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# The vertical distribution of cloud feedback in coupled ocean-atmosphere models

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[1] We assess the vertical distribution of cloud feedbacks in coupled climate models, taking care to distinguish between cloud feedbacks and a change in cloud forcing. We show that the effect of cloud changes on the longwave fluxes provides a strong positive feedback that is broadly consistent across models. In contrast, the effect of cloud changes on the shortwave fluxes ranges from a modest negative to a strong positive feedback, and is responsible for most of the intermodel spread in net cloud feedback. The feedback from high clouds is positive in all models, and is consistent with that anticipated by the Proportionately Higher Anvil Temperature hypothesis over the tropics. In contrast, low cloud cover is responsible for roughly three-quarters of the difference in global mean net cloud feedback among models, with the largest contributions from regions associated with low-level subtropical marine cloud systems. **Citation:** Soden, B. J., and G. A. Vecchi (2011), The vertical distribution of cloud feedback in coupled ocean-atmosphere models, *Geophys. Res. Lett.*, *38*, L12704, doi:10.1029/2011GL047632.

## 1. Introduction

[2] Climate models exhibit a large range of sensitivities in response to increased greenhouse gas concentrations and much of this discrepancy is attributable to differences in their treatment of clouds [*Cess et al.*, 1990; *Bony et al.*, 2006; *Stephens*, 2005; *Webb et al.*, 2006]. It is useful, when approaching this problem, to understand which aspects of cloud feedback are consistent across climate models and which are not. The consistent aspects presumably derive from a robust physical mechanism in these models, while the inconsistent aspects are more likely to arise from details of the physical parameterizations that are specific to an individual model. By identifying the robust aspects of cloud feedback, we hope to facilitate theories that can explain the behavior, thereby increasing our understanding of this common response. Similarly, by highlighting those aspects of cloud feedback which differ among models, we hope to identify regions or types of clouds where improvements in modeling are needed.

[3] Several studies have diagnosed climate feedbacks in GCM simulations prepared for the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC-AR4) [*Bony et al.*, 2006; *Forster and Taylor*, 2006; *Ringer et al.*, 2006; *Soden and Held*, 2006; *Soden et al.*, 2008; *Webb et al.*, 2006; *Dufresne and Bony*, 2008; *Zelinka and Hartmann*, 2010]. Cloud feedback has been demonstrated to be the dominant source of intermodel spread in climate sensitivity in these models and low-level clouds are believed to be the primary contributor to this spread [*Webb et al.*, 2006; *Williams and Tselioudis*, 2007; *Medeiros et al.*, 2008]. Other studies have also identified systematic biases in the model simulations of low cloud cover and its response to changes in climate [*Zhang et al.*, 2005; *Bony and Dufresne*, 2005; *Clement et al.*, 2009], although some GCMs appear to show a sensitivity of subtropical low clouds to SST that is comparable to that in observations [e.g., *Broccoli and Klein*, 2010]. Others have argued that much of the uncertainty arises from rapid cloud adjustments that are a direct response of clouds to changes in carbon dioxide rather than to changes in surface temperature [*Gregory and Webb*, 2008; *Andrews and Forster*, 2008].

[4] In this study, we extend the above analyses by looking at a larger group of modeling results with an emphasis on the horizontal and vertical structure of cloud feedback. The regional patterns of cloud feedback are diagnosed separately for low and high clouds, on the basis of their impact on shortwave and longwave fluxes. We are also careful to distinguish between cloud feedbacks and changes in "cloud forcing". However, because we are analyzing transient simulations from coupled models, we are not able to distinguish changes which may arise directly from CO2 increase from those which are a response to surface temperature change. By analyzing cloud feedback as a function of region and altitude, we provide a clearer picture of the physical processes which underlie the intermodel spread in global mean cloud feedback and highlight several aspects of cloud feedback which are robust across models.

## 2. Data and Methods

[5] We use the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (formerly known as the IPCC-AR4 database) to identify patterns of robust and non-robust behavior in cloud feedback across models. Analyses are performed for climate change simulations from 12 different coupled climate models integrated under a transient climate change scenario in which atmospheric $CO_2$ increases at 1% per year until the concentration of $CO_2$ is doubled, at which point the concentrations are held constant for the remainder of the integration. Table S1 of the auxiliary material summarizes the models used here.[1] For each of the models we use only one ensemble member. While we only present results from

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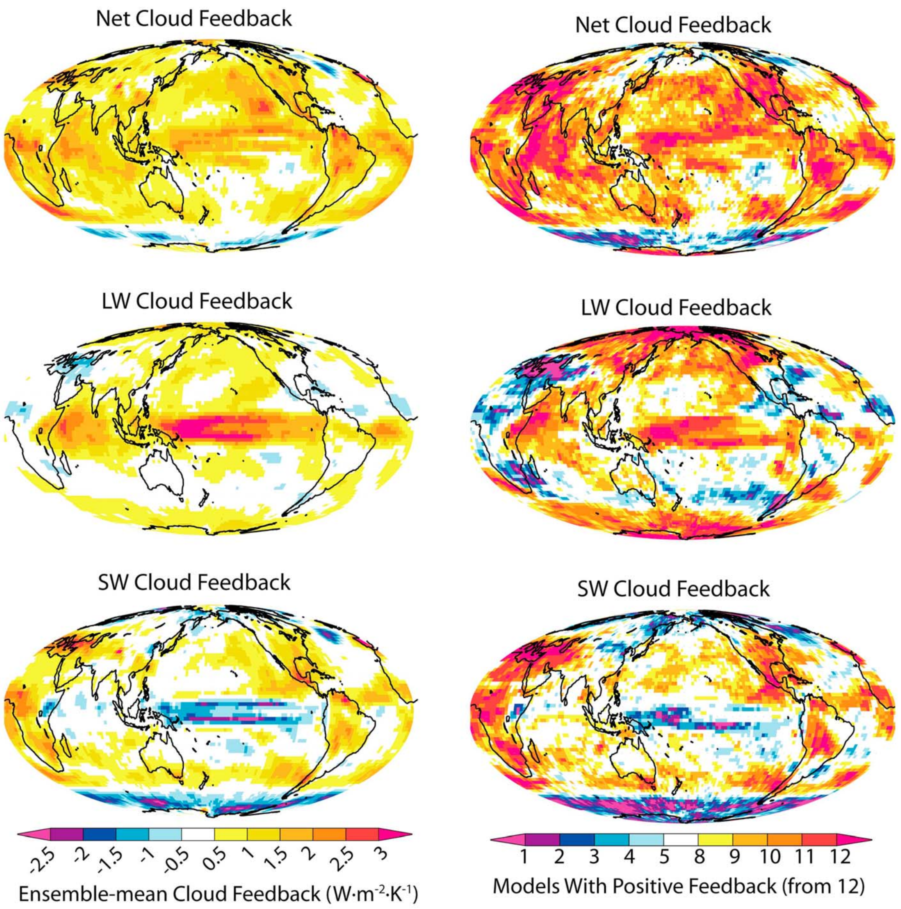

**Figure 1.** (left) Maps of the multi-model ensemble mean (top) net, (middle) longwave, and (bottom) shortwave cloud feedback in units of W/m$^2$/K. (right) The number of models (out of a total of 12) for which the cloud feedback is positive for (top) net, (middle) longwave and (bottom) shortwave.

this set of model experiments, similar behavior is noted in other scenarios (e.g., A1b, 4xCO2).

[6] We estimate cloud feedback using as input the change in cloud radiative forcing, defined as the difference in net radiation $R$ at the top of the atmosphere between clear-sky and total-sky conditions; $C_{RF} = R_{clr} - R$. We examine the change in cloud radiative forcing between the first 20 years and last 20 years of the 21st Century and normalize this difference by the corresponding change in global mean surface temperature (denoted as $\Delta C_{RF}$).

[7] However, as shown by *Colman* [2003] and *Soden et al.* [2004], to correctly interpret the changes in cloud radiative forcing as a cloud feedback, one must account for the effects of clouds in masking both the external radiative forcing and the non-cloud feedbacks. For example, an increase in CO$_2$ while holding all other variables fixed would reduce the contrast between the clear-sky and total-sky fluxes, resulting in $\Delta C_{RF} < 0$ even though no changes in cloud (or other variables) had occurred. Similar biases arise in $\Delta C_{RF}$ from changes in temperature, water vapor and surface albedo. In this study, we adjust the cloud radiative forcing to correct for these effects using the method outlined by *Soden et al.* [2008]. As demonstrated in that study, the adjusted change in cloud radiative forcing provides a more accurate description of the regional structure and sign of cloud feedback. This correction has its largest effect on the longwave forcing, tending to make longwave cloud feedback more positive than the change in longwave cloud forcing. The magnitudes of these adjustments are typically ~0.5 W/m$^2$/K on the global-mean, but can be as large as 1.5–2.0 W/m$^2$/K in some regions. Full details of these corrections and their regional structure are presented by *Soden et al.* [2008].

## 3. Results

### 3.1. Regional Structure of Multi-model Means

[8] Figure 1 (left) displays maps of the multi-model ensemble-mean net cloud feedback (Figure 1, top), longwave cloud feedback (Figure 1, middle) and shortwave cloud feedback (Figure 1, bottom) for annual mean conditions in response to a doubling of CO$_2$. The right-hand column displays the corresponding maps of the number of models (out of a total of 12) for which the annual mean cloud feedback is positive, and provides insight into the commonality of the patterns noted in the multi-model mean. Positive values of net cloud feedback dominate the multi-model mean, with maximum values occurring over convectively active land and ocean regions. Positive feedbacks are also found over the majority of subtropical to mid-latitude oceans and over virtually all land regions. Negative values of net cloud feedback are generally restricted to the high latitude southern oceans and the northern Atlantic. Maps of the net cloud feedback for

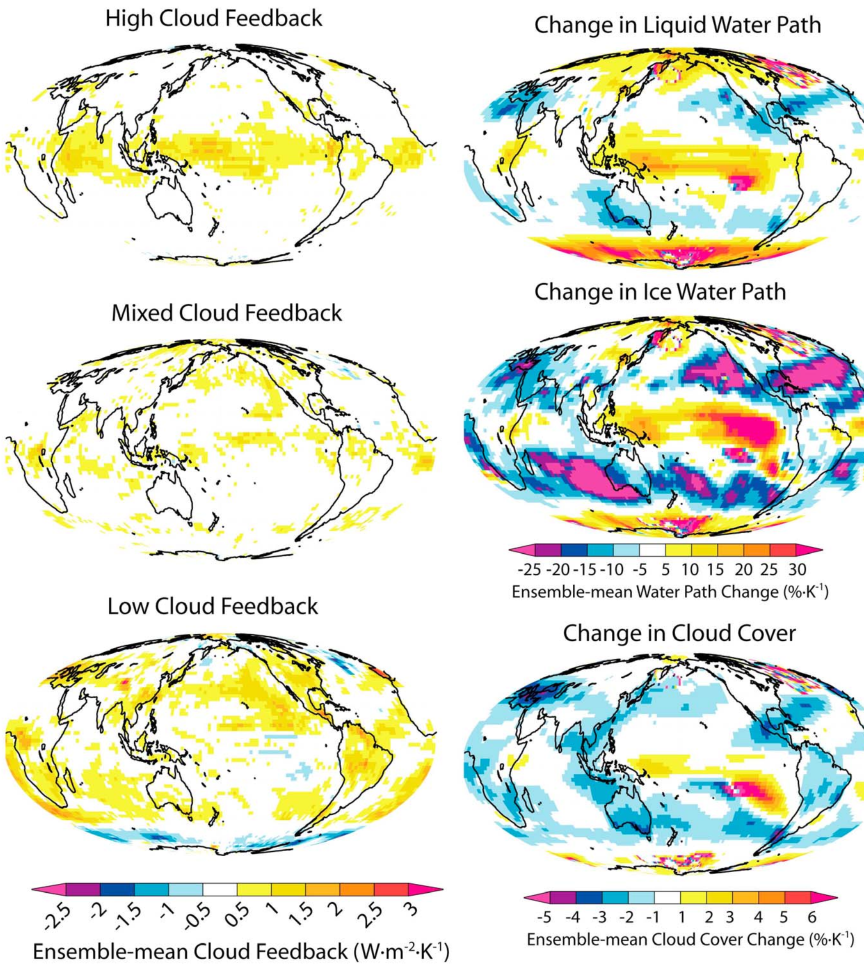

**Figure 2.** (left) Maps of the multi-model ensemble mean feedback from (top) high clouds, (middle) mixed clouds, and (bottom) low clouds in units of $W/m^2/K$. (right) The multi-model ensemble mean change in (top) cloud liquid water path, (middle) cloud ice water path and (bottom) cloud amount in units of %/K. All changes were first normalized by the global mean surface air temperature change before ensemble averaging.

each of the individual models and the internodel variance in net, longwave, and shortwave cloud feedback are provided in the auxiliary material (Figures S1 and S2, respectively).

[9] When separated into the longwave (LW) and shortwave (SW) components, the LW feedback is positive over most ocean regions, with a distinct maximum along the equator, and near-neutral to slightly negative values over many subtropical land regions. In contrast, the SW cloud feedback is positive over most land regions, but can be either positive or negative over the oceans. In particular, the negative net feedback over the high-latitude oceans is attributable to a strong negative SW feedback from clouds. The equatorial Pacific is also characterized by a strong negative SW feedback, but it is more than compensated for by a large positive LW feedback. These large, but offsetting values of LW and SW feedback coincide with regions of increased convective mass flux which is generally restricted to the equatorial Pacific in these models [*Vecchi and Soden*, 2007a]. The equatorial Pacific is also one of the few regions which show a consistent increase in cloud cover, liquid water path and ice water path in the models (Figure 2).

[10] Following *Webb et al.* [2006], we separate the net cloud feedback into contributions from high, low, and mixed clouds based upon their SW and LW values. Low clouds are distinguished by having a large feedback in the SW (either positive or negative), but little effect on the LW (categories A, E of *Webb et al.* [2006]); whereas high clouds are distinguished by having large, but opposing feedbacks in both the SW and LW (categories B, C, F, G). The "mixed" category refers to regions which have feedbacks in the LW with no change in the SW or a change which is of the same sign (categories D, H). The feedback from mixed clouds are generally positive and interpreted as regions which experience an increase in thin high clouds and either no change or a slight reduction in low clouds. The reader is referred to *Webb et al.* [2006] for complete details on this method.

[11] Maps of the multi-model mean net radiative feedback from high (Figure 2, top), mixed (Figure 2, middle) and low clouds (Figure 2, bottom) derived in this fashion are shown in Figure 2 (left). High clouds provide a positive feedback in a narrow belt along the tropical convergence zones, due primarily to the large positive feedbacks on the longwave fluxes noted above. This feature is a robust projection of the models - the vast majority of which simulate a positive high cloud feedback over this region, and this is the only region for which such commonality in the sign of the response is found.

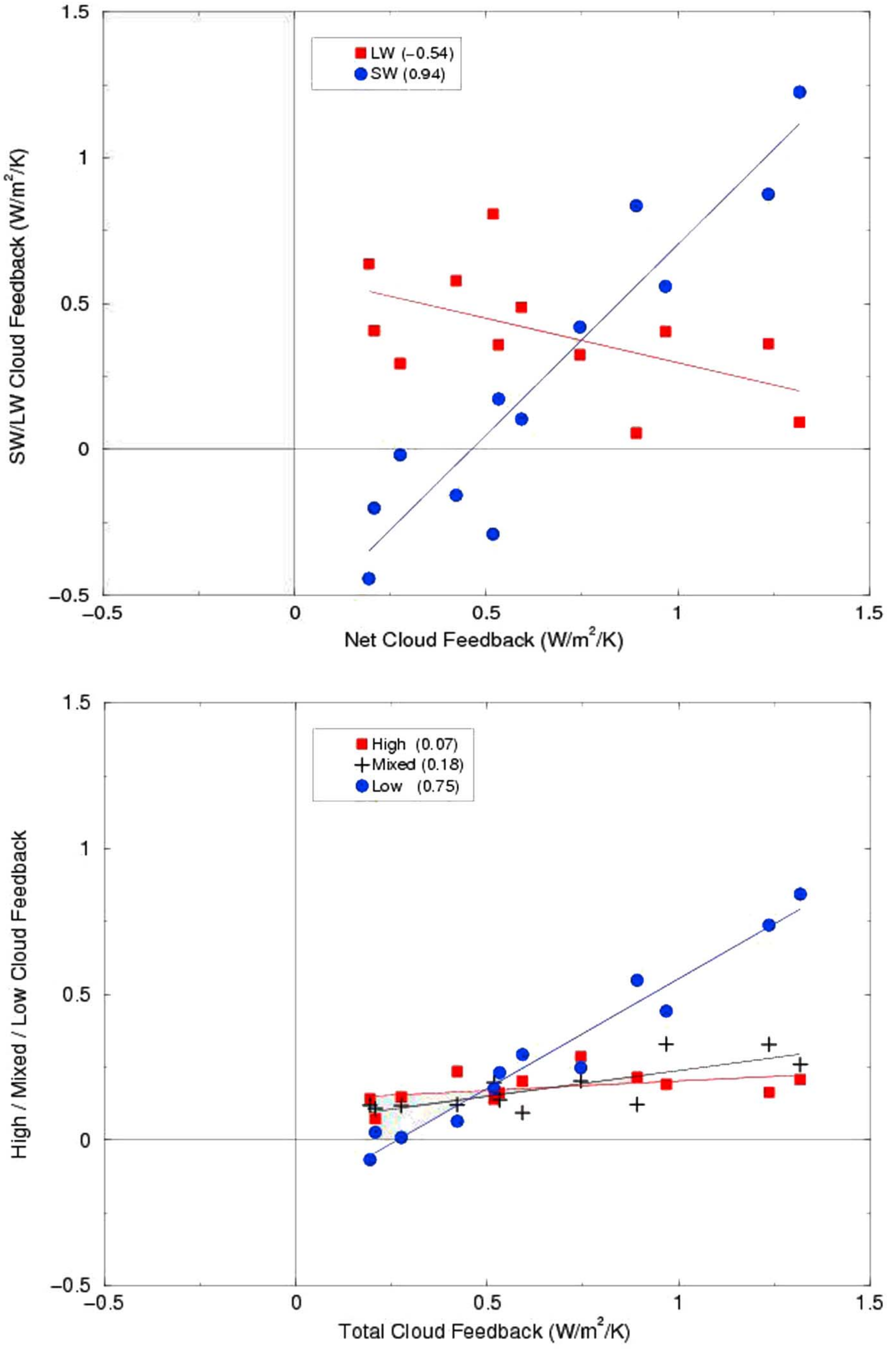

**Figure 3.** (top) Scatter plot of the global mean net cloud feedback for each model as a function of the corresponding global mean LW (red square) and SW (blue circle) feedback in that model. (bottom) Scatter plot of the global mean net cloud feedback as a function of the feedback from high clouds (red), mixed clouds (black cross) and low clouds (blue). The slope of the linear, least-squares regression is listed in parentheses.

[12] The similarity of the response suggests a simple underlying mechanism. *Zelinka and Hartmann* [2010] have shown that model predictions for high clouds are consistent with the "Proportionately Higher Anvil Temperature" (PHAT) hypothesis – a modification of the "Fixed Anvil Temperature" hypothesis originally proposed by *Hartmann and Larson* [2002]. *Zelinka and Hartmann* [2010] show that assuming the high-cloud temperature follows the upper tropospheric convergence-weighted temperature provides an excellent prediction of the longwave cloud feedback in the AR4 models. The tendency of the tropical cirrus anvils to conserve cloud top temperature reduces the rate at which the TOA LW emission will increase in response to a surface warming and results in a positive feedback. We note that the uniformity of the high cloud feedback in the absence of any similarly-uniform changes in cloud amount or ice water path (Figure 2, right) is consistent with a feedback which results from a vertical re-distribution of clouds, rather than a change in cloud amount or optical properties.

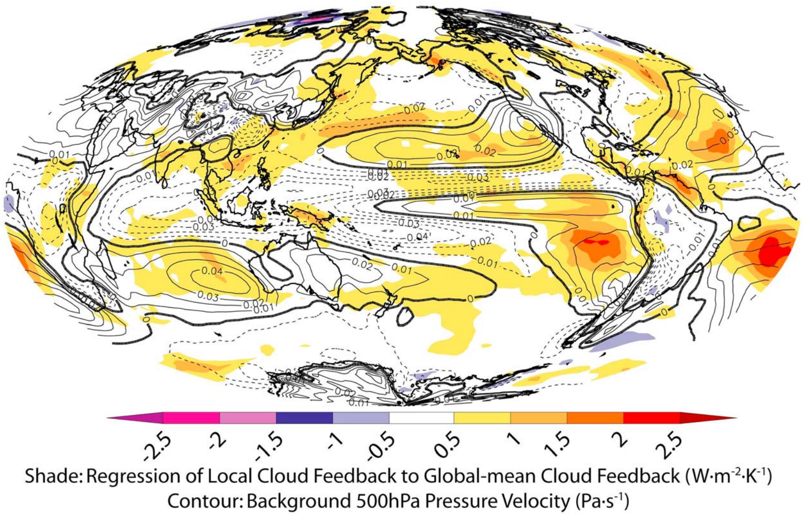

**Figure 4.** The intermodel regression of the global mean cloud feedback against the local cloud feedback for the 12 models used (see Table S1). Larger values of the highlight those areas which contribute the most to the intermodel spread in global mean net cloud feedback. The multi-model ensemble-mean 500 hPa pressure velocity from the first 20 years of the model integrations are shown in contours.

[13] In contrast to high clouds, the low cloud feedback (Figure 2, bottom left) is positive over low to middle latitude ocean and land areas, consistent with a reduction in cloud amount (Figure 2, bottom right) and liquid water path (Figure 2, top right) in these regions. The changes in cloud cover are predominantly negative and likely tied to the widespread reduction in free-tropospheric relative humidity in these models. In response to increased $CO_2$, the marine subtropical regions in these models generally exhibit increased mid-tropospheric subsidence [e.g., *Lu et al.*, 2007; *Vecchi and Soden*, 2007a] and an associated decrease in lower tropospheric relative humidity [e.g., *Vecchi and Soden*, 2007b]. It is worth noting, however, that most GCMs underestimate both the low cloud amount [*Zhang et al.*, 2005] and their sensitivity to interannual SST changes [*Bony and Dufresne*, 2005].

[14] Low clouds are also responsible for the regions of negative net cloud feedback over the high latitude southern and northern Atlantic oceans. The regions of negative low cloud feedback are associated with substantial increases in the cloud liquid water path, but little change in cloud amount; implying that it is the brightening of existing clouds which is primarily responsible for the negative feedback. These are associated with the poleward shift of storm tracks which results in the location of a positive feedback on their equatorial flank.

### 3.2. Intermodel Differences

[15] To investigate the contribution of LW and SW cloud feedbacks to the intermodel differences in net cloud feedback, Figure 3 (top) plots the global, annual-mean SW and LW cloud feedback against the net cloud feedback for each of the 12 models. The global-mean net cloud feedback ranges from ~0.25 $W/m^2/K$ to ~1.5 $W/m^2/K$. All models show a positive global-mean LW cloud feedback (red), with the majority of models clustering near 0.5 $W/m^2/K$. However, there exists little relation between a model's LW and net cloud feedback, although a slight tendency for larger LW feedbacks to be associated with smaller net feedbacks is evident. In contrast, the SW cloud feedback (blue) exhibits a noticeably larger range ($-0.5$ to 1.25 $W/m^2/K$) and has a much higher correlation with changes in net cloud feedback ($r = 0.94$).

[16] Figure 3 (bottom) plots the global-mean high, mixed and low cloud feedback versus the corresponding total cloud feedback for each model. Since the sum of the high, mixed, and low cloud feedback add up to the total feedback, the slope of the regression line (listed in parentheses) provides a measure of the contribution of each cloud type to the intermodel range of the total feedback. The intermodel spread in the net cloud feedback is largely attributable to discrepancies in their projected feedback from low clouds, which contribute roughly 75% of the intermodel spread. Differences in high cloud feedback are responsible for only about 7% of the spread in total cloud feedback, and the feedback from mixed clouds contributes the remaining 18%.

[17] To further assess which cloud types are responsible for the intermodel differences in net cloud feedback, we regress the local change in cloud feedback for each model against the corresponding global mean net cloud feedback for that model. The regressions are computed across model space using annual mean values for all 12 models. A map of the regression slope (Figure 4) highlights those areas for which the intermodel spread in global mean net cloud feedback is most strongly associated with the changes in cloud cover in that region. The regression values are negative in these regions, indicating that models with increased (decreased) marine low clouds tend to have anomalously small (large) values of global-mean net cloud feedback. That is, the strong positive cloud feedback in high sensitivity models is primarily attributable to their simulated reduction in low-level marine clouds. Overlain are contours of the ensemble-mean 500 hPa pressure velocity. The largest regional contributions to the intermodel spread in cloud feedback occur over areas of large-scale subsidence typically associated with subtropical marine low clouds, including both stratocumulus and trade cumulus regimes. While local maxima tend to coincide with traditional stratocumulus regions in the eastern ocean basins, the contributions from trade cumulus regions further to the

west are smaller in magnitude but more spatially extensive. We note that regression of local cloud amount versus global mean cloud feedback (Figure S3) yields very similar results, suggesting that it is primarily changes in low cloud amount rather than low cloud optical properties which drive the intermodel spread in cloud feedback.

## 4. Summary

[18] We compare the cloud feedback simulated in 12 coupled climate models from the CMIP3 database (also used in the IPCC-AR4). Consistent with previous studies [*Colman*, 2003; *Soden and Held*, 2006; *Soden et al.*, 2008] the total cloud feedback is neutral to positive in all models. The consistently positive nature of the cloud response is primarily attributable to a strongly positive LW feedback, whereas the intermodel spread arises principally from differences in the SW feedback, which ranges from modestly negative to strongly positive. We find that high clouds provide a relatively consistent and weakly positive feedback in these models, whereas low cloud feedback is variable in both magnitude and sign. The uncertainty in low clouds is shown to originate primarily from regions of subtropical subsidence and marine stratocumulus and trade cumulus clouds, suggesting that efforts to reduce uncertainty in cloud feedback should focus on this cloud type. These results both support and extend previous work [e.g., *Webb et al.*, 2006; *Williams and Tselioudis*, 2007; *Wyant et al.*, 2006] by quantifying the contribution of low clouds to the intermodel spread in global mean cloud feedback, and highlighting the robustness of positive longwave feedback by taking into account the distinction between cloud feedback and changes in cloud forcing.

[19] Low clouds are not only a source of inconsistency among models, but their simulation is also known to be deficient in most models. It has been shown that most GCMs underestimate the occurrence of low-level clouds [*Zhang et al.*, 2005]; and underestimate their sensitivity to interannual SST changes [*Bony and Dufresne*, 2005]. Decadal trends in satellite-observed radiative fluxes also tentatively suggest a decrease in low cloud cover over the past two decades [*Wong et al.*, 2006] that may lay outside the current range of GCM simulations.

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