Energy balance in a warm world without the ocean conveyor belt and sea ice

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[1] Under a strong global warming scenario, the global mean temperature could rise up to 10°C, causing the global ocean conveyor belt to collapse and the summer sea ice to disappear. This will lead to profound changes in our climate system and to impact drastically the living conditions of the globe. Here we study how the global heat redistribution and regional heat balance will respond to these changes using the National Center for Atmospheric Research Community Climate System Model version 4. Results show that the collapsed ocean conveyor belt reduces the oceanic northward meridional heat transport (MHT) by nearly 60% with a minor increase in the atmospheric MHT. The polar amplified warming is primarily caused by the increased absorption of longwave radiation due to the increased greenhouse gases and cloudiness and by the increased absorption of shortwave radiation due to a lower albedo associated with the disappeared summer sea ice.


1. Introduction

[2] The long-term energy balance of the Earth is achieved by transporting the net surface heat gain in the tropics to the polar regions via the atmospheric and oceanic general circulations. Without any change of the external climate forcings, the amount of the total poleward meridional heat transport (MHT) is roughly constant on decadal or longer time scales. This is achieved by the compensating changes of the atmospheric and oceanic circulations [e.g., Cheng et al., 2007; Farneti and Vallis, 2013], referred as “Bjerknes compensation” [Bjerknes, 1964; Shaffrey and Sutton, 2006]. Previous studies suggest that this compensation on decadal time scales is caused by the atmospheric MHT which compensates the decadal internal climate variability in the oceans [Shaffrey and Sutton, 2006; van der Swaluw et al., 2007; Cheng et al., 2007; Vellinga and Wu, 2008; Farneti and Vallis, 2013]. One of the significant mechanisms for internal climate variability on decadal to multicentury time scales in the ocean is the Atlantic Meridional Overturning Circulation (AMOC) [Broecker, 1997]. This global-scale ocean circulation, often referred to as the “ocean conveyor belt,” transports warmer and saltier upper ocean water into the subpolar North Atlantic, where the water loses its heat and becomes dense, sinks to depth and flows southward, and upwells elsewhere in the world ocean. Changes in this circulation can significantly influence regional and global climate [e.g., Stouffer et al., 2006; Hu et al., 2011, 2012].

[3] Here we study the quasi-equilibrium changes of the MHT and regional heat balance under the representative concentration pathway 8.5 (RCP8.5) scenario—a scenario assuming minimum mitigation steps would be taken (Observational evidence suggests the current greenhouse gas emission is on the track of this scenario [Peters et al., 2013]) which leads to a greenhouse gas induced radiative forcing about 8.5 W/m² by the end of the 21st century—relative to the 20th century climate using the National Center for Atmospheric Research Community Climate System Model version 4 (CCSM4). Our specific focus is on how the MHT and regional heat balance will respond to a significantly weakened AMOC and a nearly year-round sea ice-free condition in the polar regions under the RCP8.5 scenario.

2. Model and Experiments

[4] CCSM4 is a fully coupled climate model that contains the Community Atmospheric Model version 4 with 26 vertical levels and a horizontal resolution of 1°, the Parallel Ocean Program version 2 with 60 levels vertically and nominal 1° resolution horizontally, the Community Land Model version 4, and the Community Ice Code version 4 [Gent et al., 2011]. The experiments analyzed here are mainly the 20th century all forcing simulations [Meehl et al., 2012] and the extension of the RCP8.5 scenario with all forcings kept constant at year 2300 levels to year 2600. The equilibrium climate sensitivity to a CO2 doubling is 3.2°C and the transient climate response from 1% CO2 simulation around the time of CO2 doubling is 1.7°C for CCSM4, lying the midway among the Coupled model intercomparison project phase 5 (CMIP5) models [Meehl et al., 2012].

3. Results

[5] Figure 1 shows the time evolution of the global mean surface air temperature (SAT, Figure 1a), AMOC index (Figure 1b), summer minimum, and winter maximum sea ice extent for Northern (Figures 1c and 1d) and Southern (Figures 1e and 1f) Hemispheres from 1850 to 2005 for the 20th century all forcing simulations, and RCP2.6, RCP4.5, RCP6.0, and RCP8.5 from 2006 to 2300, and the extension of RCP8.5 to 2600 with all forcings kept constant at 2300 level. In the RCP8.5 scenario, the global mean SAT rises by 9.7°C averaged over 2400–2599 relative to the mean of 1900–1999, much higher than all the other RCP scenarios. The AMOC collapses after the middle 22nd century.
and stays collapsed until the end of the simulation. The Northern Hemisphere sea ice totally disappears in summer starting in the early 22nd century and reduces to less than 1 million km² in winter after middle 23rd century. In the Southern Hemisphere, the summer sea ice disappears by late 22nd century and the winter sea ice extent reduces to less than 1 million km² in the 25th century. The question is how do these climate changes alter the earth’s energy balance?

Figure 2 shows the mean MHT due to the atmosphere and ocean general circulations, and the MHT inferred from the top of atmosphere (TOA) radiation balance (or total MHT) averaged over the 20th century (solid lines) and over the 25th and 26th centuries (dashed lines, 25-26C hereafter). The total MHT reduces in the Northern Hemisphere but increases slightly in the Southern Hemisphere (Figure 2a and Table S1 in the supporting information). For example, at 30°N this MHT reduces by about 7% and increases by only 1% at 30°S. The corresponding atmospheric/oceanic MHT increases/decreases in the Northern Hemisphere. In the Southern Hemisphere, the atmospheric MHT is nearly unchanged north of 40°S, but with an increase of atmospheric MHT south of 40°S with a reduced oceanic MHT associated to the changes of the Antarctic circumpolar currents (Figure S1). At 30°N and 60°N, the northward oceanic MHT in 25-26C reduces by 0.86 (54%) and 0.27 (55%) petawatts (PW), respectively, relative to the 20th century. This reduction is primarily caused by the collapsed AMOC which changes the Atlantic MHT from 1.05 PW at 30°N in the 20th century to 0.28 PW (−0.77 PW) in 25-26C and from 0.48 PW to 0.18 PW (−0.30 PW) at 60°N (Figure 2b). On the other hand, the northward atmospheric MHT increases by 0.50 and 0.05 PW at these two latitudes, respectively, which only makes up for about 58% and 19% of the reduced oceanic MHT. In the Southern Hemisphere, the southward MHT by the ocean and atmosphere both increase slightly at 30°S (about 0.7% for the atmosphere and 3.6% for the ocean, Table S1). The majority of the increased southward oceanic MHT is due to the reduced northward MHT from the collapsed AMOC. The southward MHT in the Pacific and Indian Oceans actually are reduced by about 50% (Figure 2b and Table S1). At 60°S, the increased southward MHT is by the atmosphere since the oceanic MHT actually reduces. The result of these changes is a reduced net heat divergence between 30°N and 30°S to 10.87 PW in 25-26C from 11.17 PW in the

Figure 1. Time evolution of (a) global mean temperature, (b) Atlantic meridional overturning circulation (AMOC), March and September sea ice extent in (c, d) Northern, and (e, f) Southern Hemispheres in 20th century (historical, 1850–2005), and the RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios, and the RCP8.5 extension to 2600 with all forcings kept constant at year 2300 levels.
20th century (2.7% reduction), with a reduced oceanic MHT divergence by 0.83 PW (37%) and an increased atmospheric MHT divergence by 0.54 PW (6%). Thus, the reduced MHT divergence in the tropics by the ocean is only partially compensated by the increased atmospheric MHT divergence.

[7] The time evolution of the MHT due to the atmospheric and oceanic circulation changes at the latitudes of 30° and 60° north and south is shown in Figure S2. As the global mean SAT increases and the AMOC weakens, the southward oceanic MHT at 60°S reduces, but the southward atmospheric MHT increases as AMOC weakens and peaks at −5.40 PW in the late 22nd century from −3.72 PW in 20th century when AMOC collapses. Afterward, the southward atmospheric MHT starts to decrease to about −4.58 PW and oceanic MHT stabilizes at about −0.27 PW. The southward atmospheric MHT at 30°S varies in a very similar way as at 60°S but with a smaller amplitude. The total oceanic MHT at 30°S only varies slightly throughout the simulation (0.03 PW increase). However, the changes in each individual basin are quite different. The northward MHT in the Atlantic reduces from 0.46 PW in the 20th century to nearly zero at the end of the 22nd century (Note: For individual basins, the MHT is based on the Eulerian mean field, but the total oceanic MHT is based on both Eulerian mean and eddy plus diffusivity (Figure S3)). The southward MHT reduces from 0.76 PW to 0.39 PW in the Pacific and from 0.14 PW to 0.01 PW in the Indian Ocean. This suggests that the collapsed AMOC reduces the required MHT from the Indo-Pacific Basin into the Atlantic, agreeing with previous studies [e.g., Hu et al., 2013]. In the Northern Hemisphere, the total MHT at 30°N reduces as the AMOC weakens and collapses with an increased/decreased northward atmospheric/oceanic MHT. The latter is primarily due to the reduced MHT in the Atlantic caused by the collapsed AMOC. After the end of the 22nd century, the northward MHTs in the Atlantic and Pacific are very close to each other (0.28 PW versus 0.32 PW). On the other hand, the changes of total MHT and atmospheric MHT occur at the same pace as the changes of the AMOC, suggesting that the AMOC changes have exerted significant influence on the global MHT and its partition between atmosphere and ocean circulations.

[8] To further investigate how these changes in MHT will affect the regional heat balance, particularly in the polar regions, we calculated the heat flux and radiation balance anomalies in 25-26°C relative to the mean of 20th century for the regions south of 60°S, 60 to 30°S, 30°S to 30°N, 30°N to 60°N, and north of 60°N (Figures 3 and S4). Both polar regions warm up to 18°C, much more than the global mean (Figure 3a). Initially, the warming is faster in the northern middle and high latitudes. By the end of the simulation, the warming in the southern middle and high latitudes is 1 to 2°C higher than that in the northern polar region. This higher warming seems to be associated with changes of the southern ocean sea ice (Figures 1e and 1f). Overall, the surface warming is close to the global mean in the midlatitudes, lower in the tropics but higher in the polar regions. The global mean TOA radiation imbalance is positive 1.2 W/m², peaking at about 2 W/m² around 2200, but up to 7 W/m² in the polar regions (Figure 3b). It starts to decrease for all regions with some delay after the AMOC collapses (Figure 1b) even though the greenhouse gas forcing is still increasing [Meehl et al., 2012]. The timing of the TOA radiation imbalance peaks at different times for different regions, with the tropics first, the midlatitudes second, and finally, followed by the polar regions, suggesting the response of the polar regions to greenhouse gas forcing will take a longer time to reach a quasi-equilibrium state associated with the delayed response of cryosphere and oceanic deep convection.

[9] The net shortwave/longwave radiation values (positive downward/upward) at TOA both increase at all latitudes with a slower increase for the latter (Figures 3c and 3d). It is this delayed response of the net longwave radiation at TOA, relative to the net shortwave radiation, that leads to the peaking of the TOA net radiation balance as shown in Figure 3b. The increased net shortwave radiation at TOA is associated with the increased absorption of solar radiation by the Earth climate system or the reduced reflection of the solar radiation at surface. The increased net longwave radiation is due to a warmer Earth surface and the atmosphere. The increased net shortwave radiation is up to 18 W/m² in both polar regions with a global mean of 8 W/m² when the forcing is stabilized (Tables S2 and S3) in comparison to the 20th century. For the longwave radiation, the increase is more than 10 W/m² in the polar regions with a global mean about 7 W/m². These induce a global mean TOA radiation imbalance by about 1 W/m² at the end of the simulation (Figure 3b).

[10] The surface heat balance shows in the tropics, the net heat gain reduces by about 2 W/m² in the 25-26°C relative to the 20th century but increases in the polar regions which peaks at 10 W/m² in the Northern Hemisphere and 8 W/m² in the Southern Hemisphere, and these increases are more than that at TOA, suggesting a more significantly reduced heat loss at surface (Figure 3c and Tables S2 and S3). In the midlatitudes, the changes of the surface heat balance are...
opposite to each other in the Northern and Southern Hemispheres in the 25-26C. In the northern midlatitudes, the oceanic MHT convergence increases from 0.55 PW in the 20th century to 1.09 PW in the 25-26C, but the atmospheric MHT convergence decreases by 0.15 PW (Tables S2 and S3). Thus, the increased oceanic MHT convergence contributes positively to the higher surface heat gain in the northern midlatitudes. In the southern midlatitudes, both atmospheric and oceanic MHT convergence reduce and contribute to the reduced surface heat gain there.

In Figures 3f–3k, we further decomposed the terms of surface heat balance to the shortwave and longwave radiation, and the latent and sensible heat fluxes. The net surface shortwave radiation (downward positive) increases in middle to high latitudes, and up to 13 W/m² in both polar regions, but decreases in the tropical region by about 4.5 W/m², with a global mean increase of 1.3 W/m² in the 25-26C (Figure 3f). This increased net shortwave radiation at the surface in middle-high latitudes is not due to increased downward shortwave radiation, which shows a significant decrease in polar regions (18 and 28 W/m² for northern and southern polar regions, respectively, Figure 3g and Table S3) associated with increased cloudiness (Table S3), but due to increased absorption associated with the reduction in surface albedo (Figure 3l). This albedo decrease is roughly 0.26 and 0.23 in the northern and southern polar regions, respectively, leading to an increased absorption of the solar radiation by 23 and 30%, respectively, in these polar regions. This albedo reduction is mainly caused by the disappearance of the sea ice and snow cover due to the warming. It is notable that the downward shortwave radiation is increased in the southern midlatitudes (Figure 3g), suggesting decreased cloud cover there (Table S3), especially the middle- and low-level clouds. On the other hand, the total cloud cover in the northern midlatitude also decreases (Table S3), but less than that in the southern midlatitudes, especially the reductions in middle and low clouds are about 40% smaller, combined with a reduced surface...
albedo leading to a nearly negligible effect on the downward shortwave radiation.

[12] At the same time, the surface net longwave radiation (>0 upward) reduces by up to 20 W/m² in the tropics and ~7 to 8 W/m² in the polar regions with a global mean reduction by 14 W/m² in the 25-26C (Figure 3h and Table S3). However, the downward longwave radiation increases by a much larger amount, up to 80 W/m² in the polar regions, around 60 W/m² in the midlatitudes, with a global mean of 66 W/m² (Figure 3i). This implies that although the warmer Earth surface will radiate more outgoing longwave radiation, the larger amplitude downward longwave radiation due to the increased greenhouse gas and water vapor (cloudiness), has overcompensated the increased outgoing longwave radiation, resulting a net reduction of upward longwave radiation at the surface.

[13] The changes of sensible heat flux in 25-26C show a small reduction in the global mean (Figure 3j) and Tables S2 and S3). This reduction is mainly due to the reduced sensible heat flux at the southern and northern midlatitudes, dominated by the former (~6 W/m² versus less than 1 W/m²), with a mild increase in the polar regions (3 W/m² and 2 W/m² in the north and south polar regions) and a small increase in the tropics (~1 W/m²). The latent heat flux in 25-26C increases in all regions with the highest increase in the southern midlatitudes, suggesting an increase in evaporation globally in response to the greenhouse gas induced warming. As shown previously, the increased downward shortwave radiation in the southern midlatitudes indicates a decrease of cloudiness there, and this decreased cloudiness combined with an intensified westerlies (Figure S5) leads to enhanced evaporation over the ocean in this region. The enhanced evaporation reduces the temperature contrast between the air and sea, resulting in reduced sensible heat flux.

4. Conclusions

[14] In this study, we analyzed the projected quasi-equilibrium changes of the global energy balance under the RCP8.5 scenario relative to the simulated 20th century climate. Our simulations show that the global mean temperature increases by approximately 10°C under RCP8.5 relative to that in the 20th century, with a roughly 70% larger increase in the polar regions. The AMOC or ocean conveyor belt circulation collapses in the late 22nd century and remains in the collapsed state thereafter. The Arctic becomes ice free starting in the early 22nd century in summer, and the ice cover is below one million km² from about the middle 22nd century in winter. In the southern oceans, sea ice-free summers start around the late 22nd century and winter sea ice cover is reduced to less than 1 million km² starting in the early 25th century. With these changes in global temperature, AMOC, and sea ice, the global and regional heat balance is significantly different from that in the 20th century. The collapse of the AMOC reduces overall northward oceanic MHT, and this reduction is only partially compensated by the increased atmospheric MHT which differ from previous studies [e.g., Shaffrey and Sutton, 2006; Vellinga and Wu, 2008; Farneti and Valls, 2013]. The total meridional heat divergence from the tropics reduces by 2.7% (0.30 PW), with an increase of 6% (0.54 PW) in the atmosphere and a reduction of 37% (0.83 PW) in the ocean, suggesting that a reduced meridional temperature gradient reduces the overall requirement for the poleward heat transport.

[15] Further analyses show that the reduced sea ice and snow coverage decrease the overall surface albedo in the polar regions, leading to increased absorption of solar radiation, although the total downward shortwave radiation reaching the surface decreases due to increased cloudiness. With a greater surface temperature increase in the polar regions, the sensible and latent heat fluxes are both increased, and the outgoing longwave radiation increases also. However, this increase is overcompensated by the increased downward longwave radiation associated with the elevated greenhouse gas concentrations and increased cloudiness. Thus, it is the increased absorption of solar radiation and reduced net loss of longwave radiation at surface that contributes to the net positive heat balance in the polar regions in our simulation. Finally, this is the result from one climate model; further study may be needed using multimodels.

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References