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High-CO_2 cloud radiative forcing feedback over both land and ocean in a global climate model

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[1] A positive feedback on high-latitude winter marine climate change involving convective clouds has recently been proposed using simple models. This feedback could help explain data from equable climates, e.g., the Eocene, and might be relevant for future climate. Here this convective cloud feedback is shown to be active in an atmospheric GCM in modern configuration (CAM) at $CO_2 = 2240$ ppm and in a coupled GCM in Eocene configuration (CCSM) at $CO_2 = 560$ ppm. Changes in boundary conditions that increase surface temperature have a similar effect as increases in CO_2 concentration. It is also found that the high-latitude winter cloud radiative forcing over land increases with increases in surface temperature due to either increased CO_2 or changes in boundary conditions, which could represent an important part of the explanation for warm continental interior winter surface temperatures during equable climates. This is due to increased low-level layered clouds caused by increased relative humidity. **Citation:** Abbot, D. S., M. Huber, G. Bousquet, and C. C. Walker (2009), High-CO_2 cloud radiative forcing feedback over both land and ocean in a global climate model, *Geophys. Res. Lett.*, *36*, L05702, doi:10.1029/2008GL036703.

1. Introduction

[2] Equable climates, which prevailed during the late Cretaceous and early Paleogene (~100 to ~34 million years ago), were characterized by warm high latitudes [e.g., *Sluijs et al.*, 2006], particularly during the winter and over continents [e.g., *Greenwood and Wing*, 1995], and tropical temperatures only somewhat higher than modern [e.g., *Huber*, 2008]. Various mechanisms have been proposed to explain either the relatively cool tropical temperatures or relatively warm polar temperatures, although recent increases in estimates of tropical sea surface temperatures during equable climates have softened this problem somewhat [*Huber*, 2008]. These mechanisms include increased ocean heat transport due to ocean mixing by increased hurricane activity [*Emanuel*, 2002; *Korty et al.*, 2008], the Hadley cell extending nearly to the pole [*Farrell*, 1990], and high-latitude longwave heating due to thick polar stratospheric clouds [*Sloan et al.*, 1992; *Kirk-Davidoff et al.*, 2002].

[3] Using idealized and single column models, a high-latitude positive feedback due to the onset of convective clouds has recently been proposed [*Abbot and Tziperman*, 2008a, 2008b, 2009]. A related suggestion was also briefly made by *Sloan et al.* [1999] and *Huber and Sloan* [1999]. In this proposed feedback, warming leads to some sea ice loss, which increases heat and moisture fluxes from the ocean surface, which leads to atmospheric convection and the development of optically thick convective clouds and increased high-altitude moisture, both of which trap outgoing longwave radiation and lead to further warming and sea ice loss. As this feedback should occur preferentially during winter [*Abbot and Tziperman*, 2008b], we will focus on winter climate here. Previous investigation of this mechanism has focused on marine regions because the ocean represents a large source of moisture to drive convection and because the ocean's large heat capacity allows it to stay relatively warm throughout winter.

[4] In this paper we investigate the convective cloud feedback in a global climate model, run in both modern and Eocene (~56 to ~34 million years ago, an archetypical equable climate) configuration, over a wide range of CO_2 concentrations and show that the winter cloud radiative forcing (CRF, the difference between the net radiative flux at the top of the atmosphere in all-sky and clear-sky conditions) increases significantly at high latitudes over land as well as over ocean. We find that the increase in CRF over land and ocean results from two distinct mechanisms: the increase over ocean is due to increases in convective clouds, whereas the increase in CRF over land is caused by increases in low-level layered clouds, which result from increased relative humidity.

[5] We use results from two related models in our analysis. First we use a version of NCAR's atmospheric general circulation model (CAM v3.1) run at T42 resolution (2.8° × 2.8°) with a slab ocean with modern parameterized-ocean heat transport, i.e., a qflux calculated from the surface heat budget when CAM is run with fixed modern sea surface temperatures (henceforth ''modern''). Second we use NCAR's fully-coupled ocean-atmosphere global climate model (CCSM v3), for which CAM is the atmospheric component, run at a resolution of T31 (3.75° × 3.75°) with best-guess Eocene topography and bathymetry (henceforth ''Eocene''), as well as sensitivity runs with CAM v3.1 at T170 (0.7° × 0.7°) resolution using Eocene boundary conditions and sea surface temperatures produced by CCSM.

2. Cloud Feedback Over Land and Ocean

[6] In the modern runs there is a strong increase in winter CRF as the CO_2 concentration is increased (Figure 1) that is

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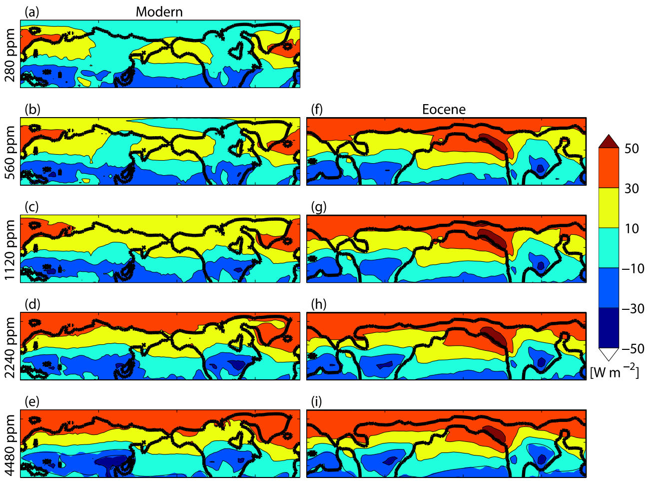

Figure 1. Northern hemisphere winter (DJF) cloud radiative forcing as a function of CO_2 concentration. Output from both (a)–(e) the CAM atmospheric GCM run in slab ocean mode with modern boundary conditions and (f)–(i) the CCSM coupled ocean-atmosphere GCM with Eocene boundary conditions are displayed. The CO_2 concentration is given to the left of the plots.

associated with large increases in winter surface temperature (Figure S2[1]) and is particularly significant once winter sea ice is completely lost at CO_2 = 2240 ppm (Figure S1). The CRF is roughly as large in the CO_2 = 560 ppm Eocene run as in the CO_2 = 2240 ppm modern run, which is related to the fact that there is almost no sea ice in the Eocene run at CO_2 = 560 ppm (Figure S1). Generally warmer conditions in the Eocene runs than in the modern runs result from the different boundary conditions in the Eocene configuration, such as the removal of ice sheets and changes in vegetation. Interestingly, the increase in CRF with CO_2 appears to occur over land as well as over ocean. For example, the high-latitude increase in surface temperature and CRF between a CO_2 of 280 ppm and 2240 ppm are roughly equivalent over land and ocean for both models (Figure S3). Here we define ocean gridpoints as those with a landfraction of zero and land gridpoints as those with a landfraction of one.

[7] Changes in CRF are significant compared to other terms affecting high-latitude heat balance. For example, the winter CRF averaged north of 60°N is 15.9 W m^{-2} higher in the CO_2 = 2240 ppm modern run than in the CO_2 = 280 ppm modern run and 15.1 W m^{-2} higher in the CO_2 = 560 ppm Eocene run than in the CO_2 = 280 ppm modern run. For comparison, winter heat transport into the region north of 60°N is 16.8 W m^{-2} lower in the CO_2 = 2240 ppm modern run than in the CO_2 = 280 ppm modern run (Table S1) and the radiative forcing due to increased CO_2 is about 12 W m^{-2} higher, assuming 4 W m^{-2} per doubling of CO_2.

[8] Changes in winter high-latitude CRF over both land and ocean are closely linked to changes in surface temperature, whether these changes in surface temperature are due to increases in CO_2 or changes in boundary conditions (Figure 2). Over ocean, according the convective cloud feedback, we expect CRF and surface temperature increases to be related to the loss of sea ice. Over land, however, the link between increases in surface temperature and increases in CRF is not clear. More generally, the similarity between CRF increases over land and ocean is an unexpected result.

[9] As an initial investigation into the cause of CRF increases over land, we test the onset of CRF increases as CO_2 is increased. Because the CRF changes more with CO_2 in the modern runs, we will focus on them for the moment. We expect that increases in CRF and surface temperature associated with the convective cloud feedback should occur over the same CO_2 doublings that sea ice is lost [*Abbot and Tziperman*, 2008b], which is the case over ocean (Figures 3a–3c). Over land, however, surface temperature (Figure 3f) and CRF (Figure 3g) increase by a roughly equal amount with each doubling of CO_2. This implies that the cause of the increase in CRF over land may not be directly associated with the convective cloud feedback.

[10] To further investigate the CRF increases with CO_2 we show the change in the winter zonal average of various cloud properties between modern runs at a CO_2 of 2240 ppm and 280 ppm over both ocean and land (Figure 4). We find similar results when we consider the Eocene runs. Over both ocean and land the cloud fraction increases at high latitudes (Figures 4a and 4b). Cloud condensate also increases over both ocean and land, although the change occurs at a lower altitude over land (Figure 4d) than ocean (Figure 4c). Consequently the change in effective cloud fraction, which is the product of the cloud fraction and cloud emissivity and is a measure of the cloud's interaction with longwave radiation, has a maximum at a higher altitude over ocean (Figure 4e) than over land (Figure 4f).

[11] CAM diagnostically calculates cloud fraction for three types of cloud: convective clouds, which are parameterized as a linear function of the logarithm of the convective mass flux; layered clouds, which are parameterized based on the relative humidity; and marine stratus clouds, which only

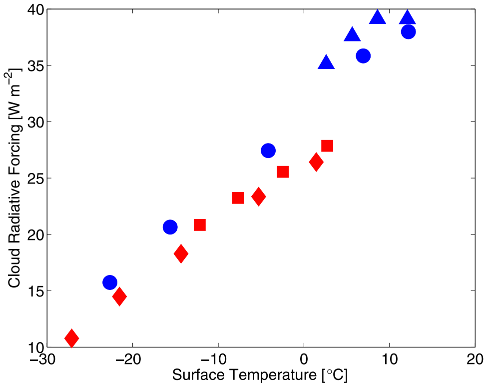

Figure 2. Winter (DJF) cloud radiative forcing averaged north of 60°N as a function of surface temperature averaged north of 60°N, which changes due to either changes in boundary conditions or CO_2. For each of the following cases, one datapoint represents one model run at a different CO_2 concentration: modern configuration land (red diamonds), Eocene configuration land (red squares), modern configuration ocean (blue circles), and Eocene configuration ocean (blue triangles).

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL036703.

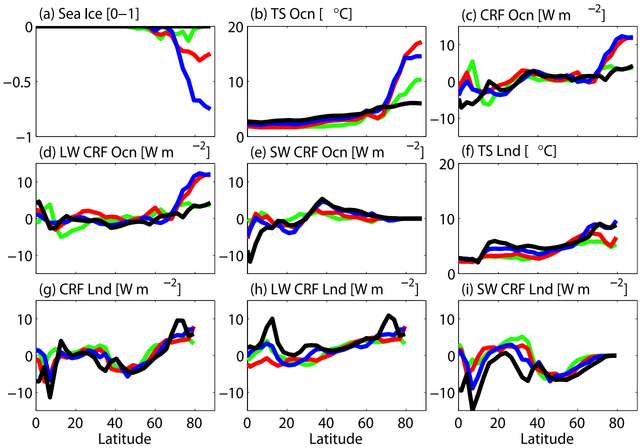

Figure 3. The onset of increases in cloud radiative forcing and surface temperature as the CO_2 is increased in the CAM atmospheric GCM run with modern boundary conditions reveals differences between the feedback over land and ocean. The difference between climate variables on successive doublings of CO_2 is plotted. Variables are averaged over winter (DJF) and either over (a)–(e) ocean or (f)–(i) land. The plots show the difference between climate variables at CO_2 concentrations of 280 ppm and 560 ppm (green), 560 ppm and 1120 ppm (red), 1120 ppm and 2240 ppm (blue), and 2240 ppm and 4480 ppm (black).

occur over ocean and are parameterized based on static stability and are not important for the runs presented below [*Boville et al.*, 2006]. The change in cloud properties over ocean can be attributed to an increase in convection, consistent with the convective cloud feedback hypothesis (Figure 4g). In contrast, over land there is no change in convective cloud fraction at increased CO_2 (Figure 4h). The increase in cloud fraction over land appears to be due to an increase in the layered cloud fraction (Figure 4j), which is diagnosed in the model based solely on the relative humidity. Indeed, there is an increase in high-latitude, low-altitude relative humidity over land (Figures 4l and S4). Therefore, it appears that two different processes are leading to similar increases in high-latitude winter CRF over land and ocean as the CO_2 concentration increases.

3. Discussion

[12] Changes in winter cloud radiative forcing over land with changing surface temperature appear to be roughly equivalent in modern configuration at T42 resolution and Eocene configuration at T31 resolution (Figure 2). Additionally, when the resolution of the Eocene run at CO_2 = 4480 ppm is increased from T31 to T170 the model still produces a strongly positive CRF at high latitudes over land, although it is about 5–10 W m^{-2} lower at T170 than T31 (Figures S5f and S6f). This indicates that the result is relatively robust to changes in configuration and resolution within CAM.

[13] It is less clear, however, whether the increase in CRF with surface temperature found in CAM over land is robust more generally. Layered cloud fraction is diagnosed in CAM using a simple quadratic function of relative humidity that is sensitive to small changes in parameters. Furthermore, the reason the low-altitude winter relative humidity increases over land with surface temperature is not clear. The decrease in low-altitude relative humidity over ocean at increased atmospheric optical thickness due to increased convection is consistent with other models [e.g., *O'Gorman and Schneider*, 2008], but it appears that other processes are more important over land.

[14] Agreement among GCMs and between GCMs and data are both poor for low-level clouds in the Arctic during winter [*Vavrus et al.*, 2008]. This appears to be due to overproduction of low-level clouds in models during extremely cold and dry conditions [*Vavrus and Waliser*, 2008]. Since this problem is only relevant at lower temperatures, it is probably not relevant for the warmer runs presented here and may imply that the increases in CRF at high CO_2 concentrations are low estimates.

[15] *Abbot and Tziperman* [2009] suggested the possibility that the CRF could increase significantly over ocean even after sea ice was removed, whereas we find only small increases (Figure 2). This appears to be due to the fact that the strength of convection decreases with increasing CO_2 after the removal of sea ice (Figure S7) [see also *Held and Soden*, 2006] and large increases in the height of convection do not occur, which *Abbot and Tziperman* [2009] found to be an important on the strength of the CRF response. The small increases in CRF with CO_2 after the removal of sea ice appear to be

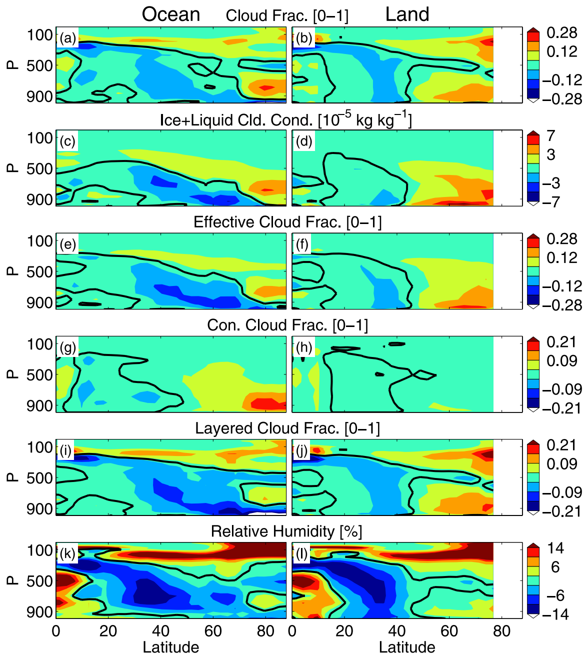

Figure 4. Different processes are responsible for the change in cloud properties over (left) ocean and (right) land in the CAM atmospheric GCM run with modern boundary conditions as the CO_2 is increased from 280 ppm to 2240 ppm. The change in the following zonally-averaged variables as a function of latitude and pressure are shown: (a) and (b) cloud fraction, (c) and (d) sum of ice and liquid cloud condensate, (e) and (f) effective cloud fraction, (g) and (h) convective cloud fraction, (i) and (j) layered cloud fraction, and (k) and (l) relative humidity. The zero contour is plotted in black.

due to increases in amount and altitude of cloud condensate (Figure S7).

[16] *Abbot and Tziperman* [2008a] suggested that transport of moisture, either as condensed cloud material or as water vapor, from over ocean to over land could potentially affect cloud formation and CRF over land. In CAM this process does not appear to be important. For example, at high latitudes and high CO_2 the wind velocity is seaward in Asia and landward in North America at low altitudes (Figure S8), even though the CRF response is relatively similar in Asia and North America (Figure 1). The fact that advection of moisture and cloud from sea to land does not appear to occur in CAM, however, does not necessarily rule it out as a potentially important mechanism.

4. Conclusions

[17] Our conclusions can be summarized as follows. (1) We have confirmed that the convective cloud feedback, which had previously been investigated using simple models, leads to a strong increase in winter cloud radiative forcing at high CO_2 over the ocean in a global climate model run at different resolutions with different boundary conditions, and found that this feedback is likely to have been active at a significantly lower CO_2 during the Eocene than in the modern continental configuration. (2) We found that the high-latitude winter cloud radiative forcing also increases over land as the surface temperature is increased by either increased CO_2 concentration or changes in boundary conditions in the global climate models we ran. This is due to increases in low-level layered clouds that form as a result of increased relative humidity and is not directly related to the convective cloud feedback that occurs over ocean. This result could potentially be important for explaining winter continental warmth during equable climates, but determining the robustness of this finding will require further study.

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