U.S. DEPARTMENT OF ENERGY | Office of Science

DOE/SC-CM-13-001

FY 2013 First Quarter Performance Metric: Quantify the Response of High Clouds to Climate Change in New Global Climate Model Simulations

December 2012

DISCLAIMER

This report was prepared as an account of work sponsored by the U.S. Government. Neither the United States nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

Contents

1.0 Product Definition 1
2.0 Product Documentation 1
2.1 Rapid Cloud Adjustments 1
2.2 Cloud Feedbacks 3
3.0 References 5

Figures

1. Multi-model mean high cloud radiative adjustments, separated into components due to changes..... 2
2. Global mean high cloud radiative adjustments for each model (dot) and for the four-model mean..... 3
3. Multi-model mean high cloud feedbacks, separated into components due to changes in cloud. 4
4. Global mean high cloud feedbacks for each model. 5

Quantify the Response of High Clouds to Climate Change in New Global Climate Model Simulations

1.0 Product Definition

Clouds have tremendous leverage on the planet's energy budget, and any small change in their properties can strongly amplify or dampen the warming caused initially by greenhouse gases. The cumulative impact of cloud changes on the planet's energy budget that occur in response to warming is referred to as cloud feedback. The cloud feedback represents the largest and most persistent source of uncertainty in projections of future climate change. Clouds are inherently difficult to model, as their formation is governed by processes on a range of spatio-temporal scales, many of which are unresolved by current models. Thus, while all models represent clouds using the best current knowledge of their relevant physics, choices made by individual modeling centers in the representation of these sub-gridscale processes lead to a wide range of responses of clouds to a warming climate. It should come as no surprise that the best predictor of whether a global climate model warms a lot or a little from an increase in greenhouse gases is the response of clouds (Dufresne and Bony 2008).

Recent work has shown that, in addition to the temperature-mediated cloud changes discussed above, clouds respond directly to CO_2, even before the climate system begins to warm. The radiative impacts of such "rapid cloud adjustments" are better thought of as responses that modify the radiative forcing from CO_2 rather than feedbacks that evolve as the planet warms. Distinguishing between them is crucial for gaining a physical understanding of how clouds respond.

Here we use novel "satellite simulator" diagnostics (Klein and Jakob 1999) along with "cloud radiative kernels" (Zelinka et al. 2012a) to diagnose the cloud feedbacks and rapid adjustments to CO_2 in an ensemble of global climate models simulating an abrupt quadrupling of CO_2. The cloud radiative kernel technique allows for a systematic quantification of the contributions of different cloud types to the cloud feedbacks and rapid adjustments, providing unprecedented insight into their components. Here we focus on the responses of high clouds, defined as those clouds with tops at pressures less than (altitudes above) 560 hPa. At the time of this writing, four models have provided the necessary diagnostics to quantify the rapid cloud adjustments and five models have provided the necessary diagnostics to quantify the cloud feedbacks.

2.0 Product Documentation

2.1 Rapid Cloud Adjustments

In Figure 1, we break down the rapid high cloud adjustments into components due to changes in high cloud amount, altitude, and optical depth. For each component, all cloud properties are held fixed except for the one in question, as described in Zelinka et al. (2012b). Upon CO_2 quadrupling, high clouds exhibit a rapid reduction in fractional coverage, cloud top pressure, and optical depth. Thus the longwave (LW) high cloud amount and optical depth adjustments are negative and the LW high cloud altitude adjustment is positive. The opposite is the case in the shortwave (SW). All three types of gross changes to high clouds contributes positively to the net cloud adjustment, which means that high clouds change in such a

way as to increase the radiative forcing from CO_2 alone (bottom row). The largest heating effect comes from the upward shift of high clouds, which–by enhancing the greenhouse effect–provides 0.23 Wm^{-2} of additional LW heating that is essentially unopposed in the SW (middle column). This is most prominent over the continents, where anomalous land-based convection in response to CO_2 favors higher cloud tops. In contrast, the SW high cloud amount adjustment is positive but very closely compensated in the LW (left column). The net heating due to cloud amount reductions is most prominent over the mid-latitude oceans in the vicinity of the storm tracks. Finally, the rapid reduction in high cloud optical depth allows more LW radiation to escape to space, but this effect is overwhelmed by a much larger decrease in the amount of SW radiation reflected to space. This thinning of high clouds is especially prominent over the regions that climatologically experience frequent deep convection, including the Indian Ocean, West Pacific Warm Pool, and the Intertropical Convergence Zone. This rapid reduction in cloud optical depth may reflect the fact that the enhanced CO_2 concentrations decrease the radiative cooling of the atmosphere, requiring less condensational heating of the atmosphere, and therefore decreasing the amount of condensed liquid in clouds, making them less reflective.

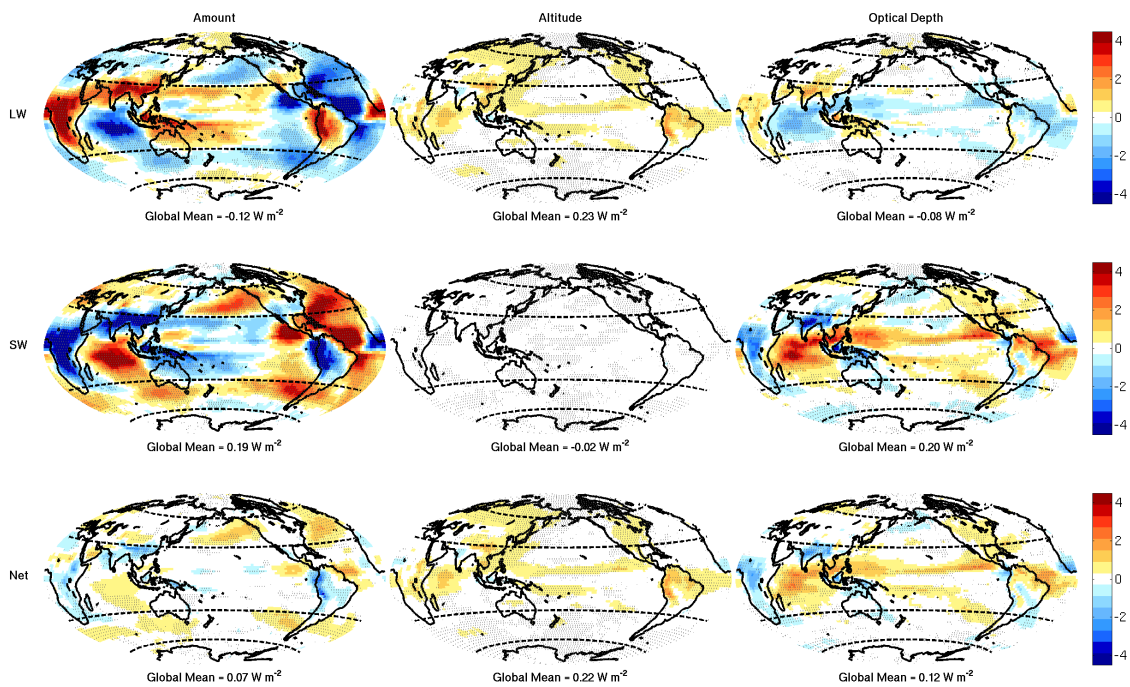

Figure 1. Multi-model mean high cloud radiative adjustments, separated into components due to changes in cloud (left) amount, (middle) altitude, and (right) optical depth for (top) LW, (middle) SW, and (bottom) LW + SW. Stippling indicates locations for which three out of four models agree on the sign of the feedback. Dashed lines are placed at 30˚ and 60˚latitude.

The global mean cloud radiative adjustments and their components are shown in Figure 2 for each of the four models (given by dots) and for the ensemble mean (given as bars). This allows for a clear identification of the adjustments that are robust and those that are not robust across models, though admittedly the sample size is currently small. The net ensemble mean high cloud adjustment is roughly 0.4 Wm^{-2}, and comes almost entirely from reductions in reflected SW radiation, though there is

considerable inter-model spread. In no model is the net cloud adjustment negative, nor are the amount, altitude, or optical depth components ever negative. Thus, it appears that the high cloud responses to CO_2 identified above (decreases in amount and optical depth and increases in altitude) occur in every model and contribute to a positive high cloud adjustment. Whereas the high cloud amount and altitude adjustments exhibit appreciable inter-model spread, the high cloud optical depth adjustment is relatively tightly constrained. The single largest contributor to the ensemble mean high cloud radiative adjustment is the upward shift of high cloud tops.

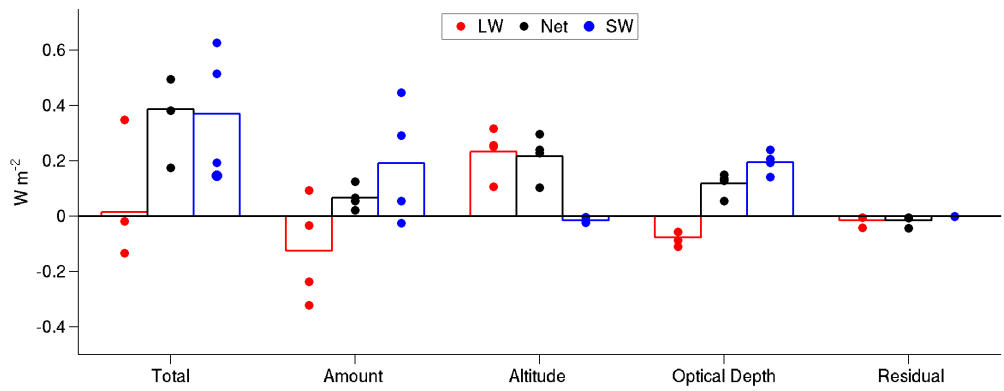

Figure 2. Global mean high cloud radiative adjustments for each model (dot) and for the four-model mean (bar), separated into (red) LW, (blue) SW, and (black) LW + SW components. The total high cloud radiative adjustments, along with their breakdown into amount, altitude, optical depth, and residual components are shown.

2.2 Cloud Feedbacks

In Figure 3 we show the ensemble mean LW, SW, and net high cloud feedbacks, broken down into its amount, altitude, and optical depth components. As the planet warms, the spatial distribution of high cloud amount changes considerably, with large increases over the equatorial Central Pacific and decreases in a horseshoe shaped region straddling this (left column). Decreases in high clouds are prevalent over the tropical continents, while the mid-latitude oceans generally exhibit increased high cloud fraction. Remarkably, despite huge local values of cloud amount feedback, the global mean LW, SW, and net cloud amount feedbacks are all identically zero. As in the case of rapid adjustments, high clouds shift higher as the planet warms, in agreement with the fixed anvil temperature hypothesis of Hartmann and Larson (2002), causing a strong positive LW cloud feedback that is essentially unopposed in the SW (middle column). The high cloud altitude feedback is quite spatially uniform, indicating that the high cloud tops are simply shifting upwards in step with the tropopause (Zelinka and Hartmann 2010). Unlike the reduction in cloud optical depth that occurs immediately upon CO_2 quadrupling, clouds become much thicker as the planet warms (right column). Increases in cloud optical depth are especially apparent for high clouds over the equatorial Pacific and over the high latitude oceans. This is likely caused by an increase in total water content as well as phase changes from ice to liquid (Tsushima et al 2006, Zelinka et al. 2012b). As in the case of rapid adjustments, cloud optical depth changes cause a much greater impact on the SW budget of the planet than on the LW. Thus, the net high cloud optical depth feedback is negative, though still less than half as large as the net high cloud altitude feedback.

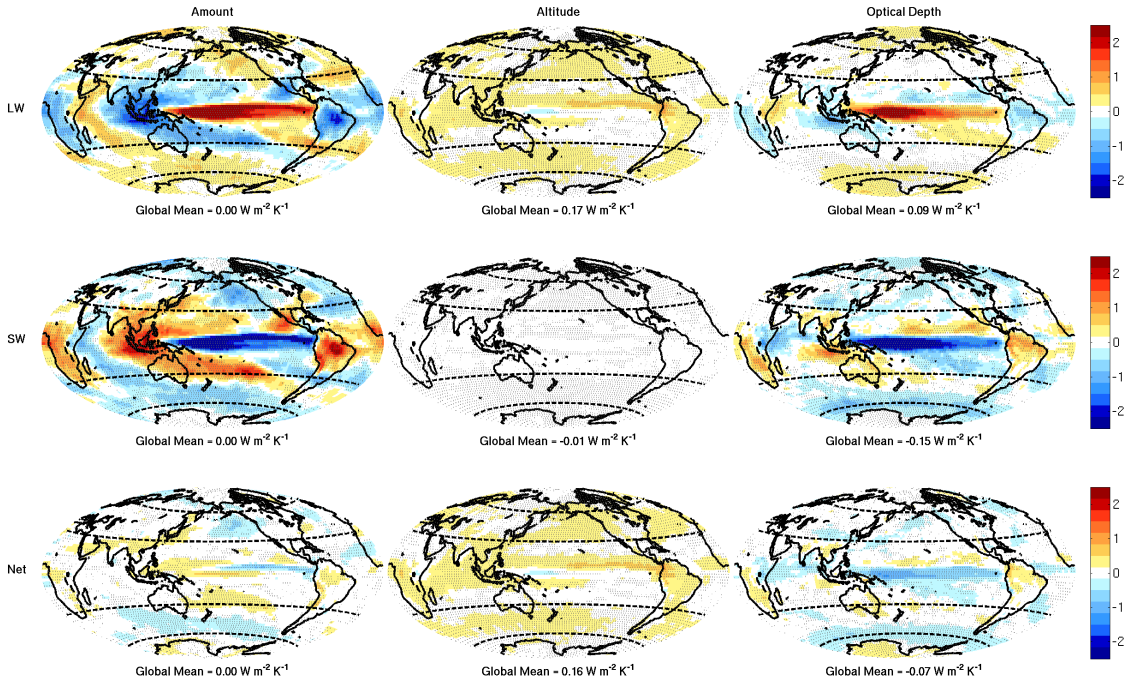

Figure 3. Multi-model mean high cloud feedbacks, separated into components due to changes in cloud (left) amount, (middle) altitude, and (right) optical depth for (top) LW, (middle) SW, and (bottom) LW + SW. Stippling indicates locations for which four out of five models agree on the sign of the feedback. Dashed lines are placed at 30˚ and 60˚ latitude.

The global mean cloud feedbacks and their components for each of the five models (given by dots) and for the ensemble mean (given as bars) are shown in Figure 4. Large inter-model spread in the LW and SW high cloud feedbacks compensate, giving a much smaller spread in the net high cloud feedback from essentially zero to weakly positive. This compensation is almost perfect for high cloud amount changes, for which the large inter-model spread in both LW and SW components disappears when they are summed, resulting in a very tightly constrained net high cloud amount feedback near zero. In contrast, the net high cloud altitude feedback, which arises purely from the LW component, is robustly positive, in agreement with expectations (Zelinka and Hartmann 2010). High cloud optical depth feedback is negative in the ensemble mean and for four out of five models, and is governed by the strength of the SW component. As was the case for the rapid high cloud adjustments, the upward shift of cloud tops is the single largest component of the high cloud feedback in the ensemble mean.

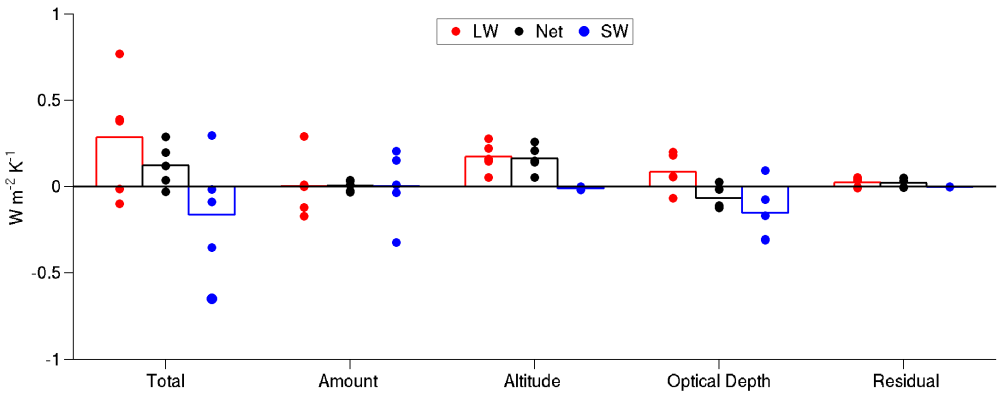

Figure 4. Global mean high cloud feedbacks for each model (dot) and for the four-model mean (bar), separated into (red) LW, (blue) SW, and (black) LW + SW components. The total high cloud feedbacks, along with their breakdown into amount, altitude, optical depth, and residual components are shown.

3.0 References

Dufresne JL and S Bony. 2008. "An assessment of the primary sources of spread of global warming estimates from coupled atmosphere–ocean models." *Journal of Climate* 21:5135–5144. DOI:10.1175/2008JCLI2239.1.

Hartmann DL and K Larson. 2002. "An important constraint on tropical cloud-climate feedback." *Geophysical Research Letters* 29:1951. DOI:10.1029/2002GL015835.

Klein SA and C Jakob. 1999. "Validation and sensitivities of frontal clouds simulated by the ECMWF model." *Monthly Weather Review* 127:2514–2531.

Tsushima Y, S Emori, T Ogura, M Kimoto, MJ Webb, KD Williams, MA Ringer, BJ Soden, B Li, and N Andronova. 2006. "Importance of the mixed-phase cloud distribution in the control climate for assessing the response of clouds to carbon dioxide increase: A multi-model study." *Climate Dynamics* 27:113–126.

Zelinka MD and DL Hartmann. 2010. "Why is longwave cloud feedback positive?" *Journal of Geophysical Research* 115:D16117. DOI:10.1029/2010JD013817.

Zelinka MD, SA Klein, and DL Hartmann. 2012a. "Computing and partitioning cloud feedbacks using cloud property histograms. Part I: Cloud radiative kernels." *Journal of Climate* 25:3715–3735. DOI:10.1175/JCLI-D-11-00248.1.

Zelinka MD, SA Klein, and DL Hartmann. 2012b. "Computing and partitioning cloud feedbacks using cloud property histograms. Part II: Attribution to changes in cloud amount, altitude, and optical depth." *Journal of Climate* 25:3736–3754. DOI:10.1175/ JCLI-D-11-00249.1.

U.S. DEPARTMENT OF
ENERGY

Office of Science