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Recent progress toward reducing the uncertainty in tropical low cloud feedback and climate sensitivity: a review

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Abstract

Equilibrium climate sensitivity (ECS) to doubling of atmospheric CO_2 concentration is a key index for understanding the Earth's climate history and prediction of future climate changes. Tropical low cloud feedback, the predominant factor for uncertainty in modeled ECS, diverges both in sign and magnitude among climate models. Despite its importance, the uncertainty in ECS and low cloud feedback remains a challenge. Recently, researches based on observations and climate models have demonstrated a possibility that the tropical low cloud feedback in a perturbed climate can be constrained by the observed relationship between cloud, sea surface temperature and atmospheric dynamic and thermodynamic structures. The observational constraint on the tropical low cloud feedback suggests a higher ECS range than raw range obtained from climate model simulations. In addition, newly devised modeling frameworks that address both spreads among different model structures and parameter settings have contributed to evaluate possible ranges of the uncertainty in ECS and low cloud feedback. Further observational and modeling approaches and their combinations may help to advance toward dispelling the clouds of uncertainty.

Keywords: Climate sensitivity, Cloud feedback, Multi-model ensemble, Perturbed physics ensemble

Introduction

Physical predictions of the Earth's climate variability and changes are ongoing challenges for the geoscience community. Uncertainty in equilibrium climate sensitivity (ECS), determined by global mean surface air temperature (SAT) increase at a state of climatic equilibrium according to doubling of atmospheric CO_2, is an unresolved issue in the climate science (e.g., Knutti and Hegerl 2008). While climate scientists are devoted to the development of realistic and reliable climate models, the uncertainty range of the modeled ECS has not been reduced efficiently since the Charney report (Charney et al. 1979) published in 1979 (Maslin and Austin 2012). The state-of-the-art estimates of ECS and transient climate response (TCR; a response of global-mean SAT to a gradually increasing atmospheric CO_2 concentration) from historical observations also have substantial uncertainty (e.g., Flato et al. 2014) due to difficulty in accurate estimations of ocean heat uptake and forcing (e.g., Yoshimori et al. 2016). Inter-model spread in feedback between the cloud and the top of the atmosphere (TOA) radiation, particularly shortwave reflectance due to cloud in the tropics, has been suggested to be the major factor for the uncertainty in ECS (e.g., Cess et al. 1990; Dufresne and Bony 2008; Boucher et al. 2014; Caldwell et al. 2016). In contrast to a less uncertain cloud feedback over land (Kamae et al. 2016a), large uncertainty in cloud feedback over the ocean contributes predominantly to the total spread of modeled ECS (e.g., Bony and Dufresne 2005; Webb et al. 2006; Vial et al. 2013).

Recent enormous challenges for quantifying and reducing the uncertainty in cloud feedback have been led by an international research framework called Cloud Feedback Model Intercomparison Project (CFMIP; e.g., Bony et al. 2015; Webb et al. 2016). In the CFMIP framework together with related research projects, a variety of approaches have been conducted: multi-model ensemble

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using climate models developed by different modeling centers independently (e.g., Andrews et al. 2012a; Zelinka et al. 2013; Vial et al. 2013), perturbed physics ensemble (PPE; detailed in a later section) focusing on the sensitivity of model physics (e.g., cumulus convection, cloud microphysics, and turbulence) on parameter settings (e.g., Collins et al. 2011; Klocke et al. 2011; Shiogama et al. 2012), climate models which have physics schemes swapped (Gettelman et al. 2012; Watanabe et al. 2012b) or turned off (Webb et al. 2015), simplified aqua planet simulations (e.g., Wang et al. 2012; Stevens and Bony 2013; Medeiros et al. 2014), single column models simulating one-dimensional atmospheric column (e.g., Zhang et al. 2013; Dal Gesso et al. 2015), high-resolution models resolving the cloud-convection system (Wyant et al. 2009; Sato et al. 2014; Bretherton 2015), or large eddy simulations (LES; e.g., Blossey et al. 2013; Bretherton et al. 2013; Bretherton and Blossey 2014). Satellite observations have been applied to assess the performance of climate model simulations and evaluate cloud feedback in a warming climate by using satellite simulators implemented in climate models (e.g., Klein and Jakob 1999; Webb et al. 2001; Bodas-Salcedo et al. 2011; Pincus et al. 2012).

One of the recent remarkable progresses is quantitative decomposition and physical understanding of the different roles of surface temperature-mediated changes and adjustment of the climate system to the imposed external forcing (Gregory and Webb 2008; Kamae and Watanabe 2013; Andrews and Ringer 2014; Ogura et al. 2014). Decomposition of the temperature-mediated cloud change (cloud feedback) and rapid cloud adjustment to increasing CO_2 contribute to accurate evaluations of cloud feedback (Watanabe et al. 2012a; Webb et al. 2013; Vial et al. 2013; Zelinka et al. 2013). Comprehensive reviews on the rapid cloud adjustment can be found in Andrews et al. (2012b), Sherwood et al. (2015), and Kamae et al. (2015).

Cloud feedback contributing to the uncertainty in ECS has been evaluated by being separated into different cloud properties (fractional coverage, cloud top height, and optical depth; Zelinka et al. 2013; Boucher et al. 2014). In addition to the tropical low cloud feedback, feedbacks due to tropical high clouds (Hartmann and Larson 2002; Zelinka and Hartmann 2010; Mauritsen and Stevens 2015) and middle latitude mixed-phase clouds (Zelinka et al. 2012b; Ceppi and Hartmann 2015; Ceppi et al. 2016; Tan et al. 2016) have also attracted much attention because of its importance for the total uncertainty in cloud feedback and resultant ECS uncertainty. In this paper, we review the recent progress and remaining issues on understanding of the tropical low cloud feedback. Recently, observational constraints of the low cloud feedback and evaluation of possible uncertainty ranges including sensitivity of physics schemes have much advanced. We mainly introduce two papers (Sherwood et al. 2014; Qu et al. 2015b) as examples of the recent works on the observational constraint of the low cloud feedback. In addition, we pick up and introduce a series of modeling approaches evaluating parametric and structural uncertainty in cloud feedback and ECS. Stephens (2005); Boucher et al. (2014); Fasullo et al. (2015); Klein and Hall (2015); and Bretherton (2015) also provided comprehensive reviews on the uncertainty in cloud feedback and ECS.

Observed and modeled variations in tropical low cloud

For physical predictions of change in shortwave reflectance due to tropical low cloud cover (LCC) in a warming climate, regional and temporal correspondences between LCC and large-scale conditions were examined by observations and models (Table 1). In this paper, we mainly discuss LCC change over the subtropical ocean where stratocumulus and cumulus clouds dominate. Subtropical boundary layer (BL) cloud typically exists over the regions characterized by low sea surface temperature (SST), strong capping inversion, middle tropospheric subsidence, and cold air advection at the surface (Klein et al. 1995). Clement et al. (2009) found that the northeast Pacific LCC, lower tropospheric inversion, and vertical velocity at 500 hPa are positively correlated over interannual and decadal time scales. The respective contribution of each large-scale property to the LCC change was examined by seasonal, interannual, and decadal correspondences between the two (e.g., Myers and Norris 2013, 2015). Here, we should note that a stronger regional anomaly compared with the tropical mean (e.g., stronger subsidence) does not necessarily correspond to an increase in LCC (detailed below; Myers and Norris 2013). Increasing SST, frequently used as a surrogate of climate change (Cess et al. 1990; Ringer et al. 2014), generally results in a reduced LCC through changes in surface latent heat flux and moisture contrast between the BL and free troposphere (FT). Increased surface latent heat flux enhances mixing of the dry FT air and moist BL, leading to a deeper BL and a less LCC (Chung and Teixeira 2012; Rieck et al. 2012). Moister BL under a higher SST condition (via increased surface moisture supply) results in an enhanced BL–FT moisture contrast. The enhanced contrast leads to a stronger drying effect of the mixing of the FT air at the capping inversion, resulting in a reduced LCC (Brient and Bony 2013) and a deeper BL (van der Dussen et al. 2015). In addition, uncertainty in regional SST warming pattern is tightly associated with cloud feedback through changing large-scale

Table 1 Factors for low cloud feedback

	Change in a warming environment	Resultant changes in BL and cloud	Resultant low cloud feedback
SST (Hanson 1991; Clement et al. 2009)	Increasing	Deeper BL, less cloud	Positive
SST-related process: Surface evaporation (Chung and Teixeira 2012; Rieck et al. 2012)	Increasing	Deeper BL, less cloud	Positive
SST-related process: Moisture contrast at inversion (Brient and Bony 2013; van der Dussen et al. 2015)	Increasing	Deeper BL, less cloud	Positive
Strength of inversion (Klein and Hartmann 1993; Wood and Bretherton 2006)	Increasing	Shallower BL, more cloud	Negative
FT relative humidity (Klein et al. 1995; Lacagnina and Selten 2013; Myers and Norris 2015)	Decreasing	Decreasing high and middle clouds, but uncertain in low cloud	Uncertain
FT subsidence (Myers and Norris 2013)	Weakening	Higher cloud top, more cloud	Negative
Surface wind speed (Klein et al. 1995; Qu et al. 2015b)	Uncertain		Uncertain
Cold advection (Klein et al. 1995; Mansbach and Norris 2007; Myers and Norris 2015)	Enhanced	More convective BL, more cloud	Negative

Left column indicates physical processes affecting low cloud cover (LCC) over the subtropical ocean. The second, third, and fourth columns from the left indicate the projected change in a warming climate, resultant change in low cloud and boundary layer (BL), and resultant low cloud feedback, respectively (Qu et al. 2015b; Myers and Norris 2016)

atmospheric circulations (Andrews et al. 2015; Long et al. 2016; Ying and Huang 2016).

The strength of inversion that caps the planetary BL controls the amount of BL cloud (Table 1). The stronger inversion suppresses the mixing of moist BL air with warmer and drier FT air, resulting in a shallower, moister, and cloudier BL (Klein and Hartmann 1993; Wood and Bretherton 2006). Strengthened subsidence in FT alone reduces the LCC, although subtropical low cloud exists over the regions where the subsidence dominates (Myers and Norris 2013). This paradoxical relationship can be explained by differences in relative contributions of the inversion strength and subsidence to LCC (stronger inversion causes an increase in the LCC and stronger subsidence reduces it a little). The relationship between FT relative humidity and LCC cannot be simply evaluated (Table 1). While high and middle cloud covers correspond well with the FT humidity (Albrecht et al. 1995), both decrease (Klein et al. 1995) and increase (Lacagnina and Selten 2013) in LCC associated with increased FT relative humidity were reported. Myers and Norris (2015) pointed out that increase in lower tropospheric (700 hPa) humidity corresponds to decrease in cloud cover in 700–850 hPa layer and increase just below and above that layer, resulting in the diverse conclusions. Variation in surface wind speed shows a high correlation with the LCC (a higher wind speed corresponds to a larger LCC; Klein et al. 1995). Enhanced cold air advection near the surface is concurrent with stronger convective mixing in the BL and increased LCC (Klein et al. 1995; Mansbach and Norris 2007; Myers and Norris 2015). These observations and modeling-based relationships between the LCC and the large-scale conditions can be applied to longer-term cloud changes including cloud feedback in a warming climate (see next section).

Constraining the uncertainty in low cloud feedback

There are attempts to reduce the large inter-model spread of ECS using observation-based performance metrics called emergent constraints (Sherwood et al. 2014; Klein and Hall 2015; Fasullo et al. 2015). Recent studies applied the observed relationship between the LCC variation and the large-scale atmospheric and SST conditions (Table 1) for reducing the uncertainty in the low cloud feedback in a changing climate (e.g., Dessler 2013; Zhai et al. 2015; Qu et al. 2015b; Myers and Norris 2016; Brient and Schneider 2016). Most of the observation-based approaches rely on an assumption that long-term change in the low cloud is largely controlled by changes in large-scale atmospheric condition and SST, so that the low cloud sensitivities are similar between the long-term change and seasonal, interannual, and decadal variabilities. Zhou et al. (2015) pointed out that long-term net cloud feedback tends to be smaller than interannual cloud feedback, although the two correspond well qualitatively among multi-models participated in the Coupled Model Intercomparison Project (CMIP). Difference in spatial patterns of SST perturbations between the two (long-term and interannual feedbacks) was suggested to be a factor for the difference in the cloud feedback, consistent with Andrews et al. (2015). Zhai et al. (2015) examined the seasonal relationship between SST and marine BL cloud in observations and CMIP models. They found that (1) modeled long-term correspondence between the two (SST and marine BL cloud) is similar to seasonal correspondence among the CMIP models and (2) models with realistic SST–cloud relationship compared with observations on seasonal timescale tend to have larger long-term positive cloud feedback, suggesting a higher ECS than the raw estimate from the CMIP models. Tsushima et al. (2013) evaluated representations of seasonal variations of cloud radiative effects of cloud regimes in climate models and found that models that capture the seasonal variation of stratocumulus cloud regimes tend to have higher ECS.

Qu et al. (2015b) developed a heuristic model relating future LCC change to changes in the atmospheric conditions and SST (Table 1). They found that three large-scale controls are dominant: strength of temperature inversion, strength of BL–FT humidity contrast, and surface latent heat flux (Fig. 1). This approach is an extension from Qu et al. (2014), which examined the SST effect as a surrogate for multiple processes including the latter two (latent heat release and humidity gradient; Fig. 1; Table 1). Contribution of the inversion strength (negative feedback) is relatively smaller than the total contribution of the SST (positive feedback; Table 1; Fig. 1), resulting in a small positive feedback (reduction of LCC) in a multi-model ensemble mean. By comparing with observed LCC sensitivity to the predictor variables, they concluded that observations suggest a systematic LCC reduction (−7 to −3 % during the twenty-first century) and a reduced reflection of solar radiation under a warming climate (Qu et al. 2015b). Myers and Norris (2016) also conducted a similar analysis and concluded that the SST effect and the inversion effect largely compensate each other, leading to a weak positive cloud feedback (0.4 ± 0.9 W m^{-2} K^{-1}) while uncertainty ranges due to observations and regression method are both substantial.

The analyses conducted in Qu et al. (2015b) and Myers and Norris (2016) exhibited that contributions of the three (inversion strength, humidity contrast, and latent heat flux) to LCC change are dominant compared with the other factors (Table 1). The CMIP models tend to show decreasing trends in the subtropical FT relative humidity in a warming climate (Sherwood et al. 2010; Qu et al. 2015b). However, the contribution of the FT relative humidity to the future LCC change is not robust among the models (Qu et al. 2015b; Myers and Norris 2016). Future change in sea surface wind speed is also highly uncertain among multi-models, resulting in a minor contribution compared with the others (Qu et al. 2015b).

Sherwood et al. (2014) suggested an emergent constraint, lower tropospheric mixing (LTM), for the uncertainty in low cloud feedback and ECS. The LTM, namely

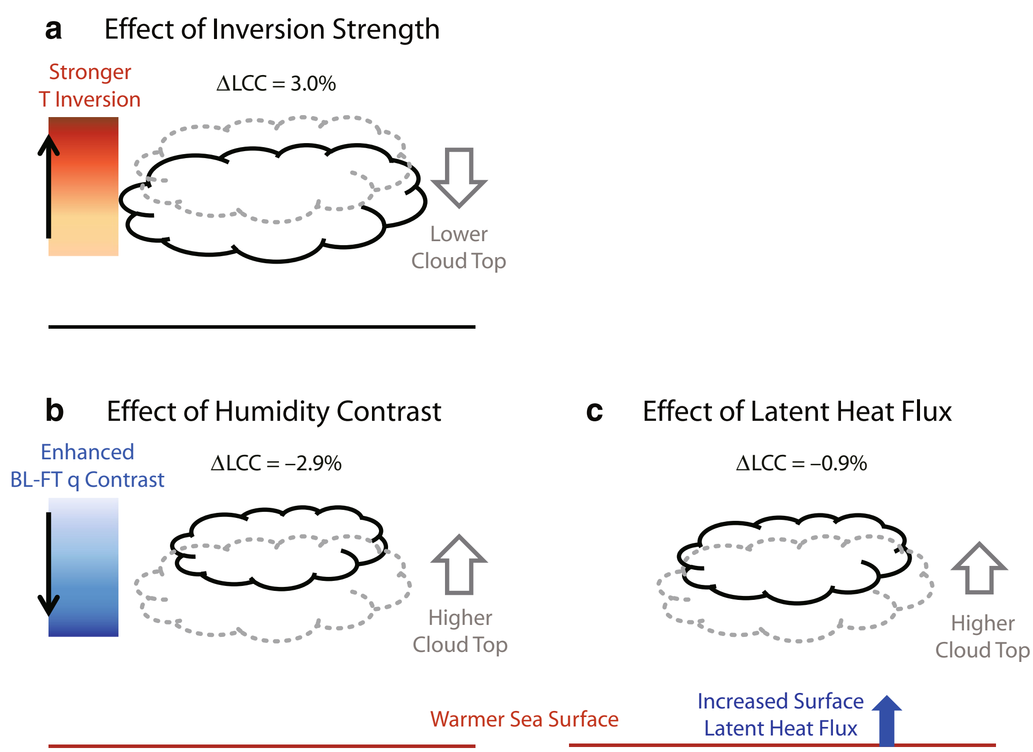

Fig. 1 Summary of key processes associated with low cloud feedback. *Dashed gray* and *solid black balloons* represent low clouds over the subtropical ocean in a base state and in a warmer condition, respectively. See Table 1 for references. **a** Effect of change in inversion strength. **b** Effect of sea surface temperature (SST)-induced moisture contrast between the boundary layer (BL) and free troposphere (FT). **c** Effect of SST-induced latent heat flux. Values shown in individual panels are multi-model mean of low cloud cover (LCC) change (%; from Qu et al. 2015b)

shallow upward moisture transport from BL to FT (via cumulus congestus and shallow overturning circulation over the ocean), cannot be evaluated directly but can be diagnosed indirectly by model outputs (differences of temperature and relative humidity between the BL and the lower FT; Fig. 2a, and vertical profile of atmospheric circulation; Fig. 2b, see Sherwood et al. 2014 for detail) and can be compared with observations. The LTM consists of two components: small-scale (parameterized process; Fig. 2a) and large-scale LTM (resolved atmospheric circulation; Fig. 2b). In the tropics, water vapor and temperature in the BL air are transported to FT via deep convection (blue arrow in Fig. 2) and LTM. The large-scale LTM (orange arrow in Fig. 2b) is commonly called shallow ascent in the tropics. In the lower FT (Fig. 2a), air parcels transported to the upper troposphere by deep convection turn back with relatively higher temperature and lower relative humidity compared with the environment (red circle in Fig. 2a) due to rain out within the updraft. In contrast, the small-scale LTM (white arrow in Fig. 2a) transports cool and moist air to the lower FT (blue circle in Fig. 2a). In a warming climate, increase in surface evaporation tends to be smaller than the convective BL dehydration (e.g., Demoto et al. 2013). In addition, models with stronger LTM in the current climate tend to show larger increase in LTM in a warming climate, leading to an LTM control for change in the intensity of convective BL dehydration and resultant cloud feedback. Actually, the sum of the two estimated LTM can explain a half of the ECS spread among 48 CMIP models (Sherwood et al. 2014). The observational constraint suggested a higher ECS range (higher than 3 K) than the raw ECS estimate from the multi-model ensemble. While correspondence of LTM and low cloud feedback was not examined sufficiently (Klein and Hall 2015), this conclusion is consistent qualitatively with the above works (Zhai et al. 2015; Qu et al. 2015b; Myers and Norris 2016).

Structural and parametric uncertainty in low cloud feedback

In the previous section, we reviewed the spread of the low cloud feedback among different climate models. However, the limited size of the CMIP model ensemble does not necessarily cover the whole possible uncertainty range (Tebaldi and Knutti 2007; Collins et al. 2011). Parameterizations of model physics (e.g., convection, cloud microphysics, and turbulence) for reproducing realistic current climatology (Mauritsen et al. 2012) could lead to a biased estimate of the cloud feedback and ECS. Recently, uncertainty due to the behavior of physics schemes implemented in climate models has been addressed by single or multi-model frameworks. PPE is an effective approach to evaluate a sensitivity of cloud feedback and ECS to parameter settings in physics schemes (Murphy et al. 2004; Stainforth et al. 2005; Sanderson et al. 2010; Collins et al. 2011; Klocke et al. 2011). Webb et al. (2015) compared uncertainty ranges of cloud feedback between models which have their convection schemes turned on and off. They concluded that convective parameterization is important in some models, but other processes also contribute to the spread of the cloud feedback among different models.

Yokohata et al. (2010) and Sanderson (2011) compared uncertainty in cloud feedback between PPEs developed

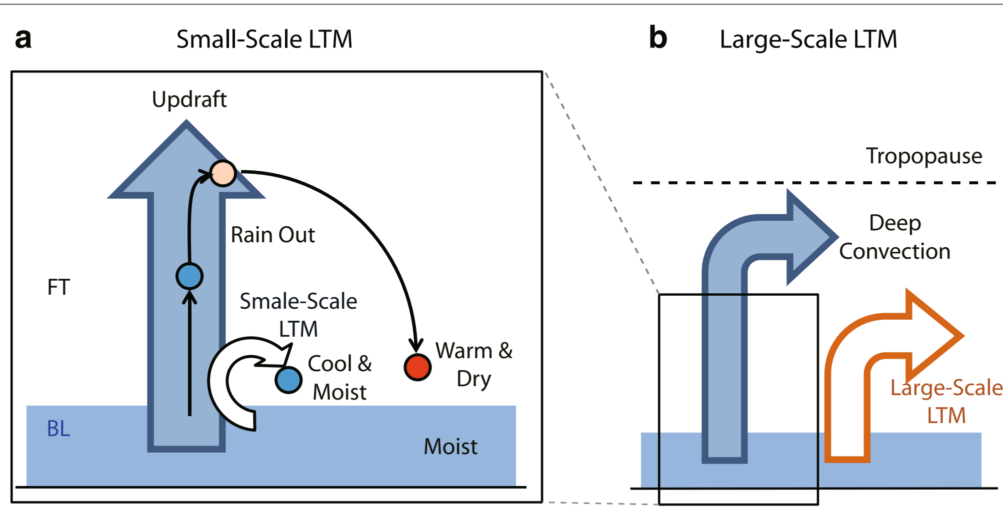

Fig. 2 Schematic of lower tropospheric mixing. **a** Small-scale lower tropospheric mixing (LTM; *curved white arrow*) between moist BL and dry FT over the tropical ocean (Sherwood et al. 2014). *Blue*, *pink*, and *red circles* represent cool and moist to warm and dry air parcels, respectively. **b** Large-scale LTM (*orange arrow*)

by different climate models. They showed that sensitivity of cloud feedback to parameter perturbations was dependent on model structures, suggesting a necessity for evaluating both the parametric and structural (i.e., model configuration) uncertainty. Gettelman et al. (2012) and Watanabe et al. (2012b) developed multi-physics ensembles (MPEs) by swapping model physics schemes between two climate models (old and new versions of the model). They showed that cloud feedback and ECS vary substantially among MPE models (Fig. 3; detailed below), contributing to the difference in cloud feedback and ECS between the two versions of the climate model (Gettelman et al. 2012; Watanabe et al. 2012b). However, MPE also relies on particular parameter settings, implying a possible parametric uncertainty that cannot be addressed by MPE models alone.

To evaluate both the parametric and structural uncertainty, Shiogama et al. (2014) developed a multi-parameter multi-physics ensemble (MPMPE) based on the MPE models developed by two versions of Model for Interdisciplinary Research on Climate (MIROC; Table 2; Watanabe et al. 2012b). They developed PPEs based on the eight MPE models and examined the uncertainty in cloud feedback and ECS. Figure 3 shows the shortwave cloud feedback in the MPMPE (Kamae et al. 2016b) evaluated using the International Satellite Cloud Climatology Project (ISCCP) simulator (Klein and Jakob 1999; Webb et al. 2001) implemented in the models and ISCCP cloud radiative kernel (Zelinka et al. 2012a). Estimated feedbacks were generally consistent with estimates (difference in all-sky and clear-sky TOA radiation) of Shiogama et al. (2014). Compared with MIROC5A with a large negative shortwave cloud feedback and a low ECS, models with swapped physics schemes (cloud, convection, and turbulence) to older ones generally show larger cloud feedback and higher ECS (Table 2; Fig. 3; Watanabe et al. 2012b; Shiogama et al. 2014; Kamae et al. 2016b). The difference in the shortwave cloud feedback among the eight MPE models can largely be attributed to spreads in low cloud and middle cloud feedback over the tropical ocean (Watanabe et al. 2012b). Shiogama et al. (2014) further compared parametric uncertainty between the eight MPE models and concluded that (1) uncertainty in low cloud feedback, middle cloud feedback, and ECS are sensitive to model the structure (consistent with Yokohata et al. 2010 and Sanderson 2011); and (2) the relationship of cloud feedbacks between different cloud levels can influence the total spread of the cloud feedback in a given PPE (e.g., a positive correlation between low and middle cloud feedbacks results in large spreads in total feedback and ECS).

Multiple PPEs with different model structures like MPMPE can cover both the parametric and structural uncertainty. It is needed to examine the physical processes determining total cloud feedback and its components (fractional coverage, clout top height, and optical depth) including low cloud feedback in the multiple PPEs. However, it has not been clarified why different PPEs show different parameter sensitivity of low and middle cloud feedback (Shiogama et al. 2014; Kamae et al. 2016b). Swapping physics schemes like cumulus convection may result in a different behavior of cloud in a control climate and its change in a perturbed climate (Watanabe et al. 2012b). Kamae et al. (2016b) applied the observational constraint of low cloud feedback (LTM) to the MPMPE and concluded that LTM is effective to constrain the uncertainty in low cloud feedback, but is not applicable to total cloud feedback and ECS, at least for a part of PPEs. The physical reasons for the differences in the LTM–ECS relationship among different ensembles are still unclear. Further works are needed to evaluate the uncertainty range of cloud feedback and constrain the ECS uncertainty among multiple PPEs developed by different climate models.

Conclusions

Historical observations including satellite and implementation of satellite simulator enable to evaluate the reproducibility of the modeled clouds and its variations on seasonal, interannual, and decadal timescales. The accumulated observations suggest that the large-scale controls of LCC can also be applied to the long-term cloud change under global warming. The observation–model merged approaches suggest that the warmer sea surface and dryer FT relative to BL result in a less LCC, although the larger FT warming relative to BL enhances the LCC, resulting in a positive low cloud feedback. It is worthwhile to examine whether this physically robust low cloud feedback is also confirmed in multiple PPEs that can cover wider uncertainty ranges than the CMIP multi-models.

In the previous studies, observation-based constraint of the tropical LCC change in a warming climate (Qu et al. 2015b; Myers and Norris 2016) consists both of the temperature-mediated cloud change and the rapid adjustment (see "Introduction"). Qu et al. (2015a) pointed out the importance of the rapid adjustment on the inversion strengthening in global warming simulations. Bretherton et al. (2013) decomposed the rapid adjustment and temperature-mediated change in low cloud using single LES. Decomposed cloud adjustment and temperature-mediated change should be compared among different models in comprehensive frameworks. In the CFMIP, it has been planned that multiple SCMs are used to conduct sensitivity experiments with SST increase or CO_2 increase

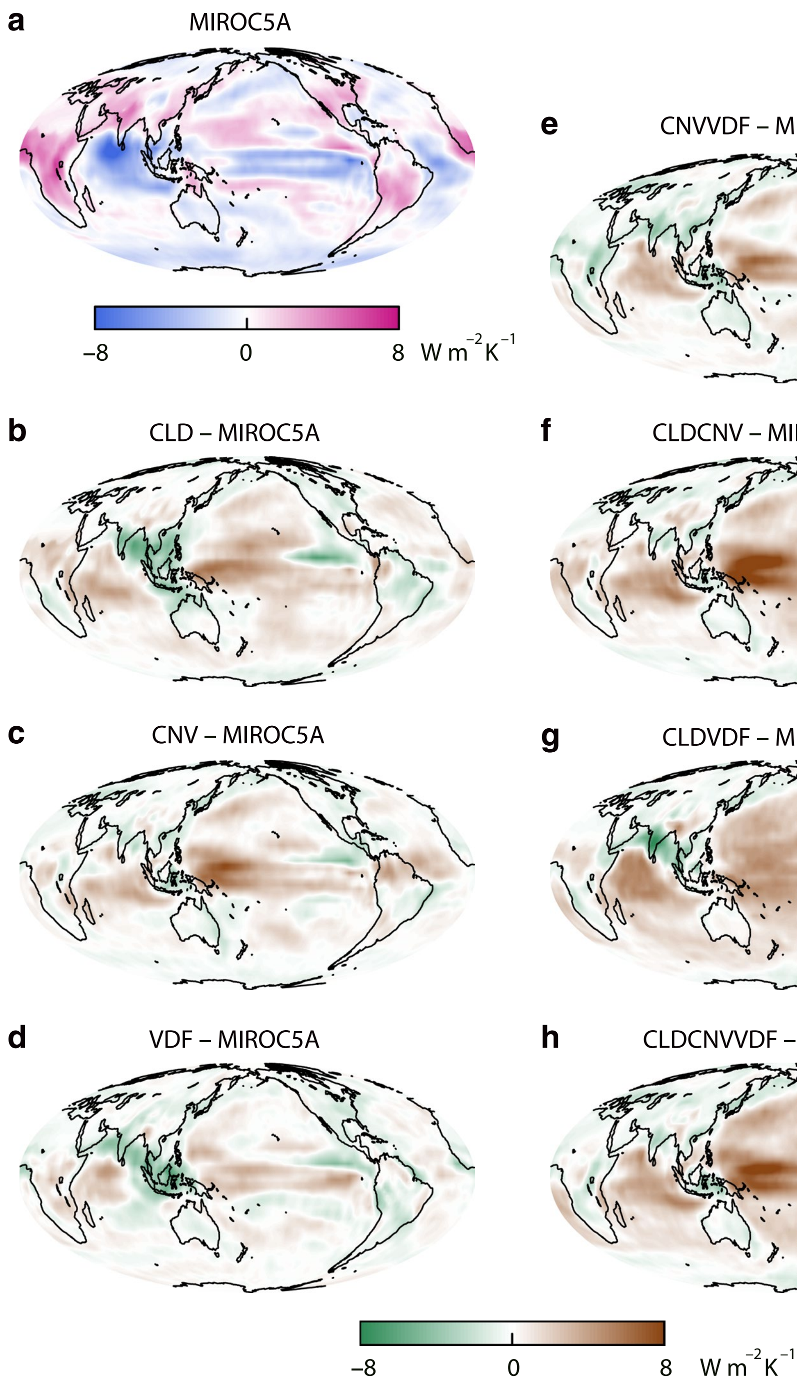

Fig. 3 Variation in shortwave cloud feedback in the MPMPE. **a** Shortwave cloud feedback (W m^{-2} K^{-1}) in MIROC5A model averaged for the PPE members (Table 2; Shiogama et al. 2014; Kamae et al. 2016b). **b**–**h** Differences in CLD, CNV, VDF, CNVVDF, CLDVDF, CLDCNV, and CLDCNVVDF models compared with MIROC5A

to evaluate the two effects on the LCC separately. The results of the simulations could contribute to evaluate the robustness of CO_2, SST, and other controls of the low cloud feedback among different models.

Evaluating the dependency of uncertainty in cloud feedback on physics schemes is also an ongoing issue. PPEs developed by different models can facilitate the evaluation of the structure dependency of the PPE cloud

Table 2 Shortwave cloud feedback and ECS in the MPMPE

Model	Cloud	Convection	Turbulence	λ_{SWcld} (W m^{-2} K^{-1})	ECS (K)
MIROC5A				−0.24	2.35
CLD	MIROC3			−0.08	2.81
CNV		MIROC3		−0.07	2.48
VDF			MIROC3	−0.36	2.69
CNVVDF		MIROC3	MIROC3	−0.17	2.83
CLDCNV	MIROC3	MIROC3		0.39	3.16
CLDVDF	MIROC3		MIROC3	0.50	4.86
CLDCNV-VDF	MIROC3	MIROC3	MIROC3	0.45	4.41

The left column indicates the eight models constituting the multi-parameter multi-physics ensemble (MPMPE; Shiogama et al. 2014). The second to fourth columns from the left indicate the implemented physics schemes (blank indicates a scheme identical to MIROC5A, and MIROC3 indicates a scheme identical to MIROC3 climate model; see Table 3 in Shiogama et al. 2014 for details). λ_{SWcld} represents the global mean shortwave cloud feedback (W m^{-2} K^{-1}) averaged for the PPE members (Kamae et al. 2016b) diagnosed by the satellite cloud simulator (Klein and Jakob 1999; Webb et al. 2001) and cloud radiative kernel (Zelinka et al. 2012a; see text). ECS (K) is derived from Shiogama et al. (2014)

feedback. Different roles of uncertainty in low cloud and middle cloud feedback in multiple PPEs and its physical reasons have not been examined sufficiently. Multi-PPE comparison frameworks may be effective to explore PPE uncertainty in the low cloud feedback and ECS and constrain it by the accumulated observational insights.

Abbreviations

BL: boundary layer; ECS: equilibrium climate sensitivity; CFMIP: Cloud Feedback Model Intercomparison Project; CMIP: Coupled Model Intercomparison Project; FT: free troposphere; ISCCP: International Satellite Cloud Climatology Project; LCC: low cloud cover; LTM: lower tropospheric mixing; MIROC: model for interdisciplinary research on climate; MPE: multi-physics ensemble; MPMPE: multi-parameter multi-physics ensemble; PPE: perturbed physics ensemble; SAT: surface air temperature; SST: sea surface temperature; TCR: transient climate response; TOA: top of the atmosphere.

Authors' contributions

YK wrote the first draft of this paper. TO, HS, and MW commented on the draft. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The code of cloud radiative kernel used in this paper is available from the CFMIP code repository (https://www.code.google.com/archive/p/cfmip-compute-cloud-feedbacks/).

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