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Key Points:

- It is argued that ameliorating a CGCM's extratropical errors can improve the model's performance in the tropics
- The responses of two CGCMs to an idealized reduction of shortwave radiation over the Southern Ocean are compared
- The CGCM with stronger stratocumulus-SST feedbacks produces stronger SST reduction in the southern subtropics

Supporting Information:

- Supporting Information S1

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Can reducing the incoming energy flux over the Southern Ocean in a CGCM improve its simulation of tropical climate?

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Abstract Atmosphere-ocean general circulation models (CGCMs) show important systematic errors. Simulated precipitation in the tropics is generally overestimated over the oceans south of the equator, and stratocumulus (SCu) clouds are underestimated above too warm sea surface temperatures (SSTs). In the extratropics, SSTs are also too warm over the Southern Ocean. We argue that ameliorating these extratropical errors in a CGCM can result in an improved model's performance in the tropics depending upon the success in simulating the sensitivity of SCu to underlying SST. Our arguments are supported by the very different response obtained with two CGCMs to an idealized reduction of solar radiation flux incident at the top of the atmosphere over the Southern Ocean. It is shown that local perturbation impacts are very similar in the two models but that SST reductions in the SCu regions of the southern subtropics are stronger in the model with the stronger SCu-SST feedbacks.

1. Introduction

Precipitation over the tropical Pacific and Atlantic oceans is characterized by marked interhemispheric asymmetry in nature and largely erroneous symmetry in contemporary climate models. The observed band of climatologically strong precipitation known as the Intertropical Convergence Zone (ITCZ) occurs primarily along and north of the equator over both oceans, while in climate models there exists a "double ITCZ" defined by strong precipitation *both* north and south of the equator [*Mechoso et al.*, 1995; *Davey et al.*, 2002; *de Szoeke and Xie*, 2008; *Wang et al.*, 2014; *Xu et al.*, 2014; *Oueslati and Bellon*, 2015; *Richter*, 2015; *Zuidema et al.*, 2016]. In addition, model simulations show severe biases in sea surface temperature (SST). In the southeastern Pacific (SEP), too warm surface waters form a broad warm plume extending west to the dateline and from the equator south to about 25°S, with higher values near South America. A similarly erroneous configuration in SST is found in the southeastern Atlantic (SEA) [e.g., *Toniazzo and Woolnough*, 2014]. Moreover, cold SSTs at the equator extend too far west from the continents [*Patricola et al.*, 2012]. These errors greatly compromise the reliability of the models' predictions of climate variability and change.

Analyses of coupled general circulation model (CGCM) simulations of the SEP and SEA climates have indicated that a local reduction of errors can be achieved by improving the representation of two outstanding features of the regional climate: (1) the extensive and persistent stratocumulus (SCu) cloud decks that cover these regions shielding the ocean surface from solar radiation and (2) the oceanic upwelling that brings cold waters to the surface along the coasts [*Ma et al.*, 1996; *Philander et al.*, 1996; *Yu and Mechoso*, 1999a; *Yu and Mechoso*, 1999b; *Zhang and Delworth*, 2005]. The difficulties for reduction of model errors are compounded by a complex regional climate. In particular, there is a well-known positive feedback between SCu clouds and SSTs, according to which warmer SSTs result in less SCu and further SST warming [see *Mechoso et al.*, 2014, and references therein]. Another compounding factor is the difficulty in simulating the small horizontal scales (~10 km) that characterize coastal upwelling and ocean eddies associated with strong coastal currents [*Toniazzo et al.*, 2009; *Colas et al.*, 2011, 2013; *Holte et al.*, 2013]. The models' errors have also substantial values in regions of the extratropics. For example, simulated SSTs tend to be too warm over the Southern Ocean in association with cloud biases such as too low cloud optical thickness and/or too small cloud fraction and with biases in ocean mixing processes [*Kang et al.*, 2009; *Wang et al.*, 2014].

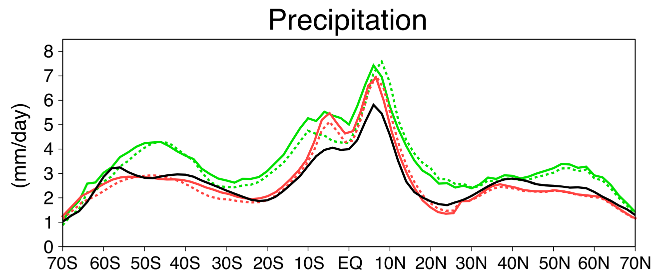

Figure 1. Annual mean precipitation averaged over latitude circles in the UCLA CGCM control (solid green line) and experiment (dashed green) runs, the NorESM control (solid red) and experiment (dashed red) runs, and observations (black).

The plausibility that ameliorating these extratropical errors can result in an improved CGCM performance in the tropics has gained importance in light of the limited progress toward this goal from model development work focused on the better representation of tropical processes.

Of particular relevance to this study is the work by *Hwang and Frierson* [2013, hereafter HF13]. HF13 argued that CGCMs with more net energy flux into the Southern Hemisphere atmosphere (at the top of the atmosphere and at the surface) in reference to the Northern Hemisphere tend to have a stronger double ITCZ bias. The proposed mechanism for connection is based on alterations of the Hadley circulation and the interhemispheric energy fluxes [see also *Kang et al*., 2008].

The present study addresses the following question: Can reducing the incoming energy flux over the Southern Ocean in a CGCM improve its simulation of the tropical climate? In answering this question we both test the hypothesis of HF13 and address the mechanisms for tropical-extratropical connection. We use two comprehensive models of the global climate with which we are very familiar: (1) the University of California Los Angeles (UCLA) coupled atmosphere-ocean general circulation model (CGCM) and (2) the Norwegian Earth System Model (NorESM) (see Text S1 in the supporting information for a description of the models). The models differ in many ways, of which one is key to the present paper: The relationship between outgoing shortwave (SW, solar) radiation at the top of the atmosphere (TOA) and SST in the major SCu regions is indicative of a stronger SCu-SST feedback in the UCLA CGCM than in the NorESM (Figure S1 and Text S1). Furthermore, the feedback is stronger than observational estimates in the former model and weaker in the latter model.

With the UCLA CGCM and the NorESM models we perform two idealized runs in which the influx of SW radiation incident at the TOA of each model is artificially reduced in a latitude band that covers the Southern Oceans. This perturbation is equivalent to increasing the cloud radiative forcing in a region where models tend to underestimate low cloud cover and reflect too little solar radiation [*Bodas-Salcedo et al*., 2012, 2014; *Naud et al*., 2014]. Specifically, the SW flux in the idealized runs is reduced between 30°S and 60°S by a time-independent amount with an average value of 8.14 W m^{-2} in the Southern Hemisphere (details are given in Text S2). The selection of perturbation amplitude is made a posteriori. First, it approximately cancels the local errors of TOA SW flux by the UCLA CGCM. Second, it is approximately the asymmetry in extratropical SW radiative forcing for the CGCMs that have the less outstanding double ITCZ problem (see Figure 3 in HF13). The perturbation results in a local cooling of the underlying SSTs and hence a reduction of the SST biases. In the following sections we analyze the global differences between model runs that incorporate the SW modification ("experiments" or EXPT) and simulations with the original model versions ("controls" or CTRL). Our analysis concentrates on 25 year periods of model runs because our interest is to gain insight into the role of cloud effects on the time scale of the Ekman-driven oceanic circulation before a modified deep ocean circulation sets up.

2. The Tropical Precipitation Bias in the Models

Figure 1 shows the annual mean precipitation averaged along latitude circles in the control runs and experiments of both models as well as in observations (Text S3). The control simulation of the UCLA CGCM overestimates precipitation at almost all latitudes, while that of the NorESM obtains more realistic values everywhere except in the tropics (10°S to 10°N), where precipitation is too high and there is a well-defined double ITCZ. The experiment with the UCLA CGCM results in a clear reduction of precipitation in reference to the control from 10°S to the equator, which signifies a reduction of the erroneous double ITCZ feature (see also Text S4 and Figures S2, S3, and S4). Moreover, precipitation north of the equator

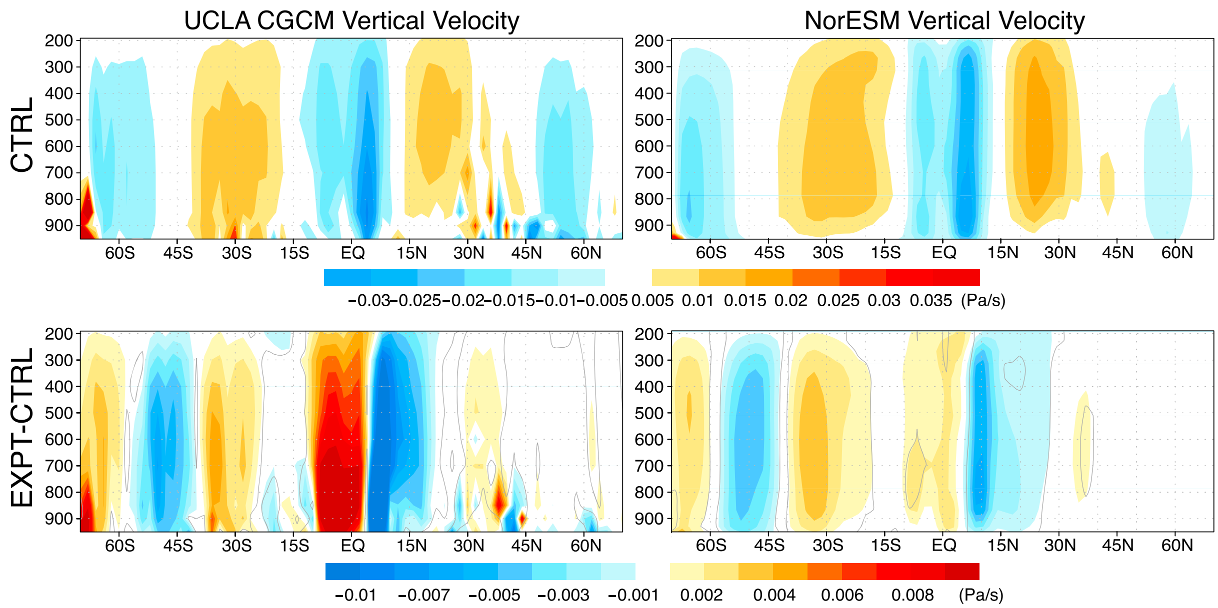

Figure 2. Change in pressure vertical velocity in the experiment. Latitude-pressure cross sections of annual mean vertical velocity averaged over latitude circles for the control run (top left) and the experiment minus the control run (bottom left) in the UCLA CGCM and that for the control run (top right) and experiment minus control run (bottom right) in the NorESM.

is slightly enhanced. The experiment with the NorESM obtains changes in tropical precipitation with a similar structure but much weaker amplitudes.

The circulation of the atmosphere is substantially modified by the SW perturbation and consistent with the impacts on tropical precipitation. In the experiments with the two models, the core of the southern subtropical jet moves equatorward (Text S4 and Figure S5). At the surface, westerlies intensify in the middle latitudes between 30°S and 50°S. In conjunction with this change in the zonal wind and associated transient motions in the atmosphere (eddies), the overturning atmospheric circulation is also modified. Figure 2 shows the annual mean vertical velocity averaged along latitude circles in the controls and its change in the experiments. Qualitatively, the two models produce similar results. The ascending branch of the Hadley circulation in the control runs (top row of Figure 2) appears as a broad band of upward motion around the equator, with strongest values corresponding to the ITZC at around 5°N. The descending motions are over the subtropics, where values of the lower tropospheric static stability in the SCu region over the Atlantic [*Klein and Hartmann*, 1993] become more realistic in the experiment (Text S4 and Figure S6). There is also clear evidence of indirect and direct cells in the extratropics and high latitudes, respectively. The bottom row in Figure 2 illustrates that the magnitude of the differences in vertical motion tends to be stronger in the UCLA CGCM than in the NorESM. In the experiments, upward motion south of the equator weakens in both models. This indicates a reduction of precipitation south of the equator and a northward shift of the ITCZ, especially in the UCLA CGCM and to a much lesser extent in the NorESM (Figure 1). Subsidence is also enhanced around 30°S, as the indirect (Ferrel) cell intensifies in response to the increased heat transport by midlatitude transients into the latitude band where the perturbation is introduced. In the Northern Hemisphere extratropics, changes are comparatively small.

3. Atmosphere-Ocean-Cloud Feedbacks

According to the results described so far, the effect of the SW flux perturbation over the Southern Ocean on the simulation of tropical precipitation by both models is relatively similar, with a tendency to be more pronounced in the UCLA CGCM than in the NorESM. Given the energetic arguments proposed by HF13 to explain the double ITCZ bias, we plot in Figure 3 the differences in net radiation incident at the TOA between the experiment and control for both models. As expected, there is a reduction in both cases over the Southern Ocean where the TOA radiation is perturbed (~45°S). The magnitude of the impact is stronger in the UCLA CGCM. In the tropics, this model shows negative values with large magnitudes

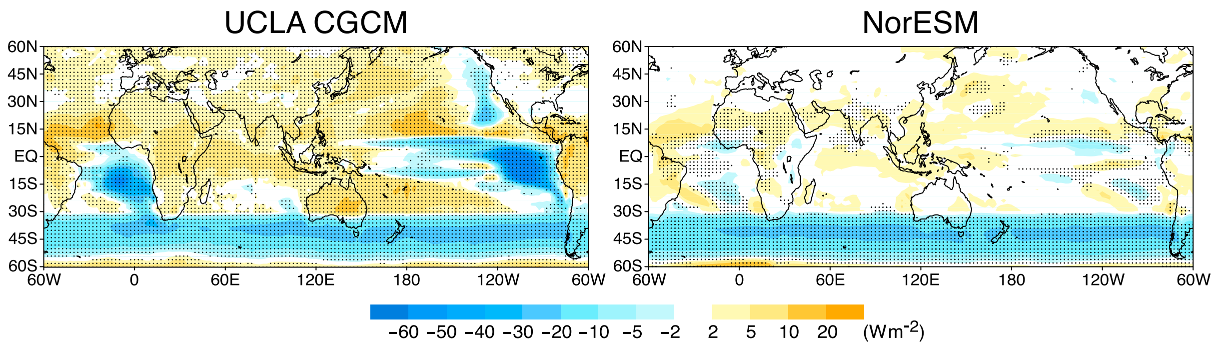

Figure 3. The change in net radiation in the experiment. Annual mean net radiative flux incident at the top of the atmosphere in the experiment minus that in the control run in the (left) UCLA CGCM and (right) NorESM. Stippling indicates where the difference in flux is statistically significant at the 95% level using a *t* test.

over the SEP, SEA, and northeast Pacific. These strong negative values result from local enhancements in upward SW radiation due to an increase in low-level marine cloud coverage in the experiment (Text S4 and Figure S7). By contrast, the NorESM produces small differences in radiative flux and marine cloud fraction in the tropics (Figure S7). The interhemispheric change in net radiation produced by the UCLA CGCM in the experiment is therefore stronger than the one produced by the NorESM. In agreement with HF13, the stronger cooling in the Southern Hemisphere in the UCLA CGCM is associated with a northward shift of the Hadley circulation and greater reduction of the double ITCZ bias in this model. Cooler SSTs in the southern tropics, consistent with an increase in cloudiness, may also contribute to decreased precipitation south of the equator.

Next we discuss the different representations of marine clouds in the tropics by the two models. We had already pointed out in discussing Figure 2 that between 10°S and the equator at low levels in the atmosphere, the vertical circulation is modified in the direction favorable for the formation of low-level, marine clouds. To examine other factors that influence marine cloud formation, we display in the top row of Figure 4 the difference in annual mean SST between the model experiments and their corresponding control simulations. In the UCLA CGCM, SST is reduced everywhere in the World Ocean, except in the northwestern Pacific. Cooling is strong in the zonal band where downward SW radiation is reduced, and in the southern tropics, particularly in the Atlantic and Pacific. The NorESM also obtains a general cooling everywhere except in the northwestern Pacific and stronger values in the zonal band where downward SW radiation is reduced. The magnitudes of cooling are clearly smaller than in the UCLA CGCM, which is physically consistent with the NorESM's smaller increase in southern tropical cloudiness. In both models, the cooling generally implies a reduction of their warm SST biases in the SCu regions of the southern subtropics (Text S5 and Figure S8).

The changes in the large-scale motion described in the previous paragraph are associated with others in sea level pressure, which are shown in the bottom row of Figure 4. Values decrease markedly in both models around the latitude band where incident SW radiation is reduced and upward motion is increased. Also, in both models, the Aleutian low weakens in the North Pacific (the classical atmospheric response to a colder equatorial Pacific). Elsewhere, the model results have important differences. In the UCLA CGCM, sea level pressure is increased over both the southern tropical Pacific and Atlantic. This intensification, together with the decrease of sea level pressure around Antarctica, is consistent with stronger surface winds arriving from the west to the coasts of the African and South American continents (see also Figure S5). The stronger surface westerlies set up an equatorward and shallow Ekman circulation in the ocean, advecting the colder SSTs from the Southern Ocean to lower latitudes. Moreover, these westerlies turn into southerly winds along the South American and African coasts, which enhance Ekman pumping and oceanic coastal upwelling locally and cool down surface waters. In the UCLA CGCM, such perturbed conditions lead to the triggering of a feedback among SCu, SST, and atmospheric circulation. Once SSTs decrease, cloud coverage increases, inducing further surface cooling and additional cloud formation [*Mechoso et al.*, 2014]. The cooler SSTs and increase in boundary layer radiative cooling caused by the additional cloud coverage then further enhance sea level pressure over the southern tropics, completing a positive feedback loop. The NorESM obtains much smaller sea level pressure differences in the tropics, consistent with a weaker feedback among SCu, SST, and the atmospheric circulation.

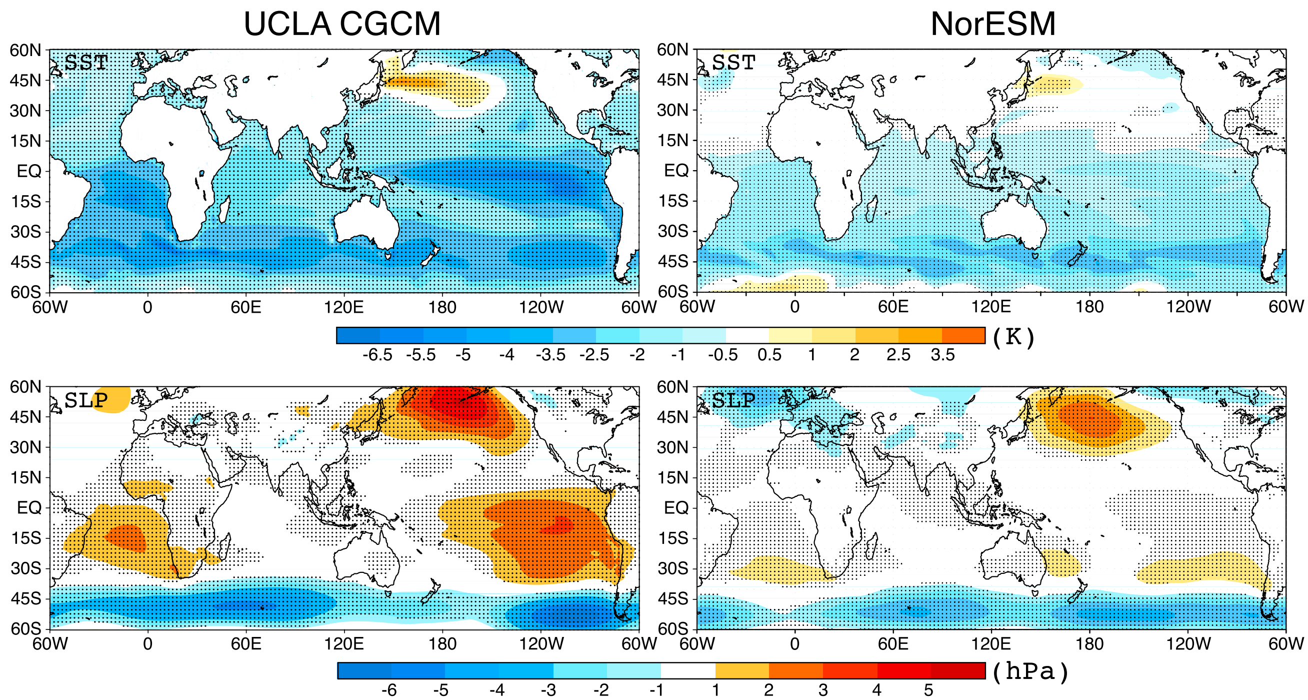

Figure 4. Changes in sea surface temperature and atmospheric circulation in the experiment. Annual mean SST (top left) and sea level pressure (bottom left) in the experiment minus that in the control run in the UCLA CGCM and the equivalent SST (top right) and sea level pressure (bottom right) changes in the NorESM. Stippling indicates where the difference in the plotted quantity is statistically significant at the 95% level using a *t* test.

4. Interhemispheric Energy Transport

The simulated climate responds to an energy loss in the Southern Hemisphere by reducing the amount of energy transferred to the Northern Hemisphere [*Hwang and Frierson*, 2013; *Kang et al*., 2008]. In the atmosphere, this occurs, as expected according to HF13, by a northward shift in the Hadley circulation and ITCZ in the experiments. The energy transport in the ocean also responds to the Southern Hemisphere cooling. To illustrate these responses, we display in Figure 5 the difference in northward heat transport across the equator by the atmosphere and the ocean in the experiments and their respective controls. In the UCLA CGCM, the northward heat transport in the atmosphere decreases in the experiment agreeing with the northward displacement of the Hadley circulation and ITCZ. The upper ocean shows a shallow southward heat transport in the upper 100 m, i.e., toward the hemisphere that is cooled down. This is partially compensated by northward heat transport at thermocline level. In the NorESM, perturbations in cross equatorial transports are weaker in a way consistent with the smaller impacts of the perturbation in this model. We highlight the absence of a clear drift with time and the presence of substantial interannual variability during the runs.

In a recent paper using the Community Earth System Model with the Community Atmosphere Model version 5, *Kay et al*. [2016] show that excessive absorption of SW radiation in the Southern Ocean by the model results in part because low-level clouds contain insufficient amounts of supercooled liquid. In view of this, they introduce a modification to the shallow convection detrainment that brightens low-level clouds and substantially reduces the Southern Ocean SW radiation bias. Despite this improvement, the impacts on tropical precipitation are small and the double ITCZ feature remains strong. The paper by *Kay et al*. [2016] is a comprehensive attempt to correct CGCM biases by improving the parameterization of cloud processes. In this framework, the consequences of model changes cannot be restricted to the Southern Ocean and can extend globally. Moreover, *Kay et al*. [2016] run their model long enough to include the response of the deep ocean circulation. Therefore, *Kay et al*. [2016] and the present paper are not strictly comparable. Nevertheless, we can ask whether our work can help to formulate a hypothesis on the small impact they find to reduce the Southern Ocean SW radiation bias. In this regard we note that there are many similarities between the atmospheric components of the NorESM and the model

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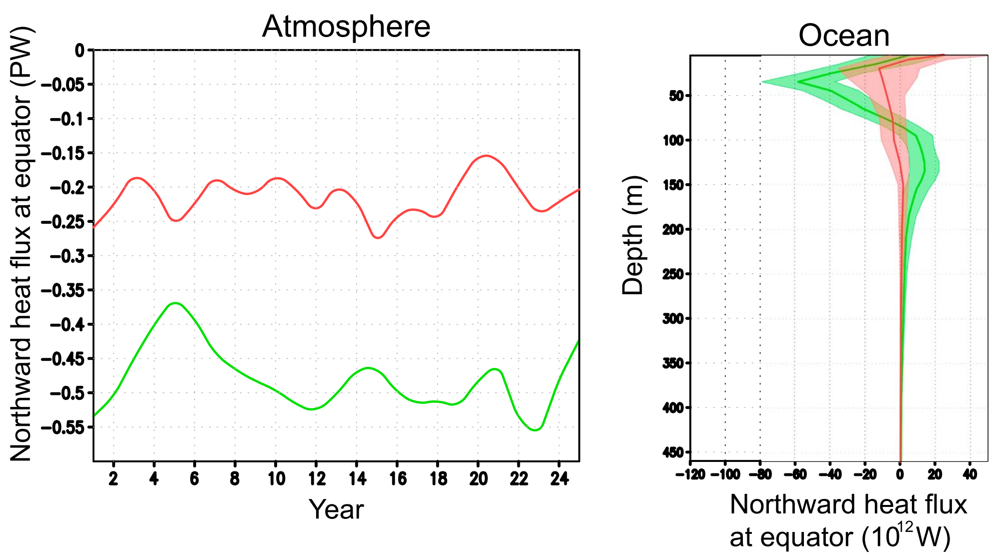

Figure 5. Change in northward heat flux at the equator in the atmosphere and ocean in the experiment. (left) Time series of the atmospheric northward heat flux at the equator in the experiment minus that in the control in the UCLA CGCM (green) and NorESM (red). (right) The annual mean oceanic northward heat flux as a function of depth in the experiment minus that in the control run in the two models. Shading shows the standard deviation of this difference.

used by *Kay et al*. [2016]. We can tentatively posit that the sensitivity of the atmosphere-ocean interactions that determine the SCu-SST feedback in their model may be too weak, especially because the small impact is already noticeable in the first 25 years of their simulation.

5. Conclusions

The present study supports the notion that reducing the incoming energy flux over the Southern Ocean in a CGCM can improve its simulation of the tropical climate. We arrive to this conclusion by exploring the response of two climate models, UCLA CGCM and NorESM, to an artificial decrease in the SW radiation input in a zonal band over the Southern Ocean (30°S–60°S). The simulation of higher cloud albedo over the Southern Ocean, which CGCMs tends to underestimate, can produce such a change in shortwave radiation.

The models' responses to the radiation perturbation are qualitatively similar in several ways: (1) the ITCZ moves northward and convection decreases south of the equator, (2) westerlies intensify in the southern midlatitudes throughout the troposphere, and (3) the upward branch of the Hadley circulations weakens in the Southern Hemisphere where the indirect and polar cells strengthen. The increased surface westerlies induce an equatorward Ekman circulation that contributes to a widespread SST reduction. This cooling tends to compensate the models' warm bias in the SCu of the southern subtropics. In this context, reducing the SST warm bias over the Southern Ocean can affect the subtropics and tropics.

However, the amplitude of the models' response is substantially larger in the UCLA CGCM than in the NorESM. The stronger response in the former model is attributed to a more active feedback among SCu, SST, and atmospheric circulation in the tropics. Therefore, we argue that the important differences between the responses to the same radiation perturbation by the two models arise from their different abilities to capture coupled atmosphere-ocean processes. The simulation of "low-level" clouds in the SEP and SEA is much more sensitive to SST perturbations in the UCLA CGCM than in the NorESM.

From a climate model development viewpoint, we are aware that a CGCM can be very sensitive to changes in a single parameterization [*Ma et al*., 1994]. Our findings in the present study confirm the need to address the problem of CGCM biases in the simulation of the tropical oceans' climate from both regional and global viewpoints. An improved simulation of cloud and other relevant processes in the Southern Ocean can contribute to a more realistic pattern of tropical precipitation if local feedbacks are properly simulated.

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