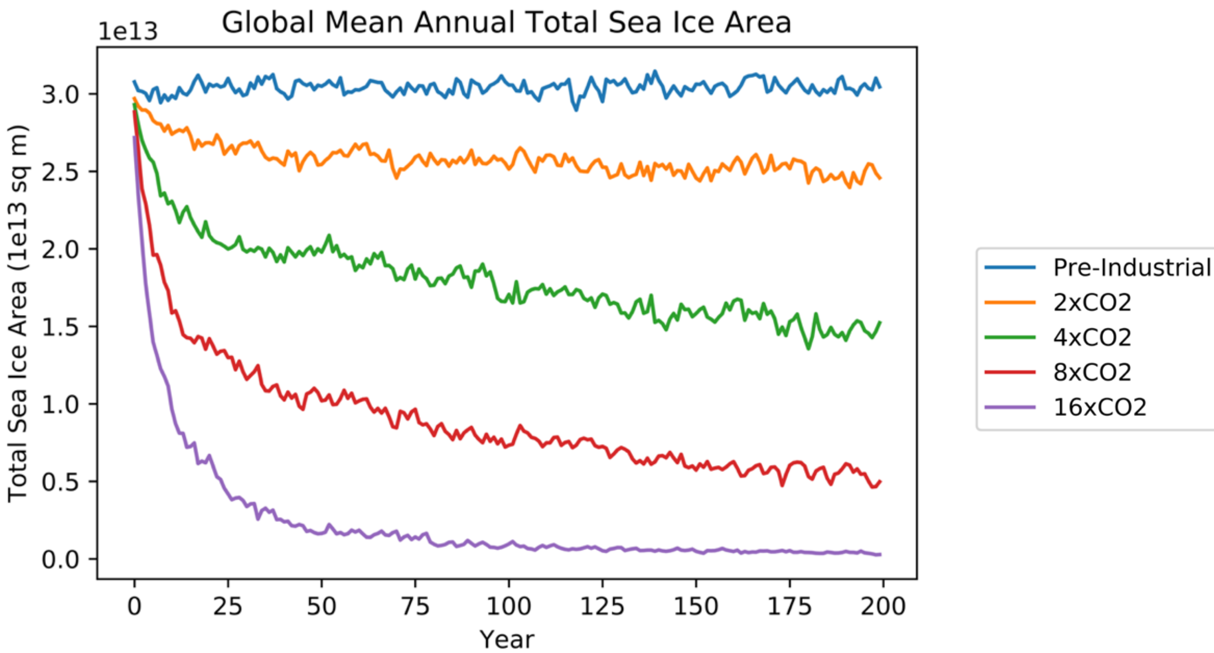

Figure 3. Global mean annual sea ice area thickness (1e13 m^2) over 200 years.

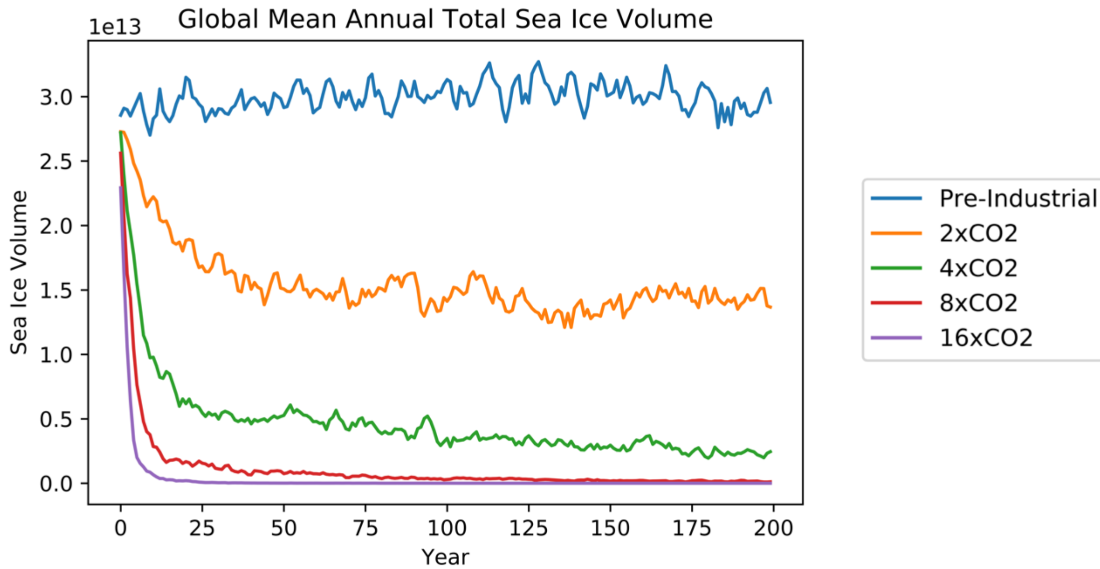

Figure 4. Global mean annual sea ice volume (1e13 m^3) over 200 years.

Global Sea Ice Decline

The global sea ice decline is correlated with the increase in global mean surface air temperature. Both in observation and in our modeling study, the decline in global sea ice thickness is more rapid in comparison with the decrease in total sea ice area. Combined, the decrease in sea ice volume is even more sensitive to climate change, decaying at an even higher rate. However, in practice, the sea ice volume is more difficult to measure directly. According to Kwok (2018), in observation, since 1958, this has been due to the loss of thicker, older ice cover. The decline in sea ice is sharpest in the 16xCO_2 experiment, with complete sea ice loss around midway through the simulation. As the thickness decreases in both the 8xCO_2 and 16xCO_2 simulations, the modeled sea ice consists predominantly of newer, younger, thinner sea ice that melts and forms seasonally, with extensive depletion of multi-year sea ice. In the 2xCO_2 and 4xCO_2 simulations, the sea ice thickness is subject to greater interannual variability after year 75, likely owing to the fact that newer ice grows more rapidly but is more susceptible to year-to-year changes in meteorology, rendering sea ice thickness more variable, rather than dominated by the effect of rising temperature.

Arctic Sea Ice Extent

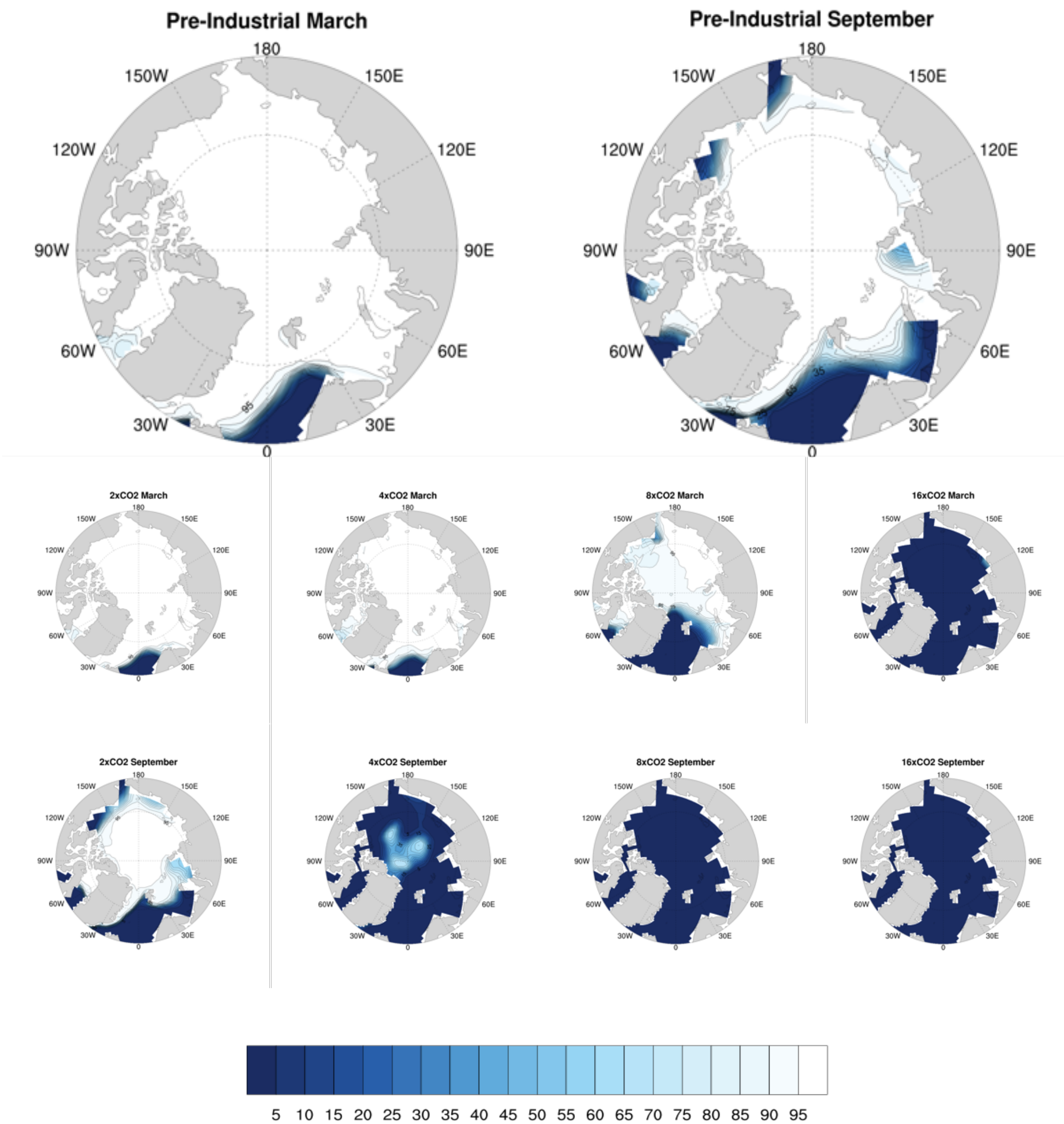

Figure 5. Arctic sea ice extent in March and September for each experiment, including the pre-industrial run, measured in percent of the model grid cell with sea ice coverage. Higher values are represented in white and lower values in blue.

Arctic Sea Ice Decline

One of the most visible signs of climate change on Earth has been the reduction in Arctic sea ice. In the last several decades, the Arctic Ocean has lost about three quarters of its sea ice volume at the end of the summer season. Because there are alternating freezing and melting seasons, the maximum Arctic sea ice extent tends to occur in March, at the end of winter, and the minimum extent at the end of summer, in the month of September. Figure 5 shows the sea ice extent in both of these months. In our experiments, we see an almost complete loss of permanent sea ice cover in the 4xCO_2 simulation, which is not an unrealistic scenario if emissions trends continue on their current path, along RCP 8.5. In the 8xCO_2 simulation, summertime sea ice is completely absent. In the 16xCO_2 simulation, there is a complete loss of sea ice year-round. There are some caveats to the applicability of these scenarios to the real world. For one, the pre-industrial simulations are initialized with more sea ice than in present day observations. In addition, the doubling CO_2 simulation does not show as much reduction in sea ice as compared with observations. There seems to be a general overproduction of summer sea ice, but this is a bias that occurs in other models as well. As previously mentioned, we have increased CO_2 abruptly rather than gradually, which is not what has occurred in nature.

Surface Air Temperature (SAT)

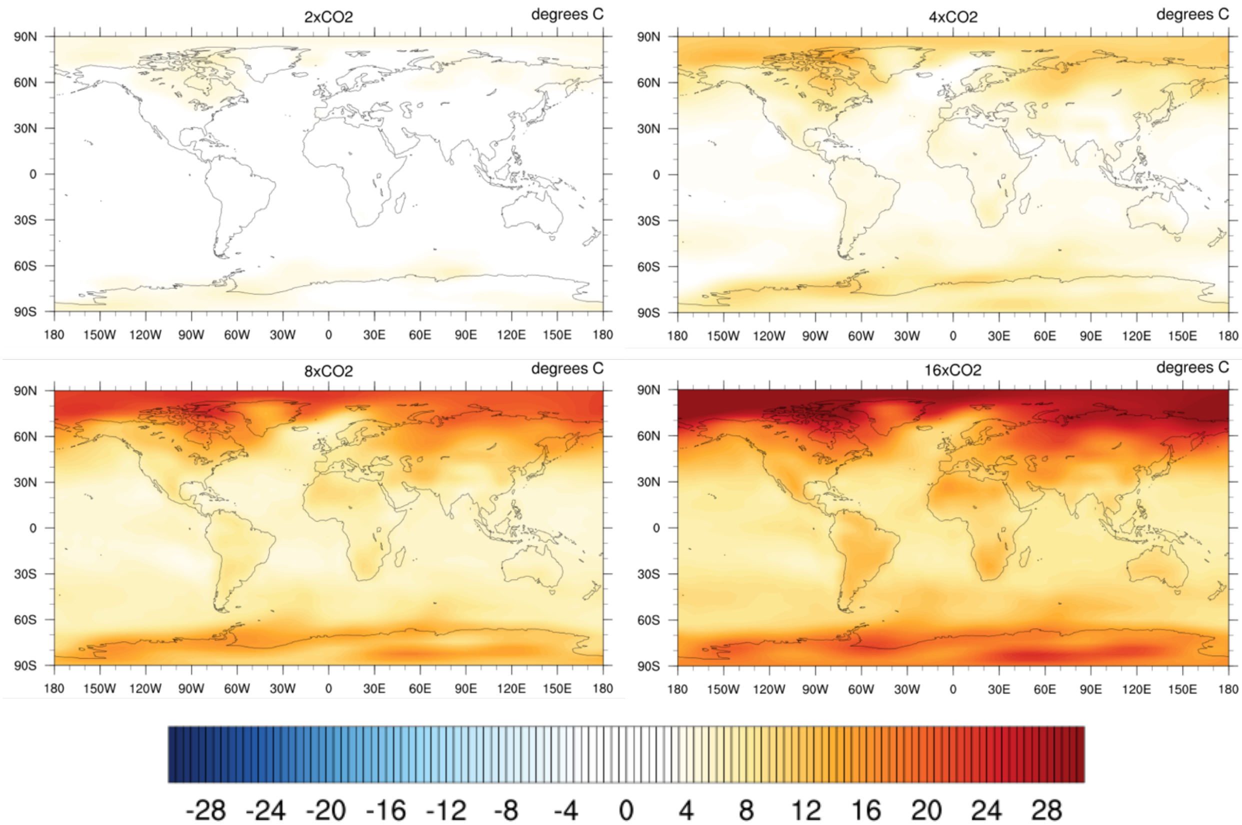

Figure 7. The global annual mean surface air temperature anomaly (relative to the control simulation) averaged over the last 50 years of model runs.

Global Surface Air Temperature Anomaly

The degree of warming in response to changes in the Earth's radiative balance depends decisively on the timescale in question. The transient climate sensitivity (TCS) characterizes the initial climate system response over the first few decades after the induced change, before the deep ocean achieves equilibrium with the change in forcing, and is represented in many experiments as a 1% per year increase in CO_2. In contrast, the ECS represents the temperature change after the climate system has reached its new equilibrium, accounting for changes in cloud cover, water vapor, lapse rate, and surface albedo, and associated feedbacks; it can take thousands of years for the Earth's climate system to reach this new equilibrium. In our experiments, we have chosen focus on the first 200 years following an instantaneous rather than linear increase in the concentration of atmospheric CO_2.

The global mean surface air temperature anomalies after 200 years in each simulation are 2.32°C (2xCO_2), 5.66°C (4xCO_2), 9.99°C (8xCO_2), and 14.1°C (16xCO_2), with maximum temperature anomalies of 6.05°C (2xCO_2), 14.0°C (4xCO_2), 24.1°C (8xCO_2), and 33.6°C (16xCO_2) occurring in the Arctic region. The mean global surface air temperature anomaly for the 2xCO_2 experiment is consistent with previous experiments involving CESM, and fall within the range of likely (probability greater than 66%) transient climate sensitivity (TCS) of 1.5°C to 2.5°C as well as the range of likely equilibrium climate sensitivity (ECS) of 1.5°C to 4.5°C, as defined in the Intergovernmental Panel on Climate Change's Fifth Assessment Report (2014).

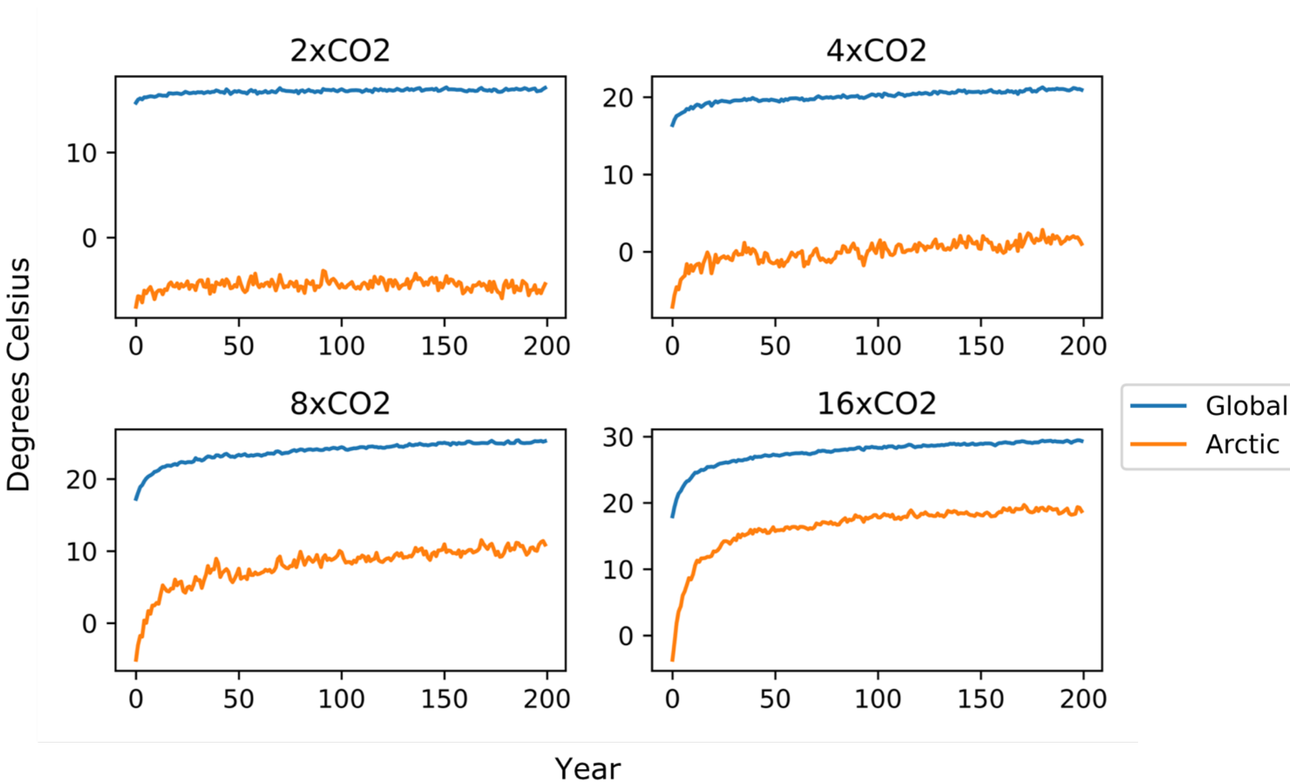

Figure 8. Global and Arctic trends in surface air temperature over 200 years.

Polar Amplification

Both the instrumental record and global climate modelling experiments have indicated that the rate of surface air temperature warming in the Arctic region tends to exceed that in the Northern Hemisphere as well as that over the globe as a whole by as much as two to three times (Serreze and Barry, 2011). This phenomenon, known as Arctic – or polar – amplification, has been attributed to melting snow and sea ice, which affects ocean-atmosphere vertical heat fluxes; the surface-albedo feedback; and poleward atmospheric and oceanic heat transport, among various other physical processes involving water vapor and clouds (e.g., Lu and Cai, 2009; Graversen et al., 2009). Increases in summer sea ice melting can also cause concomitant increases in energy release from the open ocean in the winter, resulting in additional heating of the lower atmosphere (Bintanja et al, 2011). Notably, enhanced Arctic warming is associated with changes in atmospheric circulation and the carbon cycle, with observable effects both within and beyond the Arctic region. In recent studies, the relationship between Arctic amplification and extreme weather has been investigated, with Cohen et al. (2014) postulating that Arctic amplification may be linked to more frequent extreme weather events across the Northern Hemisphere mid-latitudes, including more severe winters, via changes in storm tracks, the jet stream, and planetary waves. The recent extreme cold temperatures experienced by the US Midwest in the previous winter may be a manifestation of this, as a result of the weakening temperature and pressure gradient, causing a meandering in the jet stream, which allows for the intrusion of warmer temperatures further north and colder temperatures south.

Figure 8 shows the trends in global and Arctic surface air temperature (note the difference in vertical scale). Amplification does not appear to be enhanced in experiments with higher levels of CO_2. Rather, the rate of warming in the Arctic is roughly twice that of the mean global increase in surface air temperature across all experiments. The ratio of Arctic to global warming over the first 50 years for each simulation are 1.98 (2xCO_2), 2.13

($4xCO_2$), 2.32 ($8xCO_2$), 2.19 ($16xCO_2$). It is worth noting that much of the warming occurs in each simulation occurs within this portion of the model run, coincident with the largest decreases in model sea ice thickness and extent. This is consistent with the existing hypothesis that the snow- and ice-albedo feedback mechanism plays a substantial role in augmented high-latitude climate change, where warming leads to a reduction in snow and ice coverage, which leads to a reduction in surface albedo, which in turn results in further snow and sea ice melting, and so on. The most prominent manifestation of this feedback mechanism occurs in the upward heat ocean-atmosphere heat flux and subsequent rise in SAT (Bekryaev et al., 2010): Holland and Bitz (2003) show that polar amplification is stronger in areas with thinner ice cover, which is subject to more rapid melting, leading to a greater number of openings in the ice cover and heat release from the ocean and changes in the surface albedo. According to Manabe and Stouffer (1980), heat accumulated by the ocean as a result of the ice-albedo feedback is used partially in the process of ice thinning, which leads to greater increases in SAT in autumn and winter, when sea ice freezes again. In the summertime, the surface albedo feedback causes an increase in absorption of solar radiation by the ocean surface, some of which is released to the atmosphere as latent heat flux during subsequent seasons. It is worth noting that much of the warming amplification that occurs in each simulation occurs within the first 40 or 50 years, which coincides with the largest decreases in model sea ice volume. This is consistent with the existing hypothesis that the snow- and ice-albedo feedback mechanism plays a substantial role in polar amplification.

However, more recent studies have shown that the ice-albedo feedback mechanism alone is not enough to account for the heightened warming observed in the Arctic. In fact, Arctic amplification occurs to an only moderately lesser extent in some models when the surface albedo feedback is suppressed entirely, implying that the surface albedo feedback, which affects the absorption of incoming shortwave radiation, may not even play a dominant role in the phenomenon (Graversen and Wang, 2009). Instead, Francis and

Hunter (2007) discover an increase of downward longwave radiation at the Arctic ocean surface in the springtime, and attribute its cause to an increase in water vapor content and cloud fraction, the latter of which acts to dampen the effect of retreating ice and snow on the Earth's surface albedo. Other contributions to Arctic amplification, including an enhanced greenhouse effect resulting from the water vapor feedback, the cloud feedback, and the lapse-rate feedback affecting the vertical structure of warming, have also been speculated. In particular, Pithan and Mauritsen (2014) find that the factors that contribute most to Arctic amplification are related to temperature feedbacks: As the surface warms, more energy is radiated back to space in lower latitudes compared with in the Arctic due to the different vertical structure of warming in high versus low latitudes, in which a smaller increase in blackbody radiation is emitted per degree of warming at lower temperatures than at higher ones.

Arctic-Antarctic Warming Asymmetry

An early study conducted by Manabe and Stouffer in 1980 found roughly symmetric polar amplification in both the Northern and Southern hemispheres. However, recent studies and observations have contradicted this finding, demonstrating instead that there is an inherent asymmetry in the warming between the Arctic and Antarctic. Although there is polar amplification evident at both poles, the Arctic appears to be warming even faster than the Antarctic. In contrast to the considerable warming and sea ice loss that have occurred in the Arctic in recent decades, Antarctic temperatures and sea ice during the same time period have exhibited less evidence of change, with the exception of the Antarctic Peninsula (Walsh, 2009). Asymmetry in the climate change signal in the Arctic and Antarctic is apparent in both observations and climate modeling studies. Results from our abrupt CO_2 increase experiments also exhibit Arctic-Antarctic warming asymmetry (Figure 7): The average surface air temperature anomalies at the end of 200 years in the Arctic and Arctic are, in that order, 3.77°C and 3.71°C ($2xCO_2$), 10.25°C and 7.14°C ($4xCO_2$), 20.1°C and 12.6°C ($8xCO_2$), and 28.0°C and 18.0°C

($16xCO_2$). Our $2xCO_2$ experiment shows a similar spatial pattern as that in recent observations indicating cooling over the East Antarctic accompanied by warming over the West Antarctic and its peninsula (Steig et al., 2009), although these comparisons are limited by the nature of the experiments, as they involve abrupt increases in atmospheric CO_2 and take place on a centennial rather than decadal timescale. Previous studies, like the one completed by Singh et al. (2018), have postulated that the ocean response to CO_2 forcing magnifies the Arctic-Antarctic warming asymmetry 1) by taking up more heat in the Southern Hemisphere relative to the Northern Hemisphere, and 2) by destabilizing radiative feedbacks over the Arctic, which amplify the Arctic climate sensitivity. Geographically, the two regions are distinct: The Arctic is an ice-covered ocean basin surrounded by land masses, while Antarctica is a large land mass surrounded by a vast ocean. The continent is buffered by circulation patterns that may shelter it from large warm-air intrusions. Antarctica is also a lot drier than the Arctic and is classified as a desert.

That polar amplification occurs in the Antarctic region is indicative of the hypothesis that there are other mechanisms important for amplification other than the surface albedo feedback. For instance, an increase in moisture in the Antarctic, with the effects of the associated water vapor feedback, might have outsized effects because there is little moisture there to begin with. Recent studies have highlighted the formation of the ozone hole only over Antarctica, although there is still some Arctic stratospheric ozone depletion. The ozone hole itself has a minor cooling effect on the Earth's atmosphere because ozone in the stratosphere absorbs heat radiated to space, and loss of ozone allows more heat to escape. Moreover, because greenhouse gas forcing results in stratospheric cooling, this creates even better conditions for polar stratospheric cloud formation, and leads to more depletion of ozone in the stratosphere.

Sea Surface Salinity (SSS)

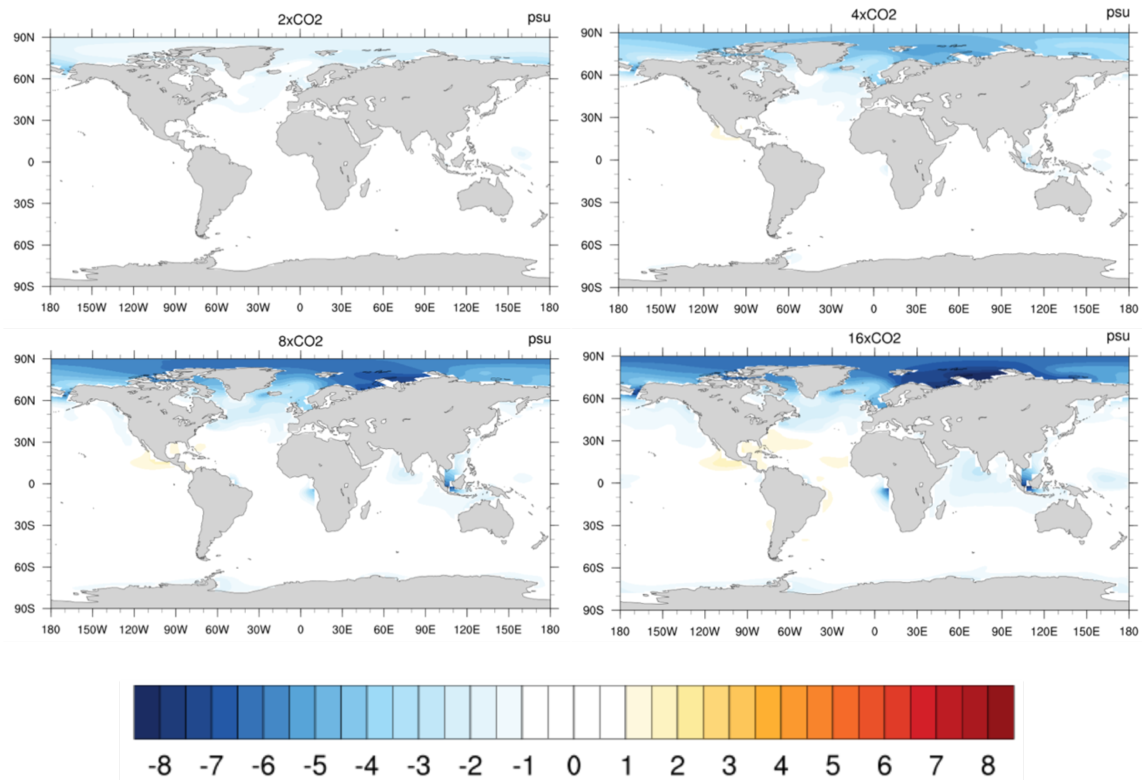

Figure 6. The global annual mean salinity anomaly (relative to the preindustrial simulation) averaged over the last 50 years of model runs.

Global Sea Surface Salinity Anomaly

There is a significant and successively greater freshening of the Arctic Ocean with increased CO_2 forcing, with the highest negative salinity anomalies occurring in the Arctic region north of Russia. The surface freshening in the Arctic ocean is closely linked to melting sea ice, and is hypothesized to be an important driver of the weakening in the meridional overturning circulation. The maximum and average salinity anomalies for each experiment are -4.33 and -0.39 psu (2xCO2), -5.50 and -1.00 psu (4xCO2), -7.64 and -1.38 psu (8xCO2), and -9.72 and -1.65 psu (16xCO2). Highly negative salinity anomalies may produce a positive warming feedback: Fresher water remains at the top of the ocean, resulting in reduced ocean mixing and more stable ocean stratification, factors that may contribute to the polar amplification observed in the Arctic.

Sea Surface Temperature (SST)

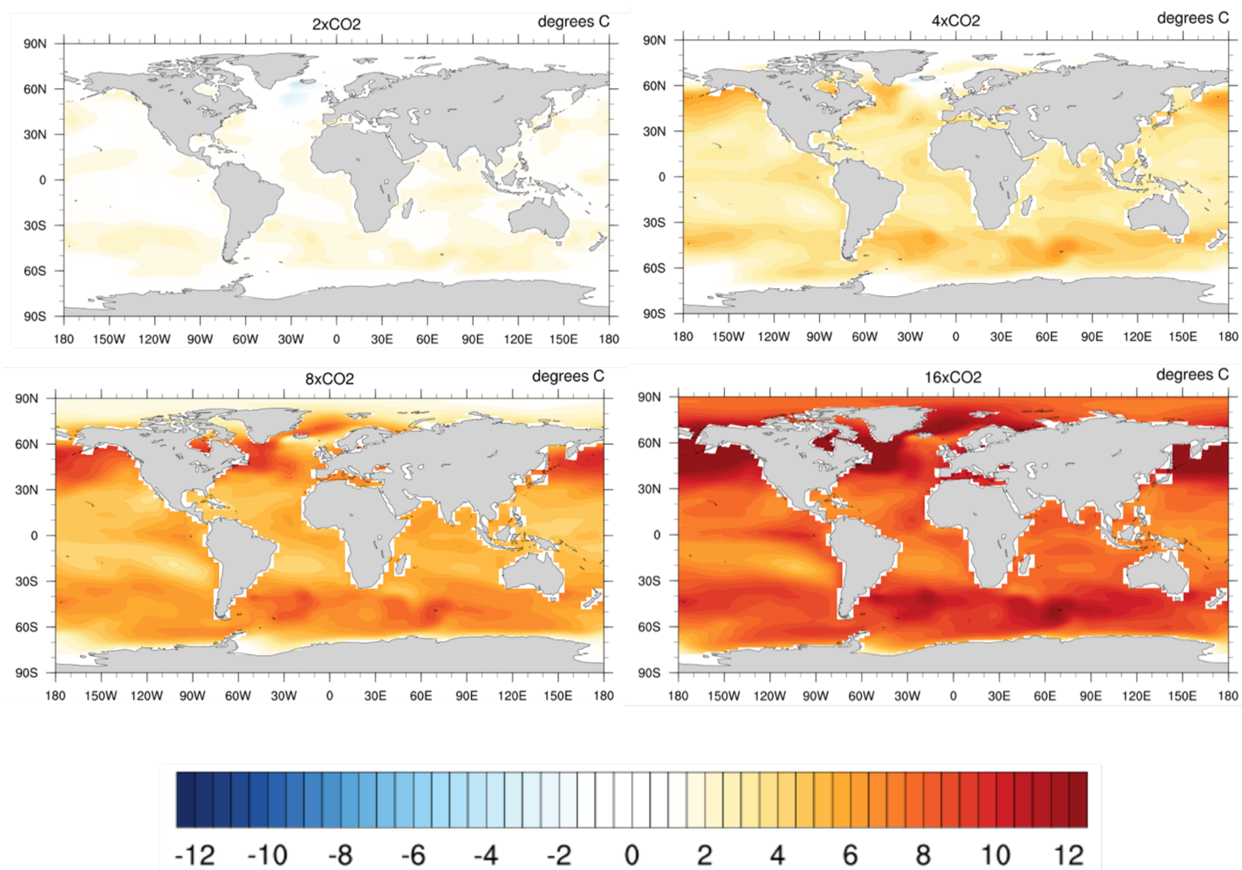

Figure 9. Global annual mean sea surface temperature anomaly (relative to the preindustrial simulation), averaged over the last 50 years of model runs.

Global Sea Surface Temperature Anomaly

We find that SST increases more in experiments with higher concentration of atmospheric CO_2. The global sea surface largely warms, but there is some cooling in the 2xCO_2 and 4xCO_2 experiments, most notably south of Greenland. This cooling is likely induced by the weakening in the meridional overturning circulation, resulting in less oceanic heat transport to the North Atlantic. Annual SSTs in the Arctic Ocean do not begin to increase visibly until the 8xCO_2 sufficient ice melting has occurred. The maximum and average SST anomalies for each experiment are 3.313°C and 0.99°C (2xCO2), 6.57°C and 2.69°C (4xCO2), 10.0°C and 5.26°C (8xCO2), and 15.0°C and 8.50°C (16xCO2).

Atlantic Meridional Overturning Circulation

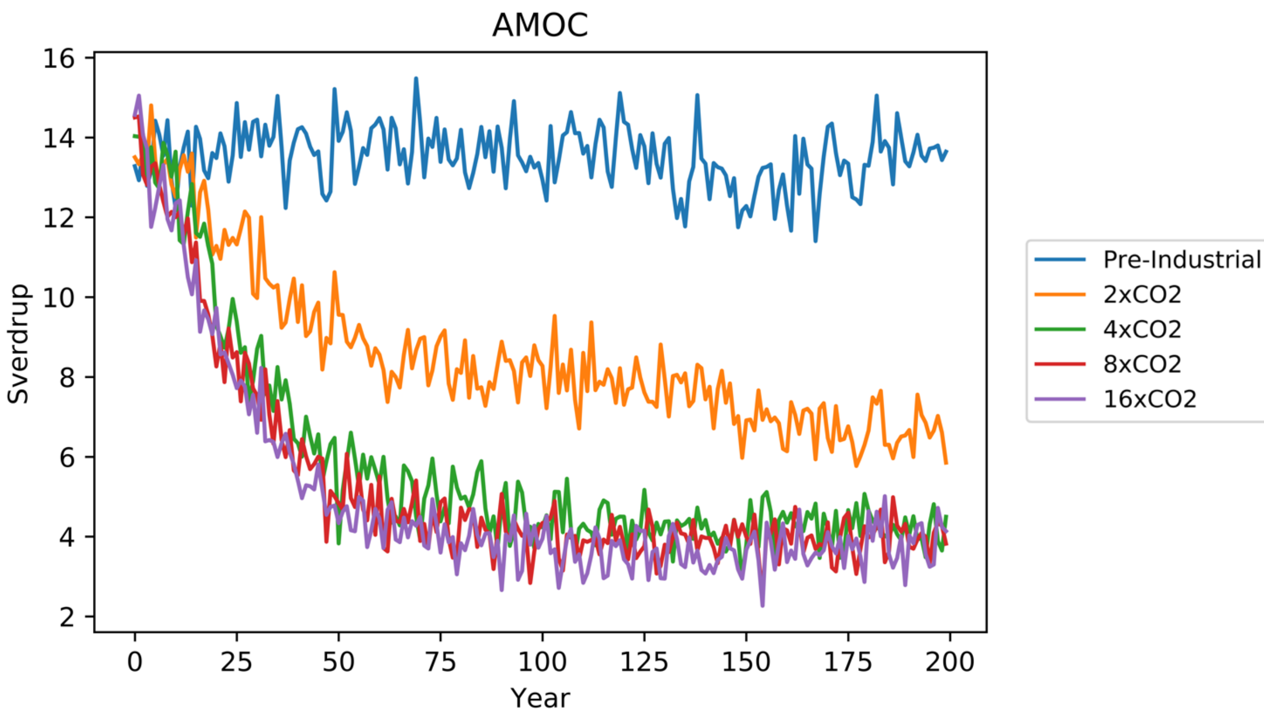

Figure 10. AMOC strength in sverdrups over 200 years.

The Atlantic Meridional Overturning Circulation (AMOC) is large network of ocean currents that transports warm water from the tropics northwards into the North Atlantic, where it becomes cooler and denser and sinks and spreads southwards. AMOC transports heat on the scale of 1 PW (Ganachaud and Wunsch, 2000), is driven by differences in temperature and salinity that determine the density of sea water, and is an important component of the Earth's climate system. Accordingly, changes to AMOC has significant consequences for the oceanic heat supply to the North Atlantic. According to Kuhlbrodt et al. (2007), AMOC consists of four major branches: upwelling processes that transport water from depth to the ocean's surface, surface currents that move relatively light water towards high latitudes, deep water regions where water become denser and sink, and deep currents that close the loop, all of which together span the entire Atlantic Ocean. Although reliable observations of AMOC strength have only been collected since 2004, multiple global climate models have predicted that AMOC will weaken in response to the continued influx of fresh water from melting Arctic sea ice and the Greenland ice sheet.

Here, the AMOC strength is defined as the maximum of the annual mean meridional stream function below 500 meters in the North Atlantic (28-90°N). In the control simulation, mean AMOC strength over 200 years is 17.1 Sv, and weakens by 44% ($2xCO_2$), 64% ($4xCO_2$), 67% ($8xCO_2$), and 69% ($16xCO_2$), in the abrupt CO_2 experiments. The weakening in AMOC reduces northward oceanic heat transport and results regional sea surface cooling in the North Atlantic (a "warming hole" south of Greenland) in the $2xCO_2$ and $4xCO_2$ experiments, although this signature is masked in the $8xCO_2$ and $16xCO_2$ experiments, suggesting that the contribution of AMOC to cooling in the region is eventually counteracted by its overall contribution to global warming.

Although AMOC does not collapse entirely as we expected in the $16xCO_2$ experiment, we note that in each of the 4x, 8x, and 16x simulations, AMOC converges to roughly 4-5 Sv. It is possible that the CESM model's sensitivity to changes in salinity and resultant AMOC weakening is biased low, or that calculations of AMOC mistakenly capture wind-driven circulation.

Precipitation

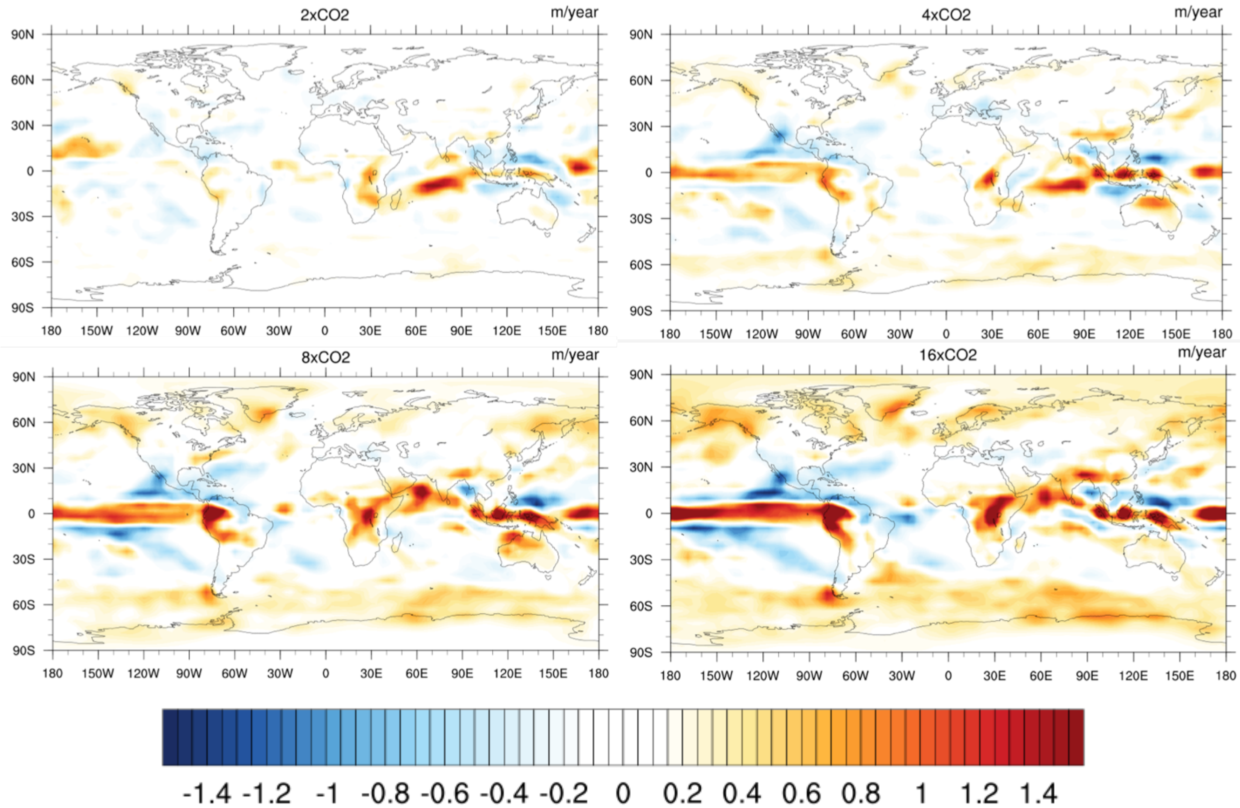

Figure 11. Global annual mean precipitation anomaly (relative to preindustrial simulation), averaged over the last 50 years of model runs.

We find an overall intensification of the hydrological cycle with abrupt increases in atmospheric CO_2. There does not seem to be any significant shifts in the location of the Intertropical Convergence Zone (ITCZ), a belt of high precipitation near the equator where the trade winds converge, which shifts north and south seasonally due to the differential heating and cooling of the hemispheres. To illustrate, when the atmosphere receives additional energy in the northern hemisphere, it attempts to rectify this imbalance by transporting energy across the equator from the north to the south. Because we do not find that a noticeable shift occurs, this suggests that the effect of a weaker AMOC is perhaps compensated by the polar amplified warming, at least at the end of 200 years in each simulation. However, this may not be the case on shorter timescales.

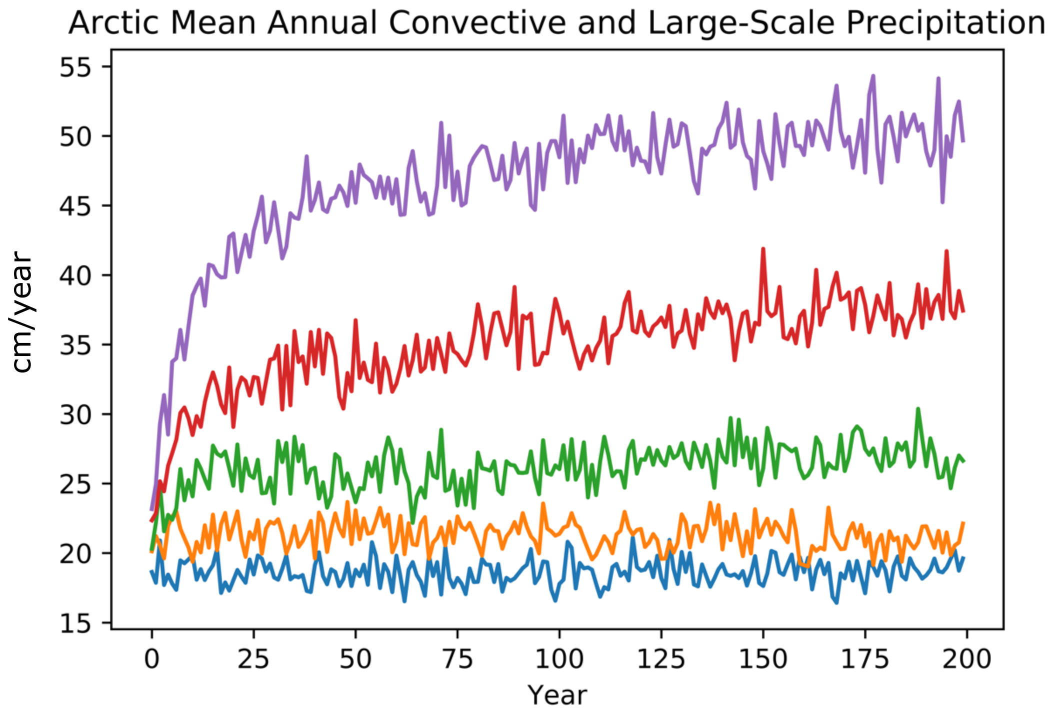

Figure 12. Trends in total annual mean convective and large-scale precipitation in the Arctic over 200 years.

Aerosol Optical Depth (AOD)

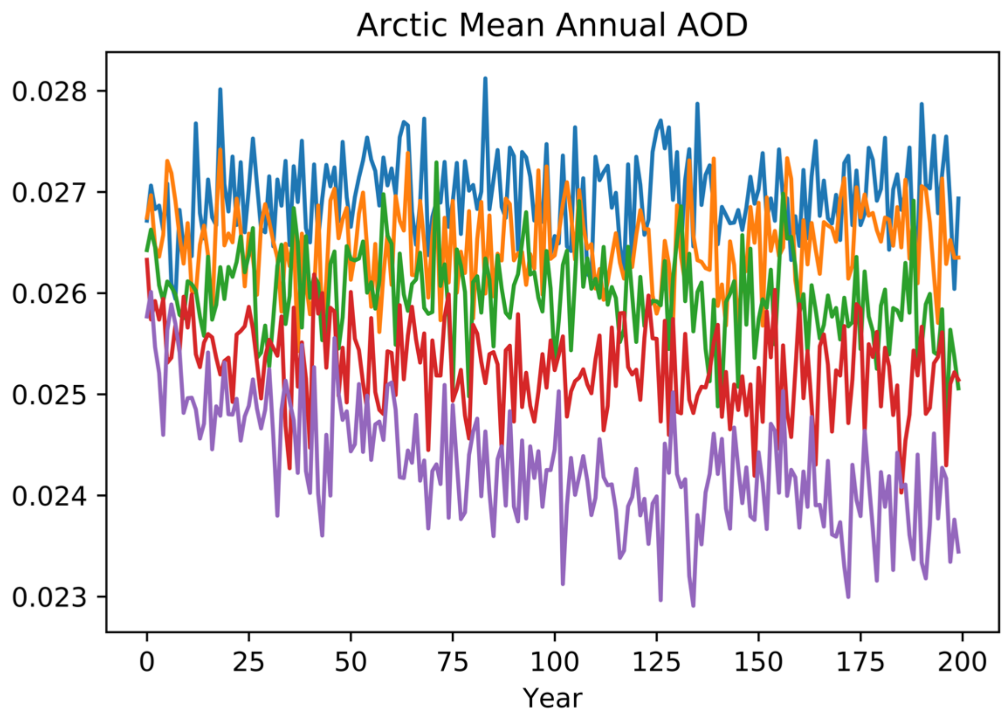

Figure 13. Trends in Arctic AOD over 200 years.

Overall, aerosols in the Arctic have a cooling effect on climate by reflecting incoming solar radiation, and can partially offset increases in the Earth's temperature. Figure 13 shows trends in total Arctic aerosol optical depth over 200 years in each abrupt CO_2 increase experiment, a measure of the extinction of the solar beam by aerosols. AOD is a measure of the quantity of direct sunlight that is unable to reach the ground due to absorption or scattering by aerosol particles in the Earth's atmosphere. The number is related to the amount of aerosol in the vertical column of atmosphere.

The CESM model simulations do not include anthropogenic emissions of aerosols, as only CO_2 in the atmosphere is increased. Thus, aerosols that are present in the Arctic are from natural sources, including sea salt from the ocean or dust transported from Asian and African deserts (Barrie et al., 1995). We find that the aerosol optical depth decreases slightly with higher levels of CO_2, ranging from 5% to 15%. This may be due to the significant concurrent increase in Arctic precipitation (Figure 12) – one of the most important mechanisms of aerosol removal is via precipitation. The decline in Arctic AOD may provide some small positive feedback for Arctic climate, because increases in precipitation will also decrease aerosol column load, which will then enhance warming, although this effect may be insignificant when one considers anthropogenic aerosol emissions.

Conclusions

This study provides a broad overview of Arctic climate change in numerical experiments with abrupt CO_2 increase of varying levels, using NCAR's Community Earth System Climate Model. Preliminarily, we have found that:

1. Permanent sea ice loss occurs with abrupt 4xCO_2 increase, and complete sea ice loss occurs with abrupt 16xCO_2 increase.
2. There is enhanced warming in the Arctic region ("polar amplification"): The Arctic warms roughly twice that of the rest of the globe in each abrupt CO_2 increase experiment, with slight increases in this ratio with higher concentrations of CO_2.
3. There is a warming asymmetry between the Arctic and Antarctic, but polar amplification occurs even over the Antarctic continent, where there is no sea ice, indicating that factors in addition to the surface-albedo feedback (e.g. water vapor/cloud feedbacks) contribute to amplified polar warming.
4. There is a significant and successively greater freshening of the Arctic Ocean with increased CO_2 forcing due to melting sea ice, which is hypothesized to be an important driver of the weakening of AMOC.
5. There does not appear to be a significant shift in the location of the ITCZ in any of the experiments, which suggests that the effects of polar amplification and weakening AMOC may counterbalance each other in the Northern Hemisphere.
6. Arctic AOD decreases 5-15% from 2x to 16x CO_2 experiments, possibly attributable to the concurrent increase in precipitation in the Arctic, and may represent some small positive feedback in Arctic warming.

Future Study

Logical next steps in the project include more detailed investigation of the changes in the features discussed both within the 200 years analyzed here, to better understand the transient climate response to abrupt CO_2 increase, and beyond it, for a better understanding of the equilibrium climate response to abrupt CO_2 increase. The seasonal cycle of sea surface salinity may be of particular interest, as we have found broadly that it intensifies at the start of each experiment and becomes more moderate by the close. In order to better constrain the contribution of aerosols to Arctic warming, closer study of these small atmospheric particles – both natural and anthropogenic – in the Arctic is warranted, both for their direct effect on the planet's radiation balance and their indirect effect on cloud formation. Aerosols represent a major source of uncertainty not just in our understanding of Arctic climate change but in global climate modeling and prediction at large. As human activity in the Arctic increases, it will become more important to understand the processes that drive aerosol transportation, scavenging, and removal.

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