CORRESPONDENCE

Comments on “Current GCMs’ Unrealistic Negative Feedback in the Arctic”

FELIX PITHAN

Max Planck Institute for Meteorology, and International Max Planck Research School for Earth System Sciences, Hamburg, Germany

THORSTEN MAURITSEN

Max Planck Institute for Meteorology, Hamburg, Germany

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ABSTRACT

In contrast to prior studies showing a positive lapse-rate feedback associated with the Arctic inversion, Boé et al. reported that strong present-day Arctic temperature inversions are associated with stronger negative longwave feedbacks and thus reduced Arctic amplification in the model ensemble from phase 3 of the Coupled Model Intercomparison Project (CMIP3). A permutation test reveals that the relation between longwave feedbacks and inversion strength is an artifact of statistical self-correlation and that shortwave feedbacks have a stronger correlation with intermodel spread. The present comment concludes that the conventional understanding of a positive lapse-rate feedback associated with the Arctic inversion is consistent with the CMIP3 model ensemble.

1. Introduction

Arctic amplification of climate change is a consistent feature of observations (Serreze and Barry 2011), paleoclimate reconstructions (Masson-Delmotte et al. 2006), and climate model simulations (Holland and Bitz 2003). Mechanisms believed to play a role in Arctic amplification include the surface albedo, cloud and water vapor feedbacks, atmospheric and oceanic heat transport, and the atmospheric lapse-rate feedback (Serreze and Barry 2011). In this comment, we discuss the impact of temperature inversions on radiative feedbacks in the Arctic and show that physically unexpected correlations between present-day inversion strength and longwave feedbacks reported by Boé et al. (2009) are largely caused by a statistical artifact.

The total longwave feedback discussed by Boé et al. (2009) is composed of the Planck, lapse-rate, water vapor, and cloud feedbacks, the sum of the Planck and lapse-rate feedbacks being the total temperature feedback. Since the supposed effect discussed by Boé et al. (2009) pertains to the clear-sky feedback, we omit further discussion of cloud feedbacks in this specific context. The negative Planck feedback corresponds to the increase in outgoing longwave radiation (OLR) caused by a vertically uniform warming. It dominates the total longwave and combined longwave and shortwave feedback and is the main cause of Earth’s climate coming to a new equilibrium after an external forcing is applied.

The second part of the temperature feedback is the lapse-rate feedback: Warming in the Arctic is stronger at the surface than in the troposphere, in part due to the stably stratified Arctic atmosphere that tends to trap heat near the surface. In contrast, moist deep convection in the tropics keeps the atmospheric temperature profile close to a moist adiabat and therefore leads to a stronger warming in the upper troposphere than at the surface. The stronger Arctic warming at the surface leads to a positive feedback, since the OLR at the top of the atmosphere (TOA) increases less than it would in the case of a vertically uniform warming (Fig. 1). Strong atmospheric stability is therefore understood to lead to a positive lapse-rate feedback in the Arctic, whereas

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Corresponding author address: Felix Pithan, Max Planck Institute for Meteorology, Bundesstrasse 53, D-20146 Hamburg, Germany.
E-mail: felix.pithan@mpimet.mpg.de

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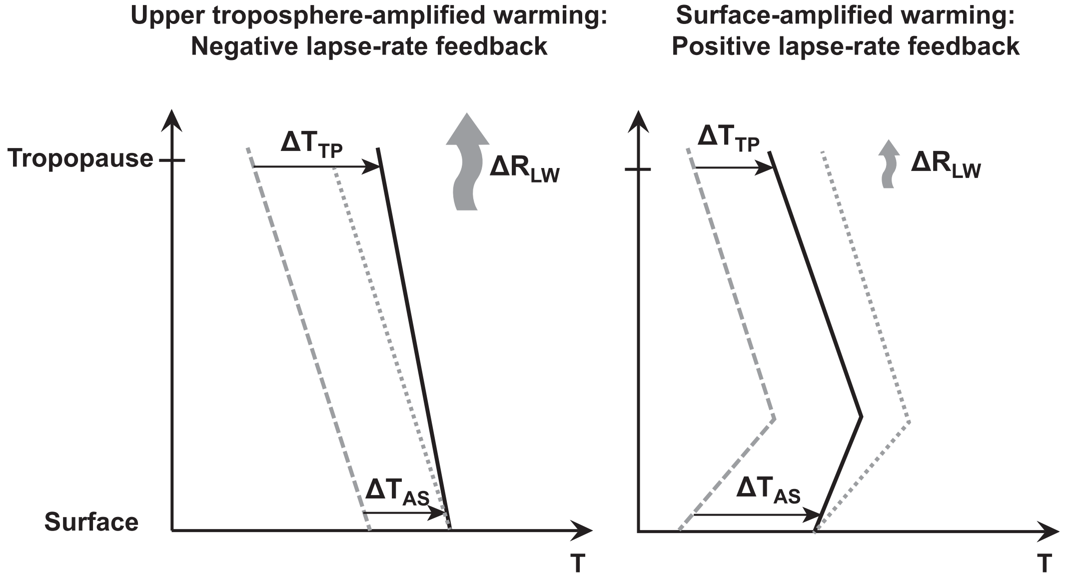

FIG. 1. Conceptual picture of (left) a negative lapse-rate feedback in the tropics and (right) a positive lapse-rate feedback in the Arctic.

moist deep convection in the tropics leads to a regionally negative lapse-rate feedback (Fig. 2). This concept of atmospheric stability in the Arctic contributing to Arctic amplification was developed in early modeling studies by Manabe and Wetherald (1975) and Held (1978) and has recently been discussed by Bintanja et al. (2012).

The water vapor feedback is due to the enhanced atmospheric emissivity of a warmer and thus moister atmosphere. It is globally positive but can be negative in the Arctic boundary layer where atmospheric temperatures are higher than surface temperatures and hence a moister, more emissive atmosphere yields an increase in OLR (Soden et al. 2008).

Arctic temperature inversions thus cause both a regionally positive lapse-rate and locally negative water vapor feedback. Their total impact on feedbacks depends on the balance of these two effects. While it should be noted that the global-mean lapse-rate feedback and associated water vapor feedback of opposed sign roughly cancel (Held and Shell 2012), the regional balance of these effects is the determining factor here. In models from phase 5 of the Coupled Model Intercomparison Project (CMIP5), the positive lapse-rate feedback in the Arctic is several times greater than the negative water vapor feedback induced by lapse rate changes (Fig. 2). Previous studies using both global models (Manabe and Wetherald 1975; Held 1978; Bintanja et al. 2012) and 1D radiative-transfer models (Bintanja et al. 2011) have concluded that the total impact of Arctic temperature inversions on feedbacks is positive.

Contrasting with this understanding, Boé et al. (2009) report that in the model results from phase 3 of the Coupled Model Intercomparison Project (CMIP3), strong inversions are associated with a stronger negative longwave feedback that leads to a weaker Arctic amplification. In the next section, we summarize the methodology used and the results obtained by Boé et al. (2009). We then discuss the problem of self-correlation and analyze how it affects the results, especially regarding the respective roles of the longwave and shortwave feedbacks in causing intermodel spread in Arctic warming.

2. Feedback analysis

The analysis of Boé et al. (2009) is based on a regional feedback framework using ocean mixed layer temperatures instead of the conventional surface air temperatures. The feedback factor is defined as

$$\lambda = \frac{\Delta R}{\Delta T_{\rm oc}}, \qquad (1)$$

with $\Delta T_{\rm oc}$ being the change in vertically averaged potential temperature of the uppermost 70 m of the ocean and ΔR the change in TOA radiation in response to the forcing. All values are annual means for the region north of 70°N and changes are differences between the period 1900–49 of the historical runs and the period 2150–99 of the Special Report on Emissions Scenarios (SRES) A1B runs.

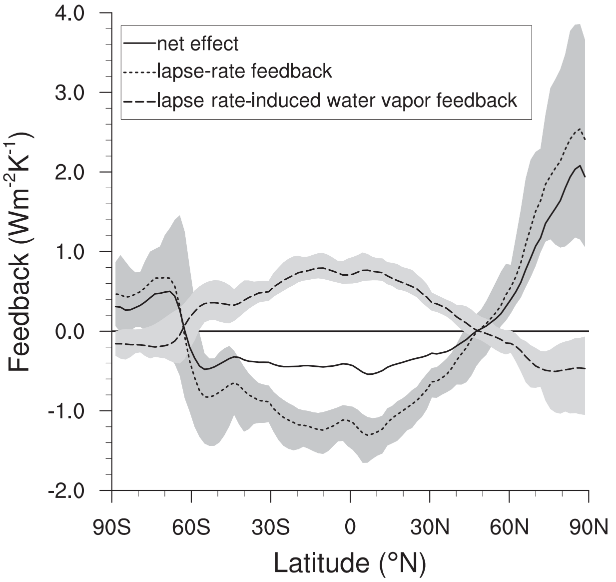

FIG. 2. Zonal-mean lapse rate–induced feedbacks in the 4×CO_2 experiments of nine CMIP5 models (shaded areas) and intermodel mean (black lines). The lapse-rate feedback is defined as the TOA response to the deviation of warming from a vertically uniform profile. The lapse rate–induced water vapor feedback is defined as the effect of this deviation on the water vapor feedback assuming constant relative humidity. The net effect of the deviation of warming from a vertically uniform profile is the sum of these two feedbacks. The feedbacks have been computed using radiative kernels from Block and Mauritsen (2013) applied to the temperature difference between the last 30 yr of the perturbed and control experiments. Using radiative kernels from Soden et al. (2008) or Shell et al. (2008) results in similar meridional structures (not shown).

Within this feedback framework, the longwave feedbacks ($\lambda_{\rm LW} = \Delta R_{\rm LW}/\Delta T_{\rm oc}$) have a correlation of r = 0.78 with ocean temperature change ($\Delta T_{\rm oc}$) across all analyzed models. This correlation is stronger than that of the shortwave feedbacks with $\Delta T_{\rm oc}$ and almost as strong as the correlation between the sum of the feedbacks and Arctic warming (0.81, column 3 in Table 1). From this, Boé et al. (2009) conclude that "a large part of the spread of Arctic climate change is explained by the longwave feedback parameter." Boé et al. (2009) also find a near-perfect negative correlation ($r = -0.96$) between $\lambda_{\rm LW}$ and the ratio of atmospheric to oceanic temperature change, concluding that this ratio, named the temperature feedback factor, "is a crucial contributor to the uncertainties of Arctic climate change." The inverse of this ratio is in turn found to correlate well with modeled present-day inversion strength. This line of reasoning lead to the conclusion that strong inversions in GCMs are associated with a stronger negative longwave feedback, posing a challenge to the conventional understanding of the lapse-rate feedback in the Arctic.

It should be noted that the use of ocean temperatures is crucial for obtaining a correlation between Arctic warming and inversion strength—no such correlation is found when using the conventional metric of surface air temperature change (Fig. 3).

3. Statistical artifacts from self-correlation

When plotting a feedback defined as $\Delta R/\Delta T$ against ΔT, the common term in the independent and the dependent variable causes a statistical self-correlation (Pearson 1896). This effect can produce artificial, albeit apparently statistically significant correlations even for perfectly random datasets (Kenney 1982). To estimate the effect of self-correlation on results, Klipp and Mahrt (2004) suggested creating randomized datasets with the same statistical moments as the original data by permuting the original values of the variables. The correlation obtained when repeating the original analysis using the randomized variables can be used as a measure of self-correlation in the analysis. Here, we perform the described permutation test using the CMIP3 data presented by Boé et al. (2009).

The correlation between $\Delta T_{\rm oc}$ and $\lambda_{\rm LW}$ obtained by Boé et al. (2009) can be easily reproduced from the randomized datasets. This is illustrated in Fig. 4, where the upper panel shows the change in OLR against ocean temperature change for the original and randomized data and the lower panel shows the apparent correlation

TABLE 1. Correlations presented by Boé et al. (2009) compared with randomized data from 10 000 permutations.

x axis	y axis	$r_{\rm data}$	$\overline{r}_{\rm random}$	p ($r_{\rm random} > r_{\rm data}$)
$\sum\lambda_i = \frac{\Delta R_{\rm LW} + \Delta R_{\rm SW}}{\Delta T_{\rm oc}}$	$\Delta T_{\rm oc}$	0.81	0.62	0.02
$\lambda_{\rm LW} = \frac{\Delta R_{\rm LW}}{\Delta T_{\rm oc}}$	$\Delta T_{\rm oc}$	0.78	0.73	0.18
$\lambda_{\rm SW} = \frac{\Delta R_{\rm SW}}{\Delta T_{\rm oc}}$	$\Delta T_{\rm oc}$	−0.51	−0.64	0.05
$\frac{\Delta T_{\rm as}}{\Delta T_{\rm oc}}$	$\lambda_{\rm LW} = \frac{\Delta R_{\rm LW}}{\Delta T_{\rm oc}}$	−0.96	−0.97	

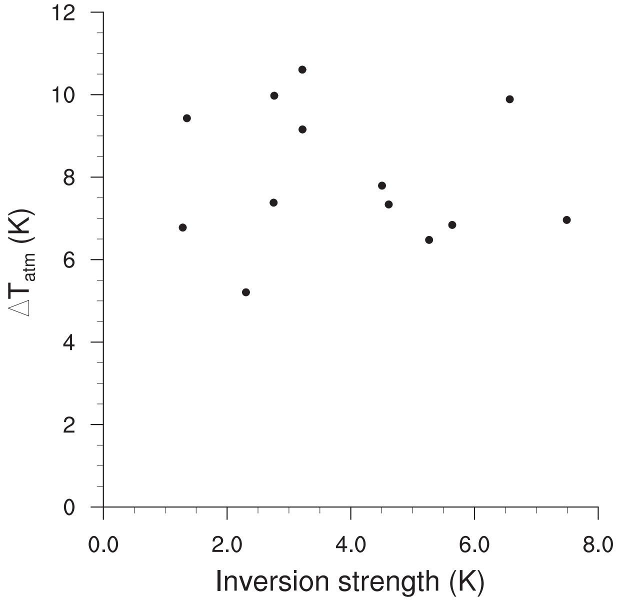

FIG. 3. Present-day inversion strength and Arctic warming measured as surface air temperature change. Inversion strength is computed as the 1960–99 mean using the same definition as in Boé et al. (2009).

between temperature change and longwave feedbacks. The randomized datasets align as well as the original data.

The correlation coefficients obtained by Boé et al. (2009) can be compared to the average correlation coefficient obtained from a large number of randomized datasets generated as described above (Table 1). Here, we permute ocean temperatures but use the correct longwave and shortwave radiation changes from each model when randomizing the sum of both feedbacks ($\sum\lambda_i$). The probability p that the correlation coefficient obtained from a randomized dataset exceeds r_{data} is computed as the fraction of all randomized datasets in which the correlation exceeds that in the original data. The null hypothesis is that two analyzed variables are uncorrelated and the probability p corresponds to the level of significance of a given correlation. Table 1 shows these probabilities and the correlation coefficients for the sum of the feedbacks ($\sum\lambda_i$) as well as for the shortwave (λ_{SW}) and longwave feedbacks (λ_{LW}) separately.

The analysis confirms that the correlations of the randomized datasets are close to those obtained from the CMIP3 dataset. The average correlation between longwave feedbacks and ocean warming from the randomized datasets is 0.73 compared to 0.78 for the original data, and 18% of the randomized datasets have higher correlations than the original data. Therefore, no correlation between ΔT_{oc} and λ_{LW} that is significant to the 0.05 level can be inferred from the CMIP3 model results. Further, the near-perfect correlation between $\lambda_{\mathrm{LW}} = \Delta R_{\mathrm{LW}}/\Delta T_{\mathrm{oc}}$ and $\Delta T_{\mathrm{as}}/\Delta T_{\mathrm{oc}}$ can be partly attributed to self-correlation. The variables ΔR_{LW} and ΔT_{as} are less strongly correlated ($r = -0.63$), but when dividing both ΔR_{LW} and ΔT_{as} by randomly permuted values of ΔT_{oc}, we obtain practically the same correlation as using the original data (-0.97 vs -0.96).

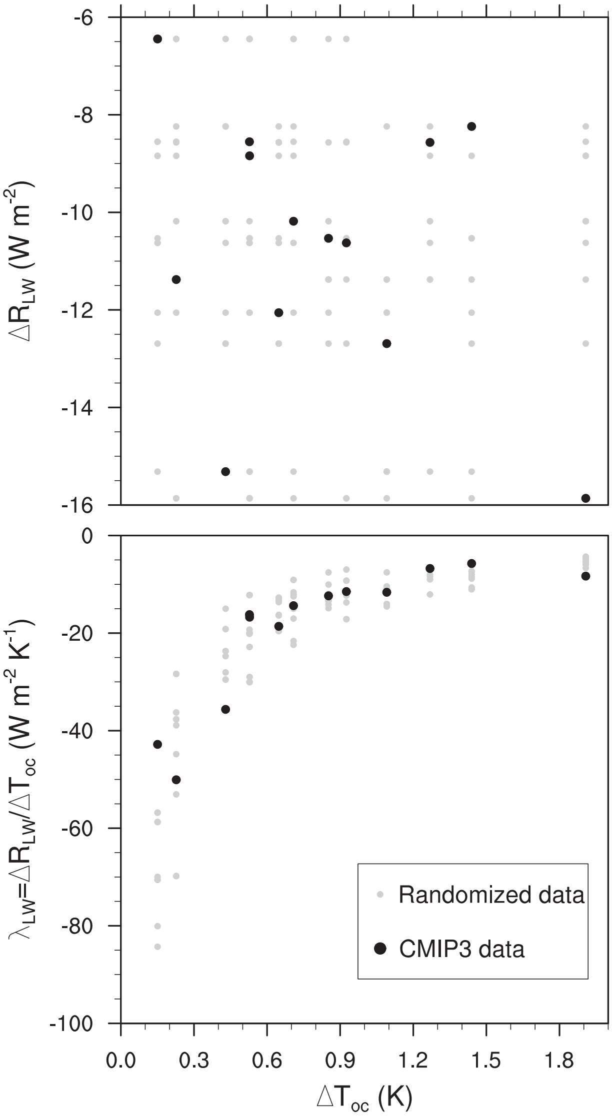

FIG. 4. Comparison of correlations between the CMIP3 data and 10 randomized datasets with the same statistical properties as the original data.

Boé et al. (2009) dismiss shortwave feedbacks as important contributors to the intermodel spread in Arctic amplification because the correlation with ΔT_{oc} is smaller than that of the longwave feedbacks, and further the correlation is negative (-0.53), which is physically not to be expected. However, the average correlation for randomized datasets is even more negative (-0.64), indicating that the true correlation between shortwave feedbacks and ocean warming is indeed positive, as we physically expect. Less than five percent of the randomized datasets have a correlation greater than -0.51, which means that the correlation between the shortwave feedbacks and ocean warming is significant to the 0.05 level. In agreement with our analysis, Winton (2006) reports that the most important cause of intermodel spread in Arctic amplification among 12 CMIP3 models is the nonsurface albedo shortwave feedbacks caused by clouds and water vapor.

The permutation test shows that the strong correlations between ΔT_{oc} and λ_{LW} and between λ_{LW} and $\Delta T_{\mathrm{as}}/\Delta T_{\mathrm{oc}}$ can be largely attributed to statistical self-correlation. This also affects the correlation between feedbacks and sea ice cover change (ΔSIC), since ΔSIC and ΔT_{oc} are strongly correlated [$r = -0.87$; see Fig. 9 in Boé et al. (2009)]. The correlation between shortwave feedbacks and the intermodel spread in Arctic Ocean warming is statistically significant, but the correlation between longwave feedbacks and warming is not; that is, the magnitude and sign of the correlation coefficients are dominated by self-correlation and do not accurately reflect physical relationships.

4. Discussion and conclusions

Boé et al. (2009) argued that strong temperature inversions in the Arctic were associated with stronger negative longwave feedbacks in the CMIP3 model results, challenging our physical understanding of a positive lapse-rate feedback associated with stable stratification in the Arctic atmosphere. Their argument is based on correlations in the CMIP3 results linking the longwave feedback to the ratio of atmospheric to oceanic warming, which in turn is related to the inversion strength.

Randomly permuting the data shows that both the correlations between Arctic Ocean warming (ΔT_{oc}) and longwave feedbacks (λ_{LW}) and between λ_{LW} and the ratio of Arctic surface air temperature change to ocean temperature change ($\Delta T_{\mathrm{as}}/\Delta T_{\mathrm{oc}}$) can be explained as statistical artifacts caused by self-correlation. When self-correlation is taken into account, we find that no robust relationship between ΔT_{oc} and λ_{LW} can be inferred from the CMIP3 data and that shortwave feedbacks have a positive correlation with intermodel spread in Arctic warming that is significant to the 0.05 level. Hence, we cannot confirm a statistical link between strong present-day inversions and strong negative longwave feedbacks in the CMIP3 data.

Radiative transfer calculations with idealized atmospheric profiles at fixed relative humidity have shown that the presence of an inversion reduces the increase in OLR for a given increase in near-surface air temperatures (Bintanja et al. 2011). These calculations also show that warming in the boundary layer has a smaller impact on OLR than warming at higher levels in the troposphere. We further show that in the Arctic, the positive lapse-rate feedback dominates over the negative lapse rate–induced water vapor feedback in CMIP5 models.

The relatively stronger surface warming for models with strong temperature inversions reported by Boé et al. (2009) therefore does not give rise to a specific negative feedback; rather, it is the response of the climate system to the positive feedback associated with the inversion: In the presence of an inversion, the radiative cooling to space is less efficient and more heat is retained near the ground, which causes additional surface warming (Manabe and Wetherald 1975). The resulting amplified warming eventually leads to an increase in OLR that restores the radiative energy balance. We conclude that the conventional understanding of a positive lapse-rate feedback associated with the Arctic inversion is consistent with the CMIP3 model ensemble and supported by current physical evidence.

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