

THE RELATION AMONG SEA ICE, SURFACE TEMPERATURE, AND ATMOSPHERIC CIRCULATION IN SIMULATIONS OF FUTURE CLIMATE

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Introduction

Observations document substantial 20-40 year trends in the past several decades in the Arctic. Studies show sea ice thickness and extent have declined, air temperature has increased, and the temperature and salinity of the upper ocean have increased (e.g., see Serreze et al., 2000). At the same time, we have seen a weakening of the tropospheric anticyclone over the Beaufort Sea that can be associated with trends in a large-scale pattern of atmospheric variability (Walsh et al, 1996; Thompson and Wallace, 1998). The fluctuations of Arctic surface temperatures, sea ice, and the upper ocean are coherent with this pattern of atmospheric variability (Rigor et al., 2000, 2001; Zhang et al., 1998) on a range of time scales. Most evidence indicates the Arctic surface climate is responding to the atmospheric circulation. If we knew what was causing variability and trends in the atmospheric circulation, we could better predict the future of Arctic climate. However, the source of the recently observed trends and the decadal variability remains a matter of debate.

The dominant relation between observed surface temperature trends and the atmospheric circulation in the Arctic may seem to contradict the commonly held wisdom, based on model studies, that Arctic warming induced by greenhouse gases (GHGs) is amplified by ice-albedo feedback primarily over sea ice. Although sea ice has receded in much of the eastern Arctic, the observed peak warming is over Eurasia. In contrast, most climate models have a warming maximum over the ocean (Raisanen, 2001). Figure 1 shows the warming in GHG forced experiments from a selection of climate models participating in the IPCC 2001 report. Climate change simulations with the sea ice held fixed to its present day extent indicate that changes in the ice extent account for 20-40% of the global warming, depending on the model (Ingram et al, 1989; Rind et al., 1995). The strength of the ice-albedo feedback in a model depends on parameterizations and the mean state. For example, a relatively strong amplification is seen in CGCM2, whose present day sea ice is arguably too thin, at less than 2 m in the central Arctic.

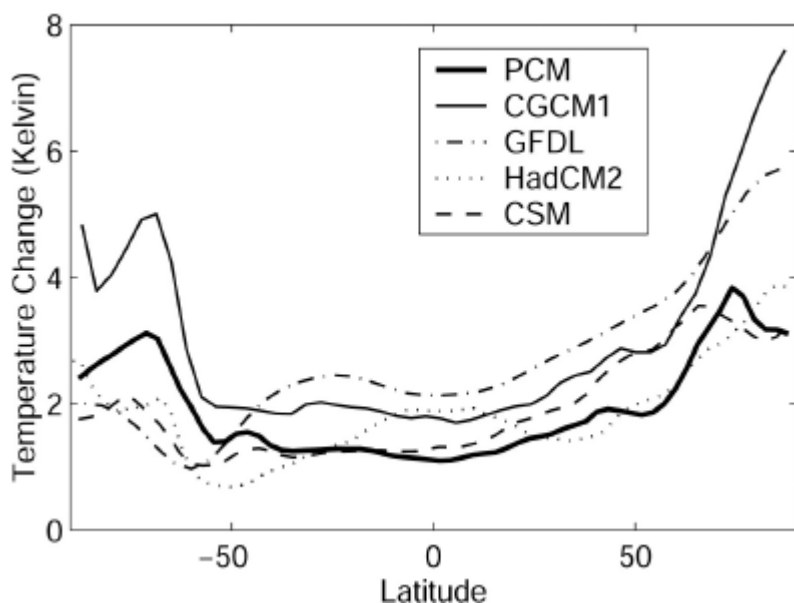


Figure 1. Changes in annual mean zonal temperature from five models archived at the IPCC Data Distribution Centre. PCM = U. S. NCAR Parallel Climate Model, CGCM2 = Canadian Climate Centre, GFDL = U. S. Geophysical Fluid Dynamics Laboratory, HadCM3 = U. K. Hadley Center, CSM = U. S. NCAR Climate System Model. The change is computed from an average over the 10-year period centered on the time of doubling.

Here we will focus on the relations among climate variables in one model to gain further understanding about the cause of observed trends in the Arctic. We will assess how well temperature trends simulated in GHG warming experiments are related to trends in the atmospheric circulation like those observed in the recent past. The results presented are from an ensemble of five runs for the period 1870-2100 with the National Center for Atmospheric Research NCAR Parallel Climate Model (PCM). Starting in 1990, carbon dioxide was increased at the rate of 1% per annum through 2100. Other GHGs were increased as well, and the cooling influence of sulfate aerosols was included. The PCM has a modest warming relative to other coupled models. Compared to observations, the PCM has a relatively weak trend in its Arctic Oscillation Index (AOI), a measure of large-scale circulation that is highly correlated with sea level pressure over the Beaufort Sea. For these reasons, the results from the PCM will be compared to those from the Canadian Climate Centre for Modeling and Analysis model CGCM2, which warms more and has a larger AOI trend than the PCM. Both models have relatively sophisticated sea ice models, which include a method for computing sea ice motion based on a rheology.

Results

Figure 2a shows the simulated trend in surface warming. The largest warming occurs in the northern North Atlantic along the present day ice edge simulated by the PCM. The present day ice extent in the PCM is greater than observed, and by the time of doubling, it recedes to the approximate location of the observed ice edge. Outside of the area where the ice is receding, the magnitude of the warming simply decreases gradually away from the Arctic Ocean. The pattern of warming is consistent with the hypothesis that the amplification of the warming is largely due to ice-albedo feedback.

The pattern of warming in Fig. 2a is in stark contrast to the observed warming for the past 40 years, which is largest over Eurasia. Some observational analyses show a slight cooling in parts of Labrador and in the southern Beaufort Sea, although the amount depends on season and length of record. A substantial fraction of the observed warming pattern has been linked to the increase in wind speed at mid-latitudes associated with the Arctic Oscillation (AO) (Thompson and Wallace, 1998; Rigor et al., 2000). The model successfully simulates a pattern of variability similar to the observed AO, with a great deal of decadal fluctuations. This same pattern projects strongly onto the surface air temperature (Fig. 2b), such that temperature anomalies of the order of 1--2 Kelvin occur when the AOI, an index that describes the intensity of the AO, is in excess of one standard deviation above or below zero. The pattern in Fig. 2b resembles the pattern of observed warming over Eurasia, but the negative values over Alaska and western Canada are too low.

The trend of the AOI in the 21st century from an ensemble mean of five integrations with the PCM is positive and significant at the 95% confidence level, although it is only about one-quarter of the observed trend for the past 40 years. Because the simulated AOI trend is relatively weak, the warming trend in Fig. 2a does not resemble the pattern in Fig. 2b. The portion of the warming explained by the AOI, shown in Fig. 2c, is the product of the AOI trend and the pattern in 2b. The fraction of the warming explained by the AOI, shown in Fig. 2d, is also rather small. A similar result is obtained using an index for the North Atlantic Oscillation (NAO) because the AOI and NAO are highly correlated. The AOI is used here because its pattern is centered on the Arctic and its relationship with Arctic climate variables is generally stronger.

Simulated sea ice thickness and extent are also strongly correlated with the AOI (not shown). As was the case for the surface temperature, the pattern of sea ice thickness and extent associated with the simulated AOI, resembles the changes observed over the past two decades. Yet the fraction of the simulated sea ice changes explained by the AOI is quite small because the AOI trend itself is small in the model.

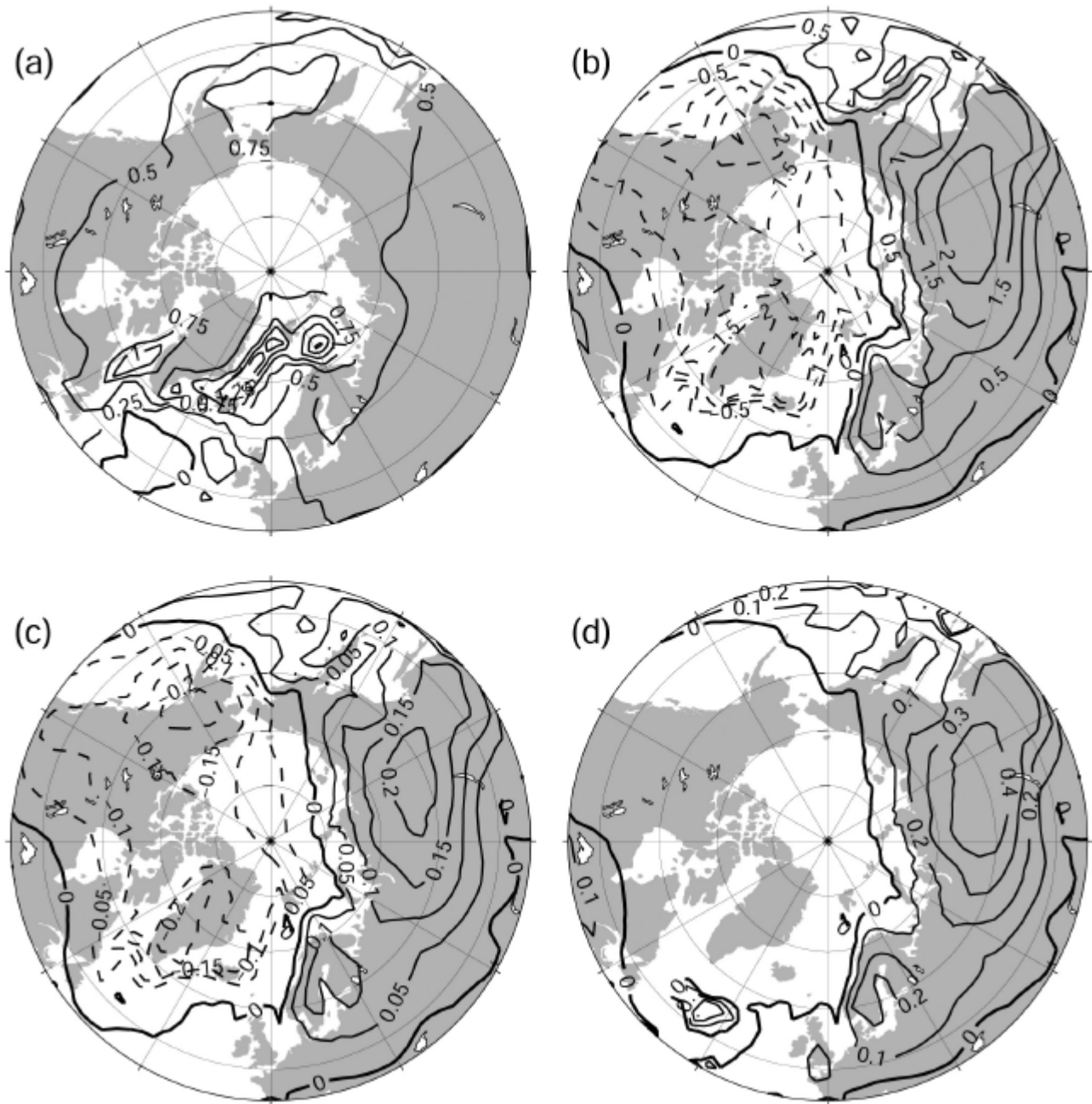


Figure 2. Contribution of the Arctic Oscillation to winter (Nov--Apr) surface temperature trends in the 21 century. (a) Simulated surface temperature trend in Kelvin per decade. (b) Surface temperature regressed on AOI in Kelvin per unit standard deviation of the index. (c) AO contribution to the surface temperature trend in Kelvin per decade. (d) Fraction of surface temperature trend explained by the AO.

Discussion

Trends in the surface air temperature simulated by the PCM are largest in area where the sea ice is retreating in GHG induced climate change integrations. The model successfully reproduces strong relationships among the atmospheric circulation, sea ice, and the surface air temperature that resemble observed patterns associated with interannual and decadal fluctuations. However, the

patterns of warming and the changes in sea ice extent do not resemble those observed warming over the past few decades. This is easily explained by the small trend in the simulated AOI in the 21 century, which is only about one-quarter of the trend observed over the past 40 years.

A similar analysis was performed on an ensemble of three simulations with the CGCM2. As mentioned in the Introduction, the AIO trend in CGCM2 is larger than in the PCM, although it is still only about 30% of the observed trend. The strength of the Arctic warming in CGCM2 is among the top 15% of the coupled models participating in CMIP2. While parameterizations, the mean state, and the resolution of CGCM2 are remarkably different from the PCM, the same conclusions are inevitable from repeating the analysis in Fig. 2.

We can extend this work to a larger group of climate models by looking at the surface warming alone. At least 19 models have provided output to the CMIP2 project from integrations forced by enhanced greenhouse gases. According to a report by (Raisanen, 2001), few of the models predict a pattern of Arctic warming that resembles the observed change, which peaks over northern Eurasia. Instead the peak warming in the models typically appears somewhere over the Arctic Ocean or subpolar oceans. The warming averaged across the 19 models peaks in the center of the Arctic Ocean. Many of the models CMIP2 participants have also reported on the simulated response of the Arctic Oscillation to enhanced GHGs. Gillett et al. (2001) have summarized these results, concluding that most models show a significant positive AO response but the rate of change is much smaller than is observed. Either the majority of these models are in error, or the observed temperature changes is at least partly caused by influences that are not represented in the models.

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