CMIP6 Abrupt CO_2 Quadrupling Scenario: Analysis of Climate Model Output to Determine the Effect of Clouds

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ABSTRACT

The largest source of uncertainty among climate models simulating the climate system response to increased atmospheric carbon dioxide concentrations is the cloud feedback, the amplification or dampening of the warming from the carbon dioxide forcing by clouds. Refining our knowledge of the cloud feedback is therefore essential to gaining a more precise understanding of how the climate system will adjust as anthropogenic emissions continue to raise carbon dioxide concentrations. Accordingly, this project's objective is to analyze the strength of the cloud feedback using model output from the newest phase of the Coupled Model Intercomparison Project (CMIP), CMIP6. To achieve this goal, output is examined from two general circulation models, the IPSL-CM6A-LR and the BCC-CSM2-MR, for two CMIP6 experiments, an abrupt carbon dioxide quadrupling scenario, and a pre-industrial control scenario (for comparison). Figures are plotted and statistical calculations are performed using the computing program Python to analyze the model output. The analyzed output for each of the models show that when carbon dioxide concentrations are quadrupled, most areas of the globe undergo significant changes in the net cloud radiative effect (CRE), the difference in the global radiation flux balance between cloudy and clear conditions. The net CRE changes such that the cloud feedback is positive, meaning that clouds adjust in a way that amplifies the warming from the carbon dioxide forcing.

INTRODUCTION

Clouds interact with both solar (shortwave) and terrestrial (longwave) radiation; they reflect incoming solar radiation back to space (a cooling effect), and they absorb and re-emit the Earth's outgoing longwave radiation (a warming effect). Whether clouds warm or cool the Earth depends on the balance between these two opposing influences. In today's climate, most clouds tend to be lower, thicker clouds whose shortwave effect dominates their longwave effect; clouds therefore tend to cool the Earth overall. This is depicted in Figure 1 below, where maps showing the shortwave, longwave, and net effect of clouds are plotted for the IPSL and BCC models using pre-industrial control output. The 500 and 600 year control datasets (for the IPSL model and the BCC model, respectively) fix carbon dioxide concentrations at their 1850 levels and only prescribe natural forcings[1]. Thus, the control runs represent the likely state of the climate without excessive human interference. Both models indicate that under these conditions, clouds cool the Earth by reducing the surface energy budget by 22.8 Wm^{-2}.

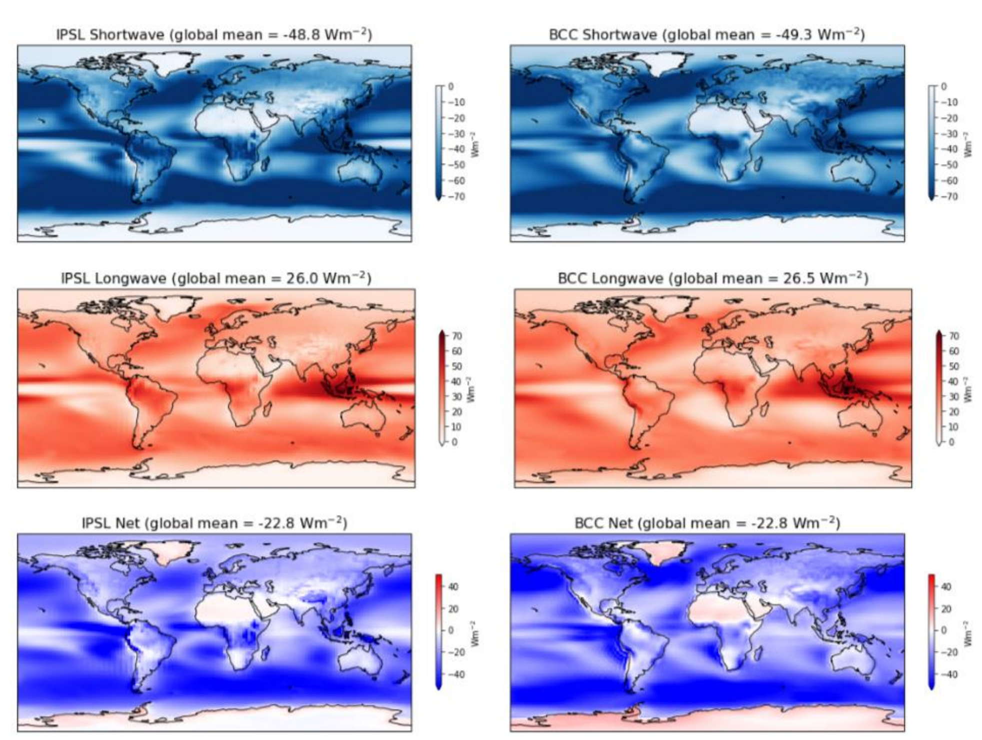

Figure 1: Global maps showing (from top to bottom): shortwave effect, longwave effect, net effect

When the climate is positively forced, there is a net surplus in the top of atmosphere (TOA) energy budget, and the temperature of the Earth increases in response until the TOA energy balance is restored. This temperature change can alter the properties (distribution, type) of clouds, which can in turn either amplify or dampen the initial climate warming. In this project, the positive forcing that is explored is an instantaneous quadrupling of the 1850 carbon dioxide concentration of the control run. All other prescribed forcings remain the same as the control[1]. After the quadrupling, the climate system is allowed to adjust over time towards a new equilibrium state. The IPSL dataset for the quadrupled experiment spans 300 years while the BCC dataset spans only 150 years, so the IPSL scenario concludes closer to climate equilibrium.

RESULTS AND DISCUSSION

The IPSL and BCC models both indicate that the change in net TOA flux (the forcing) when carbon dioxide is quadrupled is around 6 Wm^{-2}. Over time, the climate system warms up (from an initial temperature of ~287 K) and approaches a new equilibrium temperature (~ 294 K). At equilibrium, the TOA forcing has returned to 0 Wm^{-2} so the climate system is no longer forced. Figure 2 breaks down the net TOA radiative flux term into its components: longwave (LW) clear-sky, shortwave (SW) clear-sky, LW CRE, and SW CRE[2].

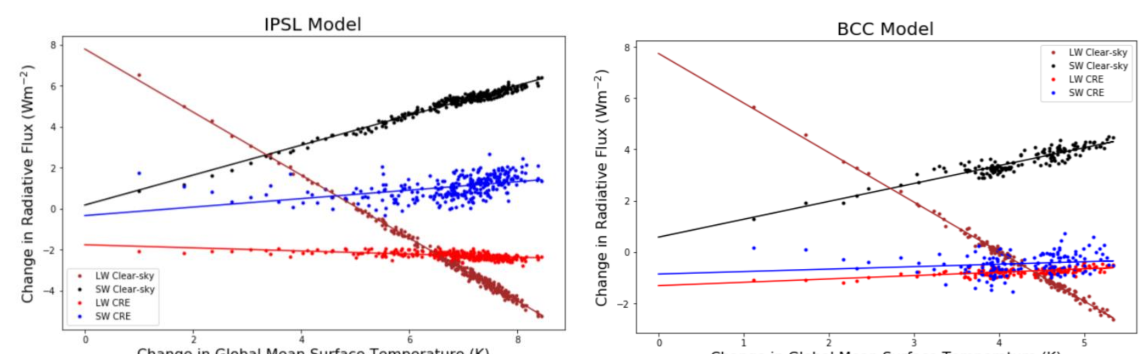

Figure 2: Plots displaying the change in TOA radiative flux as a function of the increase in surface temperature

The LW clear-sky component is a strong stabilizing component, mainly because as the Earth warms it emits more radiation, which reduces the TOA energy imbalance[2]. The SW clear-sky component shows the destabilizing effect of the ice-albedo feedback; as temperatures increase, high-albedo ice and snow surfaces melt and are replaced by lower-albedo surfaces that absorb more insolation and cause further warming. The LW and SW CRE components represent the cloud feedback. The IPSL model has a positive SW CRE, 0.21 ± 0.059 $Wm^{-2}K^{-1}$, indicating that clouds in the model changed in response to increased temperatures such that they reflected less solar radiation, and therefore enhanced the warming from the carbon dioxide forcing. The IPSL model has a negative LW CRE, -0.076 ± 0.017 $Wm^{-2}K^{-1}$, which means that the clouds changed in a way that decreased their LW warming effect, and thus dampened the warming from the forcing. The SW CRE outweighs the LW CRE; the net CRE is 0.13 ± 0.062 $Wm^{-2}K^{-1}$ for the IPSL model, signifying that the cloud feedback is positive. The BCC model has both a positive SW CRE, 0.096 ± 0.065 $Wm^{-2}K^{-1}$, and a positive LW CRE, 0.133 ± 0.022 $Wm^{-2}K^{-1}$, and its net CRE is a positive feedback of 0.23 ± .011 $Wm^{-2}K^{-1}$.

Figure 3 is a time-series of the net CRE for the quadrupled carbon dioxide scenario for both models. At the beginning of the time-series, right after the carbon dioxide forcing is applied, the CRE drops. This is due to the rapid adjustment (days-weeks) of clouds before the temperature of the climate system changes[2]. Such adjustments may include changes in cloud microphysics (e.g., the number or size distribution of droplets) solely due to the presence of the additional carbon dioxide in the atmosphere. Rapid adjustments are not part of the cloud feedback because they are not a response to a temperature change. The feedback response is illustrated by the slope of the net CRE curves starting after the rapid adjustment phase; the upward slope confirms that the cloud feedback for both models is positive. Figure 3 can be compared to Figure 4, the time-series of the net CRE for the pre-industrial control scenario for both models. Without the quadrupled carbon dioxide forcing, the net CRE naturally fluctuates by a small amount over time, but there is not a strong overall increasing or decreasing trend.

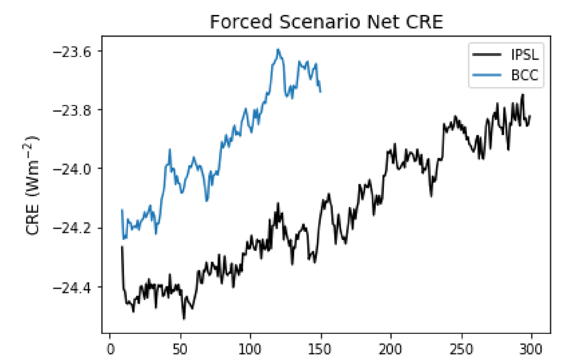

Figure 3: Time-series of forced scenario net CRE

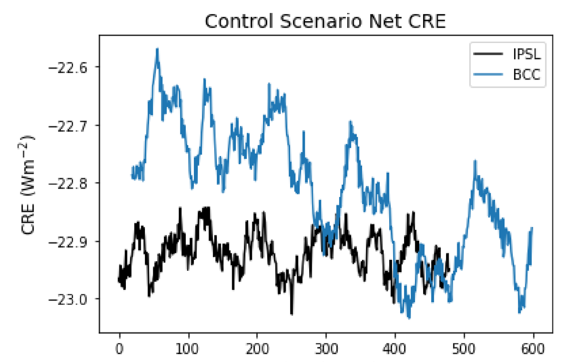

Figure 4: Time-series of control scenario net CRE

The top figures of Figure 5 display areas of the globe in dark blue if the net CRE from the last 20 years of the forced scenario was significantly different (*$p < 0.05$*) than the corresponding 20 years of the control scenario. Most areas of the globe do undergo significant changes in the net CRE due to the forcing, but there are two notable exceptions to this pattern.

RESULTS AND DISCUSSION (CONT.)

First, the mid-latitude storm tracks of the northern and southern hemispheres do not experience significant net CRE changes because their inherent natural variability makes it difficult for other signals to show through. Second, the borders between areas with positive and negative net CRE changes do not experience significant net CRE changes likely because the positive and negative signals in these transitional regions cancel each other out. Global maps that show only the areas of significant net CRE changes in color for each of the models are displayed on the bottom of Figure 5. Areas where the net CRE increased are displayed in red, and the areas where the CRE decreased are shown in blue. The red areas where net CRE increased are areas where clouds are cooling less in the forced scenario than they were in the control scenario. Note that the IPSL model has stronger trends partially due to the additional years in its dataset.

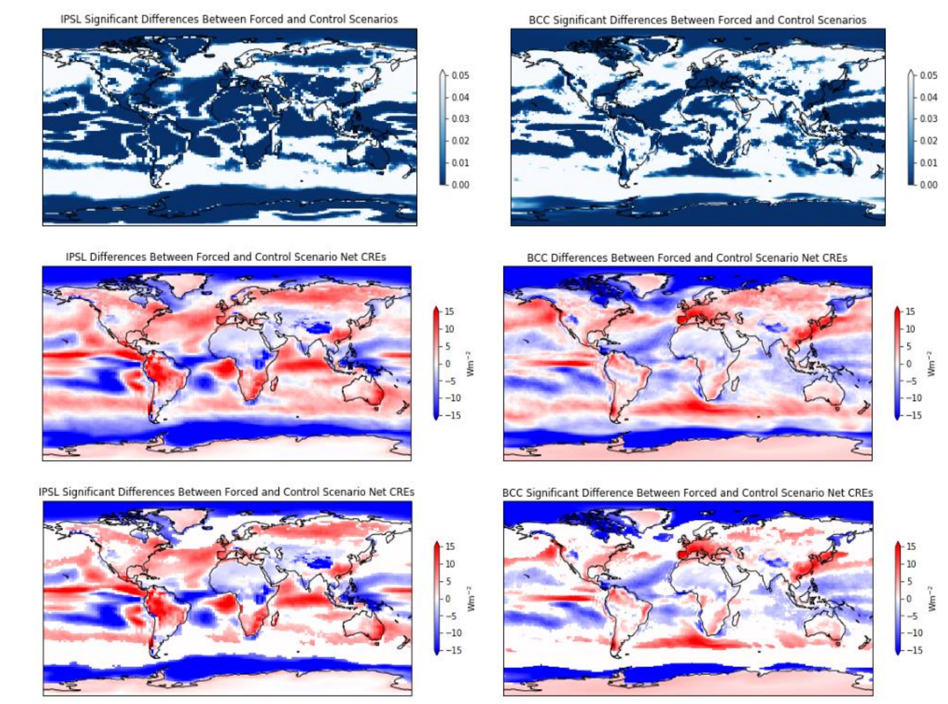

Figure 5: Global maps showing (from top to bottom): p<.05 regions, net CRE differences, p<.05 net CRE differences

The strong bands of decreasing net CRE in the high-latitudes are misleading. They are not entirely due to changes in clouds, but are instead mainly caused by changes in albedo which impact the SW clear-sky radiative flux terms in the CRE calculations; the fact that both cloud changes and albedo changes show up in CRE calculations is a limitation of using the CRE method for cloud analysis. Figure 6, shown below, displays the impact of albedo changes on the CRE data. Regions with low values on these maps are areas where it can be concluded that changes in CRE values are due to cloud changes alone.

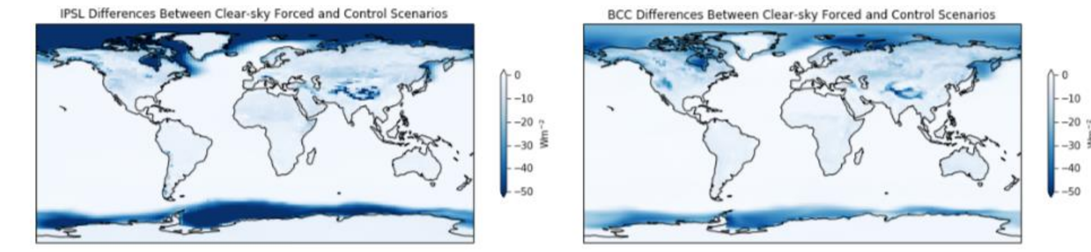

Figure 6: Global maps displaying the influence of albedo changes on CRE data

A small portion of the decreased net CRE in the high-latitudes (particularly in the BCC model, which doesn't indicate as large of a SW clear-sky effect) could possibly be attributed to the increase in high-latitude low cloud optical depth that occurs in a warmer climate[3]. As temperatures increase, atmospheric water vapor concentrations increase as well, which in turn enhances the water content of clouds. Clouds that have a higher liquid water content are optically thicker and therefore tend to reflect more solar radiation. This effect is particularly pronounced at high-latitudes because the high-latitudes warm faster than the tropics due to the positive ice-albedo feedback. The higher latitudes also tend to have more mixed-phase (liquid water and ice) clouds. The proportion of liquid water to ice in these clouds increases as temperature increases; this effect also increases the optical thickness of the clouds, causing them to reflect more radiation[3]. These processes are negative SW effects, and thus are consistent with the bands of decreased high-latitude net CREs shown in the models.

Positive SW effects, however, are the changes that tend to dominate the overall cloud feedback in most models, including this IPSL model (see the discussion under Figure 2). These changes mainly effect tropical low clouds, so they are likely the reason for the increased net CRE values in the tropics and subtropics. Many factors may cause these SW CRE changes, one of which is altered humidity levels[3].

RESULTS AND DISCUSSION (CONT.)

As global temperatures rise, the atmospheric water vapor content will rise with it, which increases the vertical gradient of specific humidity . An enhanced vertical specific humidity gradient promotes more mixing between the moist, lower boundary layer and the drier upper atmosphere; this mixing serves to decrease the water content of the lower atmosphere, which reduces the low cloud amount. A reduced low cloud amount causes less solar reflection to be reflected by clouds; this alteration in cloud properties amplifies the warming of the carbon dioxide forcing and is largely responsible for making the cloud feedback positive in many models[3].

There is also a positive cloud LW effect that occurs with atmospheric warming—this effect dominates in the BCC model (see discussion under Figure 2). The positive LW CRE is related to cloud altitude and is explained by the fixed anvil temperature (FAT) hypothesis[3]. The FAT hypothesis is based on the observation that the highest level a cloud can reach is set by temperature (since temperature is the factor that determines water vapor content). As the surface of the Earth warms in response to a positive forcing, cloud tops tend to rise to reach the same temperature they were at prior to the warming. If the atmosphere warmed and the clouds remained at their original altitude, the clouds would be at a higher temperature and would therefore give off more radiation, helping to cool the planet. Instead, by rising, the clouds emit less radiation (though this is the same magnitude of radiation they emitted prior to the warming) than if they had remained at the same altitude in the warmer world. Therefore, by rising, the clouds tend to enhance the warming of a positive forcing. This effect is most pronounced in tropical high clouds, so some of the increased net CRE values near the equator are likely caused by this effect[3]. However, some bands of decreased net CRE values are present in the tropics as well; these may be due to the changes in convectional patterns that occur as global temperatures rise.

Globally, the negative SW high-latitude low cloud effect is outweighed by the positive SW effect and the positive LW effect, causing the cloud feedback to be positive overall.

CONCLUSION

The IPSL and BCC model output both show significant changes in the net CRE over much of the globe from the pre-industrial control scenarios to the quadrupled carbon dioxide scenarios. Overall, the clouds in both models changed such that the cloud feedback was positive and enhanced the warming of the carbon dioxide forcing. The positive SW effect, likely caused by decreased tropical low cloud amounts, resulted in the IPSL model having a positive cloud feedback. The BCC model had a positive SW effect as well, though its positive LW effect, explained by the FAT hypothesis, outweighed its SW effect. The climate science community is in general agreement that the cloud feedback is positive; this project provides evidence that the newest versions of climate models are producing output that still supports this consensus. However, while the IPSL and BCC models both have positive cloud feedbacks, the BCC model appears to be far more sensitive than the IPSL model. Much research remains to be done to refine the modeling of the cloud feedback in order to reduce this inter-model spread and enhance the reliability of climate model output.

REFERENCES

Datasets obtained from: https://esgf-node.llnl.gov/search/cmip6/

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