Origin of the Arctic warming in climate models

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[1] There is a debate on whether the snow/ice change feedback or poleward energy transport from lower latitudes generates the observed Arctic warming amplification. There is another possibility that remotely induced warming in the Arctic can be amplified by snow/ice feedbacks. We demonstrate that this mechanism plays an important role in two independent climate models: CAM3 and ECHAM5. We also show with these two models that the June–August temperature structure in the vertical is a good indicator of how much the climate forcing from lower latitudes contributes to Arctic warming. Compared with the June–August 3D temperature trend in ERA Interim reanalysis, the CMIP3 models simulate warming at higher levels, suggesting that the models over-simulate the role of poleward energy transport in Arctic warming. This finding has implications for climate feedback and aerosol forcing.


1. Introduction

[2] The surface temperature rise in the Arctic is observed to be about twice as large as the global average warming in the recent decades [Hassol, 2004; Bekryaev et al., 2010]. Climate models are able to simulate both the global warming and the Arctic amplification of the warming with enhanced greenhouse gas (GHG) forcing [Hegerl et al., 2007], and so the GHG forcing is widely understood to be the primary driver of Arctic warming. The reason that the Arctic shows an amplified warming was commonly attributed to the snow and ice feedbacks [Manabe, 1983; Hall, 2004]. Other local processes such as tropospheric stability and longwave feedbacks related to water vapor and clouds were also proposed [e.g., Manabe and Wetherald, 1975; Graversen and Wang, 2009].

[3] Contrary to these local feedbacks, Alexeev et al. [2005, Figure 11] demonstrated through “ghost forcing” model experiments that the poleward energy transport from lower latitudes could create the Arctic amplification even in the absence of the ice albedo feedback. In their experiments, the warming in the Arctic was greatest well above the surface. Graversen et al. [2008] showed with the ERA-40 reanalysis [Uppala et al., 2005] that the warming was indeed greater much above the surface. Later, however, Screen and Simmonds [2011] found the trend in ERA-40 reanalysis to be erroneous for the Arctic mid-to-lower atmospheric temperatures. Using the ERA Interim reanalysis [Dee et al., 2011], Screen and Simmonds [2010a] showed Arctic warming to be greatest at the surface, essentially disproving the main conclusion by Graversen et al. [2008] that the poleward energy transport is responsible for Arctic warming amplification. Nevertheless, a possibility exists that Arctic warming is remotely induced by the GHG forcing in lower latitudes and is amplified by snow and ice feedbacks.

[4] As important as what amplifies Arctic warming is whether the GHG forcing in the Arctic, or that in lower latitudes, is responsible for Arctic warming. While the latter issue is important on its own for understanding how the climate system works, it also has practical implications. Greenhouse gases are uniformly distributed over the globe, but anthropogenic aerosols exert a substantial radiative forcing [Forster et al., 2007] which is distinctly inhomogeneous in space. This is demonstrated in Figure 1 which compares the zonal-mean radiative forcing for CO\(_2\) with the aerosol direct radiative forcing evaluated by Chung et al. [2005]. It is the total forcing, including aerosol forcing, that should be linked to Arctic warming. Whether Arctic warming is induced locally by the radiative forcing in the Arctic or remotely by the forcing in lower latitudes helps to understand the contribution of non–GHG forcing to Arctic warming. Thus, we focus on the origin of Arctic warming, as opposed to the long-debated issue on the warming amplification.

[5] Addressing the origin of Arctic warming can also give insight into the climate feedback issue which is concerned about how the atmosphere (notably water vapor and cloud) responds to an initial temperature rise. Richard Lindzen’s arguments for a low climate sensitivity are based on hypothesized negative tropical feedbacks [e.g., Lindzen et al., 2001]. Whether the feedback is indeed negative in the tropics, contrary to climate models, is being vigorously debated [Lindzen and Choi, 2009, 2011; Dessler, 2010] and will not be addressed in this paper. However, there exists a link to our study, in that a negative feedback confined to the tropics (or any latitudinal gradient in the feedback) would have implications on meridional energy transports. CO\(_2\) imposes largest radiative forcing in the tropics (Figure 1), and thus without any climate feedback would generate a greater warming in the tropics than in the polar region. In the absence of any feedback, therefore, CO\(_2\) increase will enhance the poleward transport of energy, as Cai [2006] noted. If the climate feedback is hypothetically negative in the tropics and positive in the polar region, GHG forcing would not increase the poleward energy transport and might even decrease it. Here, we will discuss how much of the Arctic warming is due to the poleward transport in observation and models, and the
answer will further the understanding of the climate feedback from a different angle.

2. Design of the Numerical Experiments

[6] We ran experiments with two climate models, which to our knowledge have been developed quite independently of each other: ECHAM5.3 [Roekner et al., 2003, 2006] and CAM3.1 [Collins et al., 2004]. The slab-ocean coupled versions are used. In both models, snow thickness/coverage over the land surface, and ice thickness/coverage over the ocean are calculated interactively. The resolution of the atmospheric model is T42/L31 for ECHAM5 and T42/L26 for CAM3. ECHAM5 (CAM3) was run for a total 45 (59) years: the first 20 (25) years were discarded as a spin-up period, and the last 25 (34) years were used for defining the model climatology for each calendar month. To ensure the statistical significance of the results presented here relative to model internal variability, a longer averaging period was used for CAM3, as we found this model to have more internal variability than ECHAM5.

[7] With each model, we conducted the following experiments: a) CO₂ concentration of 375 ppmv prescribed globally; b) CO₂ concentration of 280 ppmv prescribed globally; and c) CO₂ concentration of 280 ppmv prescribed from 90°S to 60°N, and 375 ppmv north of 60°N. To look at the effect of CO₂ increase from 60°N to 90°N, we subtract b) from c). Similarly, we subtract c) from a) to define the effect of CO₂ increase from 90°S to 60°N.

3. Results

[8] Figures 2a and 2d show the effect of the global CO₂ forcing on JJA (June, July and August) temperature in the Arctic region in ECHAM5 and CAM3. When the focus is on the 60°N–90°N region, the warming is clearly greatest well above the surface in both models. In ECHAM5 the warming peaks between the 700 hPa and 400 hPa levels, and in CAM3 around 800 hPa. To better understand the vertical structure of warming, we show the effect of the 60°N–90°N CO₂ forcing and that of the 90°S–60°N CO₂ forcing on temperature in Figures 2b, 2c, 2e, and 2f. The Arctic warming driven by the global CO₂ forcing is the sum of the warming by the local forcing and that by the remote forcing in our experiments. Clearly, in both models, the remote CO₂ forcing (i.e., CO₂ increase from 90°S to 60°N) produces a mid-tropospheric warming while the local CO₂ forcing (i.e., CO₂ increase north of 60°N) induces a low-level warming. The low-level warming by the local forcing is expected because the CO₂ forcing and the associated humidity increase give a strong radiative heating at the low levels. This is more or less the case in lower latitudes as well but active convection transports the heat upward. Reverting back to Figures 2b and 2e, largest warming occurs somewhat above the surface because the upper ocean, having a large heat capacity, restrains temperature increase near the surface. [9] The remote forcing, on the other hand, can only increase the Arctic temperature by transporting energy to the Arctic, and the mid-tropospheric warming is a corresponding feature. The connection between the mid-level warming and the poleward energy transport should be understood in the context of synoptic eddies. At 60°N, eddy flux is the dominant mechanism for the poleward heat transport [Schubert et al., 1990; Trenberth and Stepaniak, 2003] Furthermore, the Arctic has non-negligible synoptic activity [Simmonds et al., 2008], and a change in the characteristics of synoptic eddies can produce mid-level warming or cooling features. We suggest that the poleward energy transport by the remote forcing enhances the cyclone activity and produces a mid-tropospheric warming in the Arctic. We also note that surface conditions such as ice coverage can likewise affect the cyclone characteristics [Simmonds and Keay, 2009]. Unfortunately, the data archived from these experiments do not allow an analysis of cyclone characteristics, so we cannot verify these suggestions.

[10] In the DJF (December, January and February) season, however, both models show the greatest warming at the surface (Figures 3a and 3d). A striking feature in both models is that the remote CO₂ forcing produces greatest warming at the surface, as shown in Figures 3c and 3f, contrary to the remotely-induced warming in the JJA season. The remote forcing stores heat in the upper ocean layers in summer, and this heat is released from the surface in winter. The fact that the remote forcing causes the maximum warming at the surface in winter is powerful evidence that the heat released from the surface makes up a significant fraction of the winter-time warming at low levels. This heat storing/releasing mechanism is a consequence of the so-called ice feedback in the Arctic. As explained by Boé et al. [2009], in summer heat is stored by ice reduction. Reduced ice increases the surface solar absorption, and this melts the ice further. Subsequently, reduced ice cover increases the heat transfer from the ocean to the atmosphere in fall and winter, and this warming is trapped near the surface in winter, leading to the feature of maximum warming at the surface. The heat transfer increase was verified by Screen and Simmonds [2010b]. We also find in our model experiments regarding the winter-time warming that the enhanced surface-to-air moisture flux increases the low-level moisture, thereby reducing long-wave radiative cooling at the low levels. In our view, this moisture effect is part of the ice feedback. The temperature change by the local forcing differs a lot between ECHAM5 and CAM3 (Figures 3b and 3e) apparently because of the surface warming differ-
ences and the associated ice thickness differences in summer (Figures 2b and 2e).

[11] We find that the remote forcing explains about 85% of the annual-mean Arctic surface warming in ECHAM5 and about 60% in CAM3, which means that most of the Arctic surface warming is induced remotely by the poleward transport in the models. The local forcing causes the rest of the warming. The remotely-induced warming includes the warming amplification by the ice/snow feedbacks. There are other local processes, such as the tropospheric stability mechanism [Manabe and Wetherald, 1975], that can amplify Arctic warming. In this mechanism, an equal CO$_2$ forcing at the surface causes a larger surface warming in the Arctic, where the lower atmosphere is more stably stratified. However, this mechanism does not explain the remotely-induced winter-time maximum warming at the surface (Figures 3c and 3f), since there is no local CO$_2$ forcing in these experiments. The snow/ice feedback seems to be the only plausible explanation for amplifying the remotely-induced warming. In summary, the mechanism causing the majority of the Arctic surface warming in these two models is that 1) the remote CO$_2$ forcing transports energy into the Arctic and warms the atmosphere/surface therein, and 2) then the snow-ice feedback amplifies the warming at the surface and in the lower atmosphere.

[12] While both the remote forcing and local forcing give rise to maximum warming at the surface in winter, the remote forcing creates warming maxima at much higher altitudes than the local forcing in summer (Figures 2b, 2c, 2e, 2f, 3b, 3c, 3e, and 3f). Thus, we propose that the vertical structure of the JJA warming indicates how much the remote forcing contributes to the Arctic surface warming. While Graversen et al. [2008] also used the vertical structure of warming to distinguish between remote forcing and ice feedback, their analysis was based on year-round warming. We argue that the vertical structure of JJA warming is better suited for distinguishing remote forcing influence from local forcing influence. Applying this new idea, we note that CAM3 shows more low-level warming than ECHAM5 in JJA (Figures 2a and 2d), and, consistent with this, the remotely-induced warming contributes more to the total annual-mean Arctic warming in ECHAM5 (~85%) than in CAM3 (~60%).

[13] The next question is how much the remote forcing contributes to Arctic warming in reality. To address this issue, we analyze the JJA temperature structure in the ERA Interim reanalysis in comparison with that of various coupled models. Figure 4 shows the temperature trend from 1979 to 2010 in ERA Interim, and compares it with the 1970–1999 temperature trend in the average of the ensemble runs of 12 models, downloaded from the Coupled Model
Figure 4. Arctic (70–90°N) average temperature (K) change, and its uncertainty in terms of ±1.0 standard deviation (S.D.) for (a) JJA and (b) DJF. The 1970–99 trend in the average of the ensemble runs of 12 fully coupled models (red line) is compared to the 1979–2010 trend in ERA Interim (green line). The trend is shown in terms of change over the entire 30 (or 32) years. The coupled model runs are from the CMIP3 20C3M experiments conducted for the IPCC AR4. The 12 models chosen are BCCR-BCM2.0, CGCM3.1, CNRM-CM3, CSIRO-MK3.5, GFDL-CM2.1, GISS-AOM, GISS-EH, GISS-ER, ECHAM5/MPI-OM, CCSM3, PCM and UKMO-HadGEM. In addition to the CMIP3 average, we show with blue lines two models (again ensemble average) that deviate the most from the model average in 925–500 hPa slope.

Figure 3. Same as in Figure 2 except that DJF averages are shown.
Intercomparison Project phase 3 (CMIP3) archive. These models were forced with GHGs, aerosols, etc. to reproduce the observed 20th climate. As Figure 4a shows, in the JJA season, the CMIP3 runs show almost flat warming from the boundary layer to 400 hPa with a modest warming maximum around 500 hPa. Conversely, ERA Interim shows maximum warming at 925 hPa. This is strong evidence that poleward energy transport plays an overly large role in climate model simulations of Arctic warming. The difference in vertical structure between the CMIP3 runs and ERA Interim is statistically significant. To be sure, we calculated the trend of the JJA temperature difference between 925 and 500 hPa. For ERA Interim, this trend equals 0.97 ± 0.3 K (means ±1 std.dev). The corresponding trend for the average of CMIP3 models is −0.13 ± 0.048 K, and the trend for BCM2.0 (which resembles ERA Interim most) is 0.31 ± 0.22 K. This suggests that all the 12 models over-simulate the contribution of poleward energy transport to Arctic warming. Note that comparing ERA Interim with the CMIP for the overlapping period of 1979–1999 is not desirable since much of the observed Arctic warming occurred in the last 10 years while the CMIP3 ended the simulation in 1999.

In the DJF season (Figure 4b), the CMIP models generally simulate the maximum warming at the surface. Thus, we conclude that climate models simulate Arctic warming due partly to the energy transport from the lower latitudes, and this mechanism plays a much less significant role in ERA Interim.

4. Implications

Based on the vertical structure of JJA temperature trends, we have inferred that CMIP3 models overestimate significantly the contribution of poleward energy transport to Arctic warming compared to ERA Interim data. This has important implications for either climate feedbacks or climate forcing. Assuming that the forcing is represented correctly, the implication is that either (1) the model-simulated net feedback is too large (i.e. too positive) at low latitudes (<60°N), or (2) the feedback is too small (i.e. too negative) in the Arctic, or both. The first scenario would provide some support to the findings of Lindzen and Choi [2009] who argue that at low latitudes the real feedback is less positive than in climate models (or even negative), with the implication that models overestimate the global climate sensitivity. On the other hand, if the second scenario is correct so that models underestimate the high latitude feedback while representing low-latitude feedbacks more or less correctly, they tend to underestimate the climate sensitivity. The present analysis does not allow us to distinguish between these two scenarios. Note that the ice feedback in the Arctic warms the lower atmosphere, while the heat transport and general circulation respond mainly to the distribution of the mid-tropospheric temperature [Cai, 2006]. Thus, the ice albedo feedback is largely irrelevant to the strengthening/weakening of poleward energy transport.

If the models simulate climate feedbacks correctly, the indication is that models have significantly incorrect climate forcing. Since GHG forcing is well established, the problem is likely in how the models treat aerosol effects. In this scenario, the real aerosol forcing might be significantly positive in the Arctic and significantly negative outside of the Arctic, while the models miss this feature entirely. Future studies are needed to verify that the models indeed over-simulate the energy transport into the Arctic and to understand why the models do so.

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