Feedback attribution of the land-sea warming contrast in a global warming simulation of the NCAR CCSM4

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Abstract
One of the salient features in both observations and climate simulations is a stronger land warming than sea. This paper provides a quantitative understanding of the main processes that contribute to the land-sea warming asymmetry in a global warming simulation of the NCAR CCSM4. The CO2 forcing alone warms the surface nearly the same for both land and sea, suggesting that feedbacks are responsible for the warming contrast. Our analysis on one hand confines that the principal contributor to the above-unity land-to-sea warming ratio is the evaporation feedback; on the other hand the results indicate that the sensible heat flux feedback has the largest land-sea warming difference that favors a greater ocean than land warming. Therefore, the results uniquely highlight the importance of other feedbacks in establishing the above-unity land-to-sea warming ratio. Particularly, the SW cloud feedback and the ocean heat storage in the transient response are key contributors to the greater warming over land than sea.

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1. Introduction
A robust feature of climate model simulations forced by an increase in CO2 concentration is a greater surface warming of land than oceans (Manabe et al 1991, Lambert and Chiang 2007, Sutton et al 2007, Boer 2011). This phenomenon is not a transient effect due to the much larger thermal inertia of the oceans, as it is also present in equilibrium conditions (Sutton et al 2007, Boer 2011). Therefore, feedbacks must play important but distinct roles over land and ocean causing the land surface to warm more than the ocean surface. Quantifying the contribution of feedbacks to the land-sea surface warming contrast is therefore an important step for advancing our understanding of climatic impacts to an increase in CO2.

Manabe et al (1991) and Sutton et al (2007) suggested that the larger increase in evaporation over the ocean than over land is a key contributor to the greater land warming. Furthermore, the increase in CO2 will reduce the stomatal conductance of plants, leading to less evaporation over land, warming the land further (Joshi et al 2008, Joshi and Gregory 2008, Dong et al 2009). Different changes in lapse rate over land and ocean due to the limited moisture availability over land are also thought to be an important cause of the larger land than ocean warming (Joshi et al 2008, Byrne and O'Gorman 2013). Additionally, a larger reduction of clouds over land versus ocean is thought to enhance the land warming, as a larger amount of downward shortwave radiation reaches the surface leading to greater absorption (Joshi et al 2008, Dong et al 2009).

The studies above mainly relied on the analysis of the surface energy budget to give a qualitative understanding of the processes responsible for the larger land warming as compared to the oceans. The main objective of our study is to quantify the contributions to the warming asymmetry between
land and ocean from individual physical and dynamical processes in response to a steady increase of the CO$_2$ concentration at the time the CO$_2$ concentration is doubled. To do so, we use the climate feedback-response analysis method (CFRAM; Lu and Cai 2009, Cai and Lu 2009) to attribute the contributions of the CO$_2$ forcing alone (no feedbacks) and feedbacks to the land-sea warming contrast. The CFRAM allows us to quantitatively estimate the importance of the different feedbacks in establishing the land to ocean warming ratio by estimating the surface temperature change over land and/or ocean due to each individual feedback. As discussed in Lu and Cai (2009), the concept of feedback in the CFRAM differs from that of the classic feedback analysis framework. In the classic feedback analysis framework feedback is an induced input from the output (i.e., the surface temperature change), which then amplifies or suppresses the surface temperature change due to the forcing alone. In the CFRAM framework all climate system responses to a forcing (i.e., the CO$_2$ forcing) are outputs; however, the effects of induced inputs from all outputs on a single output, namely the temperature change attributed to the forcing alone. As a result, the term feedback in the CFRAM framework feedback is the induced input of one of the outputs, which then amplifies or suppresses the temperature change attributed to the forcing alone. As a result, the term feedback in the CFRAM framework does not differentiate fast adjustments to forcing from surface temperature mediated responses as in the classical interpretation of the term feedback, which just refers to the latter.

This study focuses on the surface temperature response to a 1% yr$^{-1}$ increase in the CO$_2$ concentration, at the time of CO$_2$ doubling (hereafter referred to as the transient response), simulated by the National Center for Atmospheric Research (NCAR) Community Climate System Model version 4 (CCSM4). Our paper is a follow-up study to that done by Taylor et al (2013) and Sejas et al (2014), who investigated the roles of the CO$_2$ forcing and feedbacks in causing the annual-mean atmospheric and surface temperature changes and the seasonal surface temperature response in the same CCSM4 simulation, respectively.

2. Model analysis method

The data used in this study are 20 year monthly mean data derived from the transient climate simulations of the NCAR CCSM4 in response to a 1% yr$^{-1}$ increase of the CO$_2$ concentration at the time of the CO$_2$ doubling from the 1850 level when the CO$_2$ concentration is 284.7 ppm. We choose to study the simulation with a steady increase of the CO$_2$ concentration over the abrupt increase scenario since it is more relevant to the real world case. We refer readers to the supplementary file, Taylor et al (2013), and Sejas et al (2014) for a more detailed description of the transient global warming simulations in the NCAR CCSM4.

The CFRAM application to the transient CCSM4 climate response follows just as in Taylor et al (2013) and Sejas et al (2014). For brevity only the main features of the CFRAM, as applied to the CCSM4 data, will be repeated here; for a more extensive description readers are referred to Taylor et al (2013) and Sejas et al (2014).

The CFRAM is based on the energy balance equation for each of the atmospheric layers and surface layer (Lu and Cai 2009) and the linearization of the radiative energy flux terms, similar to what is done in the partial radiative perturbation (PRP; Wetherald and Manabe 1988) and radiative kernel methods (Soden and Held 2006, Soden et al 2008). Following Taylor et al (2013) and Sejas et al (2014), at a latitude-longitude location the CFRAM equation is

$$\Delta T = \left( \frac{\partial R}{\partial T} \right)^{-1} \left\{ \Delta F_{\text{ext}} + \Delta F_{\text{wv}} + \Delta F_{\text{alb}} + \Delta Q_{\text{atmos\_dyn}} + \Delta Q_{\text{spin\_dyn\_storage}} + \Delta Q_{LH} + \Delta Q_{SH} + \left( -\Delta \text{Err} \,(S - R) \right) \right\} \tag{1}$$

where the vector $S$ represents the vertical profile of the solar radiation absorbed by the atmospheric layer and at the surface layer whereas $R$ is the vertical profile of the net infrared radiation flux divergence at each atmospheric layer and surface layer. The left-hand side represents the vertical profile of the change in temperature at each atmospheric layer and surface layer. Each term inside the curly brackets represents the vertical profile of an energy flux convergence perturbation in each of the atmospheric layers and the surface layer in units of W m$^{-2}$: $\Delta F_{\text{ext}}$, $\Delta F_{\text{wv}}$, $\Delta F_{\text{alb}}$, $\Delta Q_{LH}$, and $\Delta Q_{SH}$, respectively, are radiative terms due to the CO$_2$ forcing alone (no feedbacks), and changes in atmospheric water vapor, cloud properties, and surface albedo; $\Delta Q_{\text{atmos\_dyn}}$ and $\Delta Q_{\text{spin\_dy}}$, respectively, are non-radiative terms due to changes in surface latent and sensible heat fluxes; $\Delta Q_{\text{atmos\_dy}}$ and $\Delta Q_{\text{spin\_dy\_storage}}$ changes in energy flux convergence due to all non-radiative processes excluding surface latent and sensible heat fluxes calculated through a residual method (see supplementary file). $\Delta Q_{\text{atmos\_dy}}$ is mainly associated with atmospheric dynamics such as changes in atmospheric convective/large-scale energy transport. $\Delta Q_{\text{spin\_dy\_storage}}$ is mainly associated with changes in oceanic heat transport and ocean heat storage; over land this term is negligible since the changes in land heat transport and land heat storage are relatively small. $\Delta F_{\text{ext}}(S-R)$ is the error in the offline radiative transfer calculation due to the use of different radiative models and time mean data, instead of instantaneous data in our offline radiative calculations (Taylor et al 2013, Sejas et al 2014). $(\partial R/\partial T)$ is called the Planck feedback matrix whose $j$th column represents the vertical profile of the change in divergence of LW radiative energy fluxes due to a 1 K warming at the $j$th layer alone (Lu and Cai 2009). Following the linear decomposition principle, (1) can be solved by obtaining the vertical profile of the (partial) temperature change due to the CO$_2$ forcing alone and each respective feedback, namely

$$\Delta T^{(x)} = \left( \frac{\partial R}{\partial T} \right)^{-1} \Delta F^{(x)} \tag{2}$$

where ‘$x$’ represents one of the nine superscripts in (1). equation (2) gives the full vertical profile of the temperature change associated with process ‘$x$’; in this study we will focus
only on the surface temperature change given by (2). We wish to point out, as explained in Lu and Cai (2009), that the ‘isolation’ of the temperature changes due to individual feedback processes as described by equation (2) does not mean the feedback processes are independent of each other, as they are actually highly coupled. We just isolate the temperature change due to the change associated with one specific feedback agent (e.g. clouds) induced by the system responses collectively for a given set of climate simulations. Therefore, the temperature change attributed to an individual physical process would change if one of the other feedback processes was excluded from the model simulation or if additional feedback processes were added to the model simulation.

3. Global-mean warming over land versus oceans

The global (land and ocean) annual-mean temperature has warmed 1.67 K at the time of the doubling of CO₂ in the transient 1% yr⁻¹ CO₂ increase simulation of the NCAR CCSM4 (Taylor et al. 2013). However, the global annual-mean warming over land (2.3 K) is about 1.7 times as large as that over oceans (1.35 K). This land-sea warming ratio for the NCAR CCSM4 falls within the range of values given by the multi-model study of IPCC AR4 models of Sutton et al. (2007). Figure 1 shows that the warming due to the external forcing alone is slightly larger over land (1.18 K) than over oceans (1.05 K). In response to the anthropogenic radiative forcing, the larger increase of water vapor over oceans than over land (not shown) explains why the additional warming due to the water vapor feedback is larger over oceans (1.23 K) than over land (1.12 K). The next largest contributor to the warming over both land and oceans is the albedo feedback, responsible for an additional warming of 0.36 K over land and 0.42 K over oceans. Therefore, the total effect of the external forcing, water vapor feedback, and albedo feedback, the three largest contributors to the warming globally over both land and sea, is actually stronger over oceans (2.7 K) than over land (2.66 K).

The latent heat flux or evaporation feedback substantially suppresses the warming over the ocean (−1.15 K) due to an increase in evaporation, but warms the land (0.18 K) due to a decrease in evaporation over land. This is in accord with previous studies (e.g., Manabe et al. 1991, Sutton et al. 2007) that indicate the evaporation feedback favors a larger warming over land than sea. The sensible heat flux feedback, on the other hand, has an opposite polarity to that of the evaporation feedback. The increase in sensible heat flux over land leads to a suppression of the land warming (−1.4 K) and the decrease in sensible heat flux over the oceans contributes an additional warming of 0.62 K. Thus, the sensible heat flux feedback favors a larger warming over the oceans than land, meaning it is an important suppressor of the land-to-sea warming ratio. In fact, the net effect of changes in surface turbulent heat fluxes reduces the surface warming more over land (−1.22 K) than over oceans (−0.53 K), which, when considering the radiative processes mentioned earlier as well, would indicate a substantially greater warming of the ocean surface (2.17 K) as compared to land (1.44 K). Therefore, there must be other important feedback processes besides the evaporation feedback that substantially favor warming over land than sea.
The reduction in the global coverage of clouds in a warmer climate over land contributes to an additional land warming of 0.7 K with 0.77 K and −0.07 K coming from the shortwave and longwave cloud feedbacks, respectively. The cloud feedback has little impact on the global-mean warming over oceans (−0.02 K) due to little net change in the global-mean coverage of clouds over oceans. Therefore, the cloud feedback is also an important contributor to the larger warming over land than sea. Adding the cloud feedback land and ocean contribution to the previously mentioned contributions indicates a global warming over land (2.14 K) that still does not exceed the ocean warming (2.15 K), so to account for the above unity land-to-sea warming ratio there must be additional processes favoring a larger warming of the land than sea.

The last important piece of the puzzle is provided by the ocean heat storage/dynamics feedback, which, as expected, is nearly negligible over land but very large over the oceans. The ocean heat storage/dynamics feedback reduces the warming over the oceans globally by −0.87 K, which we attribute mostly to the large thermal inertia of the oceans in the transient response. Therefore the ocean heat storage/dynamics feedback is another important contributor to the land-sea warming ratio being above unity. Adding the contribution of the ocean heat storage/dynamics feedback to the previously mentioned contributions results in a global-mean land warming of 2.15 K and ocean warming of 1.28 K, a difference of 0.87 K. Most of the warming difference over land and ocean has been accounted for; the remaining terms are very small adding 0.14 K and 0.12 K to the global warming over land and oceans, respectively. The sum of all contributions results in a total global warming of 2.29 K over land and 1.4 K over oceans, a land-sea warming ratio of 1.64. These totals are slightly different from the values obtained from the CCSM4 simulations mentioned previously due to the linearization involved in the CFRAM calculation.

Please note that the order in which the forcing and feedback contributions to the land and sea warming are added up is not meant to imply causality. Adding them up any other way would still demonstrate our main point, namely, that there is no one process that can account for the above unity land-to-sea warming ratio.

4. Latitudinal contrast of the land-sea warming

The annual-mean meridional profiles of the temperature responses over land and ocean are shown in figure 2. The CFRAM totals over both land and ocean are shown to match up quite well with the simulated land and ocean warming, respectively. The major feature seen is the greater warming of land than sea in the tropics and mid-latitudes. In the southern hemisphere polar region the ocean warming is relatively on par with the land warming. The Arctic, however, experiences greater polar warming amplification over the ocean than land. To explain these features the CFRAM results shown in figure 3 are utilized (note that the offline error (figure 3(i)) has little effect on our feedback attribution of the land-sea warming contrast).

The CO2 forcing alone (figure 3(a)), while slightly contributing to the larger land warming in the tropics and mid-latitudes, demonstrates similar meridional structure in the warming over both land and sea. Therefore, it is feedback processes that are most responsible for the differences in meridional structure between the ocean and land warming. Remarkably, the feedback with the largest difference in temperature change between land and sea in the tropics and mid-latitudes is the sensible heat flux feedback (figure 3(c)), which favors a greater warming of the ocean than land. The increase in sensible heat flux over land but decrease over sea (not shown) suppresses the land warming and enhances the sea warming, which is opposite to the picture presented by the total response. Furthermore, the water vapor (figure 3(b)) and atmospheric dynamics (figure 3(g)) feedbacks also favor a larger warming over sea than land. Therefore, these feedbacks suppress the greater warming over land than sea. Note that the small global-mean contribution to the land and sea surface temperature response (figure 1) by the atmospheric dynamics feedback is a result of offsetting warming and cooling contributions in low and high latitudes, respectively (figure 3(g)).

As in the global context, the primary contributor to the meridional land-sea warming ratio being above unity is the latent heat flux feedback. The increase in evaporation over the ocean surface suppresses the warming of the ocean (figure 3(f)), while the decrease in evaporation over land enhances the warming of the land. The decrease in evaporation over land is in agreement with previous studies such as Joshi et al (2008), Joshi and Gregory (2008), and Dong et al (2009), which indicate there is a reduction in evaporation over land due to the reduction of the stomatal conductance of
plants induced by the increase in CO₂, also present in the CCSM4 simulations. The cloud feedback (figure 3(c)) is also an important contributor to the larger surface warming of land than sea, by amplifying the land warming and, in general, reducing the ocean warming in the tropics and warming the ocean less than land in mid-latitudes. For the tropics and lower mid-latitudes the SW component (figure 4(a)) of the cloud feedback dominates for both land and sea; therefore, the decrease and increase of clouds (not shown) over land and sea in the tropics, respectively, leads to an enhancement of the land warming and reduction of the sea warming. In the upper mid-latitudes, the LW component (figure 4(b)) of the cloud feedback takes the primary role and the increase in clouds over both land and sea leads to an enhancement of the warming for both. The final major contributor to the land-to-sea warming ratio being greater than unity is the ocean heat storage/dynamics feedback. For land this term is nearly zero as expected, whereas the change in ocean dynamics and heat energy withheld by the ocean in the transient state leads to a suppression of the ocean warming in the tropics and lower mid-latitudes (figure 3(h)). The large cooling contribution to the ocean temperature change by the ocean heat storage/dynamics feedback, seen in the northern hemisphere at upper mid-latitudes, is likely due to ocean heat uptake by the

Figure 3. The zonal and annual-mean surface temperature change (in K) for land (red) and ocean (blue) due to the (a) CO₂ forcing alone, (b) water vapor feedback, (c) cloud feedback, (d) surface albedo feedback, (e) sensible heat flux feedback, (f) latent heat flux feedback, (g) atmospheric dynamics feedback, (h) ocean dynamics/heat storage feedback, and (i) the offline error in the surface temperature response. Please note that the range of values on the x-axis vary from panel to panel.
Atlantic meridional overturning circulation, which stores a substantial amount of heat energy in the ocean in the transient state.

The melting of sea ice is the major component of the albedo feedback, thus the ocean warming due to the albedo feedback is much larger than that over land in polar regions (figure 3(d)). A large part of the additional warming due to the surface albedo feedback over the polar ocean has been offset by the cooling due to the ocean dynamics/heat storage feedback except north of 70°N, where the warming due to the albedo feedback is strong and thus mainly responsible for the larger polar warming amplification seen over the ocean as compared to land in the Arctic.

5. Discussion

It is known that the ocean and land surfaces warm because of a larger influx of energy at the surface triggered by the enhancement of the greenhouse effect due to the CO₂ forcing. Even though the CO₂ forcing warms the land surface more than the ocean (figure 1), it cannot account for the much larger land than ocean warming, as demonstrated in the previous sections. Even though our results cannot demonstrate causality between feedbacks, physical arguments can be made that are consistent with our results and theories given in previous studies. As pointed out by Manabe et al (1991) and Sutton et al (2007), over sea much of the additional energy absorbed by the surface will likely go into enhancing the evaporation. The enhancement of evaporation over the ocean means the surface temperature does not warm as much as the atmosphere above it due to evaporative cooling (and due to the larger ocean heat capacity in the transient response). The decrease of the lapse rate in the boundary layer implies a stabilization of the boundary layer and a decrease in the surface sensible heat flux, which favors a warming of the ocean. Over land the lack of moisture availability means not much of the additional energy flux at the surface will go into evaporation, but instead will be used to raise the temperature. This leads to an increase of the lapse rate in the boundary layer, increasing the instability and thus the surface sensible heat flux as well. This picture is consistent with the results displayed for the surface sensible and latent heat flux feedbacks above. The moisture availability difference over land and sea is thus an important cause of the land-to-sea warming ratio, consistent with the arguments made in Sutton et al (2007).

Along with the evaporation feedback, the cloud feedback is also an important contributor to the above unity land-to-sea warming ratio, as demonstrated in the previous sections. As with the evaporation feedback, cloud changes also depend heavily on the response of the hydrological cycle. Since the evaporation and cloud feedbacks are two of the three main contributors to the larger warming of the land than sea, our results suggest the response of the hydrological cycle is mainly responsible for the above unity land-to-sea warming ratio.
6. Summary and conclusions

Using the CFRAM method we have, for the first time, quantified the individual contributions of the CO₂ forcing and feedbacks to the land–sea surface temperature contrast given by a transient simulation of the NCAR CCSM4. This helps identify the importance of the different radiative and non-radiative feedbacks in establishing the land–sea warming contrast. The greater warming over land than ocean is a robust feature of climate simulations forced by an increase in CO₂, and is explained by previous studies (e.g., Manabe et al. 1991, Sutton et al. 2007) to be primarily due to a decrease in evaporation over land and an increase over the oceans. Our study corroborates these previous findings, as our results indicate the evaporation feedback is primarily responsible for the larger land than ocean warming, warming the land 1.33 K more than the ocean surface in the global-mean (figure 1). This, however, is not the largest difference in global-mean surface temperature change between land and sea due to an individual feedback. The 2.02 K difference between the land and ocean surface temperature change attributed to the sensible heat flux feedback is the greatest difference for any one feedback (figure 1), but it counters an above-unity land–sea warming ratio. Therefore the evaporation feedback alone cannot account for the greater warming of land than sea in the total surface temperature response.

The cloud and ocean heat storage/dynamics feedbacks are the two other main contributors to the greater land than ocean warming. The decrease in the global-mean coverage of clouds over land causes a warming of the land by the cloud feedback that is 0.72 K larger than the ocean global surface temperature change due to the cloud feedback, as a result of the small global-mean change in clouds over the ocean. The ocean heat storage/dynamics feedback then contributes to the greater warming of the land by cooling the oceans globally by −0.87 K, which we attribute mostly to the thermal inertia of the oceans in the transient state.

The results obtained here are representative only of one model, namely the NCAR CCSM4. To obtain more general and robust results a multi-model ensemble study should follow. A multi-model ensemble analysis would be particularly useful in confirming that clouds play a major role in causing the above unity land–sea warming ratio, since the simulation of clouds by climate models are known to have great model-to-model variability. Additionally, the results of this study indicate that the ocean heat uptake in the transient state plays a key role in the land–sea warming contrast. Sutton et al. (2007) demonstrated that the land–sea warming ratio remains relatively constant for most IPCC models and that even at equilibrium an above unity land-to-sea warming ratio similar to the transient response persists. For this reason, prior studies have usually dismissed the heat capacity of the ocean as an important contributor to the above unity land-to-sea warming ratio. Since this study demonstrates that the thermal inertia by the oceans is a key factor in establishing a greater warming of land than sea for the transient response, a relatively similar land–sea warming ratio in the equilibrium response would imply the influences of the other feedback processes on surface temperature would have to change to keep the warming ratio similar to the transient response. Thus, it would be fundamental to our understanding to do a follow-up study on the equilibrium state to understand how the thermal adjustment of the oceans to equilibrium still leads to a similar land–sea warming ratio.

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