CGILS: First Results from an International Project to Understand the Physical Mechanisms of
Low Cloud Feedbacks in General Circulation Models


Bulletin of American Meteorological Society

(Manuscript# BAMS-D-12-00140)

July 2012

Revised March 2013

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CAPSULE SUMMARY

Single Column Models (SCM) and Large Eddy Models (LES) and are used in an idealized climate change scenario to investigate the physical mechanism of low cloud feedbacks in models. Enhanced moistening from surface-driven boundary layer turbulence and enhanced drying from shallow convection in a warmer climate are found to be the two dominant opposing mechanisms of low cloud feedbacks in SCMs.
ABSTRACT

CGILS – the CFMIP-GASS Intercomparison of Large Eddy Models (LESs) and Single Column Models (SCMs) – is an international project in which most major climate modeling centers participated to investigate the mechanisms of cloud feedback in SCMs and LESs under idealized climate change perturbation. This paper describes the CGILS project and results from 15 SCMs and eight LES models. Three cloud regimes over the subtropical oceans are studied: shallow cumulus, cumulus under stratocumulus, and well-mixed coastal stratus/stratocumulus. SCMs simulated a wide range of cloud feedbacks in all regimes. In the stratocumulus and coastal stratus regimes, models without active shallow convection tend to simulate negative cloud feedbacks, while models with active shallow convection tend to simulate positive cloud feedbacks. In the shallow cumulus regime, this relationship is less clear, likely due to the larger cloud depth and different parameterization of lateral mixing of clouds. The majority of LES models simulated positive cloud feedback in the shallow cumulus and stratocumulus regime, and negative cloud feedback in the well-mixed coastal stratus/stratocumulus regime. A general framework is provided to interpret SCM results. In a warmer climate, there is enhanced moistening of the cloudy layer by the surface-based turbulence parameterization, which alone causes negative cloud feedback, while there is enhanced drying by the shallow convection scheme or cloud-top entrainment parameterization, which alone tends to cause positive low cloud. The net cloud feedback depends on how these two opposing effects counteract each other. These results highlight the need to treat physical parameterizations in General Circulation Models (GCMs) as systems rather than individual components.
1. Introduction

Cloud-climate feedbacks in General Circulation Models (GCMs) have been the subject of intensive study for the last four decades (e.g., Randall et al. 2007). These feedbacks were identified to be one of the most significant uncertainties in projecting future global warming in past IPCC (Intergovernmental Panel for Climate Change) Assessment Reports (AR), as well as in coupled model simulations that will be used for the upcoming AR5 (Andrews et al. 2012). Despite of many progress toward understanding cloud feedbacks (Stephens 2005; Bony et al. 2006), however, there is still a general lack of knowledge about their mechanisms. Understanding the physical mechanisms is necessary to instill our confidence in the sensitivity of climate models.

Cloud-climate feedbacks refer to the radiative impact of changes of clouds on climate change. Because clouds are not explicitly resolved in GCMs, they are the product of an interactive and elaborate suite of physical parameterizations. As a result, it has been a challenge to decipher cloud feedback mechanisms in climate models. Clouds also interact with the resolved-scale atmospheric dynamical circulations through their impact on latent and radiative heating.

In view of the challenges, CFMIP (the Cloud Feedback Model Intercomparison Project) and GASS (GEWEX (Global Energy and Water Cycle Experiment) Atmospheric System Study) initiated a joint project -- CGILS (the CFMIP-GASS Intercomparison of Large Eddy Models (LESs) and Single Column Models (SCMs)) to analyze the physical mechanisms of cloud feedbacks by using a simplified experimental setup. The focus of CGILS is on low clouds in the subtropics, because several studies have demonstrated that these clouds contribute significantly to cloud feedback differences in models (e.g., Bony and Dufresne 2005; Zelinka et al. 2012). The role played by these
clouds is consistent with the fact that low clouds have the largest net cloud radiative effect, in contrast to deep clouds in which the positive longwave and negative shortwave cloud effects largely cancel out (e.g. Ramanathan et al. 1989).

The objective of this paper is to describe the CGILS project and results from 15 SCMs and eight LES models. The paper is organized as follows. Section 2 describes the experimental design and large-scale forcing data. Section 3 gives a brief description of the participating models. Section 4 discusses simulated clouds and the associated physical processes. Section 5 discusses cloud feedback results. The last section is a brief summary.

2. Experimental Design and Large-Scale Forcing Data

a. Experimental design

Figure 1 shows the schematics of the CGILS experimental design modified from Zhang and Bretherton (2008). In the control climate (CTL), sea surface temperature (SST) is specified along the GCSS/WGNE Pacific Cross Section Intercomparison (GPCI) (Teixeira et al. 2011) in the northeast Pacific by using the ECMWF (European Center for Medium-Range Weather Forecasts) Interim Reanalysis (Dee et al. 2011, ERA-Interim). In the perturbed climate (P2S), SST is uniformly raised everywhere by 2 degrees as in Cess et al. (1990). Large-scale horizontal advection and vertical motion, corresponding to the underlying SST, are derived and used to force SCMs and LES models. The models simulate changes of clouds in response to changes of SST and the associated large-scale atmospheric conditions.

Three locations along the GPCI cross section are selected for study. They are labeled as S6, S11 and S12 in Figure 2, which also shows the distribution of low cloud amount in the summer (JJA,
June to August) from satellites (Kato et al. 2011; Xu and Cheng 2012). Typical regimes of clouds at these three locations are shallow cumulus (S6), cumulus under or above stratocumulus (S11), and well-mixed stratocumulus or coastal stratus (S12). On the basis of dominant cloud types, they are referred to as shallow cumulus, stratocumulus, and coastal stratus respectively. Table 1 gives the locations and values of summer-time surface meteorological variables in the control climate.

### b. Forcing data

The SCM and LES forcing data refer to surface boundary conditions, the large-scale horizontal advective tendencies and vertical velocity that are specified in the model simulations. The SCMs calculate the time evolution of water vapor and temperature as follows (Randall and Cripe 1999):

\[
\frac{\partial \theta_m}{\partial t} = \left( \frac{\partial \theta_m}{\partial t} \right)_{phys} - (\vec{V} \cdot \nabla \theta)_{LS} - \omega_{LS} \frac{\partial \theta_m}{\partial p} 
\]

\[ (1) \]

\[
\frac{\partial q_m}{\partial t} = \left( \frac{\partial q_m}{\partial t} \right)_{phys} - (\vec{V} \cdot \nabla q)_{LS} - \omega_{LS} \frac{\partial q_m}{\partial p} ,
\]

\[ (2) \]

where \( \theta \) and \( q \) are potential temperature and water vapor mixing ratio. Subscript “m” denotes model calculations; “LS” stands for large-scale; other symbols are as commonly used. The first term on the right-hand-side (rhs) of Equations (1)-(2) is calculated from physical parameterizations (with subscript “phys”). The last two terms contain the specified large-scale horizontal advective forcing and subsidence. In LES models, conservative variables like liquid water potential temperature and total liquid water are typically used as prognostic fields (e.g., Siebesma et al. 2004; Stevens et al. 2005); (1) and (2) represent domain averages. The atmospheric winds and initial relative humidity are specified by using the ERA-Interim for July 2003. Initial profiles of atmospheric temperature are
assumed to follow moist adiabat over the warm pool and weak gradient approximations at other locations (Sobel et al. 2001). Surface latent and sensible heat fluxes are calculated internally by each model from the specified SST and winds.

The large-scale horizontal advective tendencies and subsidence in (1)-(2) are specified according to SST. In the free troposphere, they are derived based on the clear-sky thermodynamic and water vapor mass continuity equations, in which radiative cooling in the thermodynamic equation is balanced by subsidence warming and horizontal advection, with the radiative cooling calculated by using the RRTM radiation code (Mlawer et al. 1997). Below the altitude of 900 hPa, the horizontal advective forcing of temperature and water vapor are calculated using the SST spatial gradient and specified surface relative humidity. A brief description of the derivation procedure is given in Appendix A. More detailed discussions of the forcing data can be found in Zhang et al. (2012).

Figure 3a shows the derived vertical profiles of $\omega_{LS}$ in CGILS CTL (solid lines) and ERA-Interim (dashed lines) at the three chosen locations. The obtained values match well with ERA-Interim in the lower troposphere. Among the three locations, the subsidence rate is the strongest at S12 and the weakest at S6.

Figure 3b shows the comparison of the derived $\omega_{LS}$ between CTL (solid lines) and P2S (dashed lines) used in the simulations. It is seen that subsidence is weaker in the warmer climate. Figures 3c and 3d show the corresponding profiles of horizontal advective tendencies of temperature and water vapor respectively. In the free troposphere, these profiles, along with the profiles of $\omega_{LS}$, SST, and initial atmospheric temperature and water vapor, satisfy the clear-sky atmospheric thermodynamic and water vapor mass continuity equations under July 15 insolation conditions.
Zhang et al. (2012) showed that the changes in the forcing data between CTL and P2S in Figure 3 capture the essential features in the GCMs. All data are available in the CGILS website http://atmgcm.msrc.sunysb.edu/cfmp_figs/Case_specification.html.

### c. Simulations

We use the change of cloud-radiative forcing (CRF) (Ramanathan et al. 1989) from CTL to P2S, as in many previous studies, to measure cloud feedbacks. Even though Soden et al. (2004) suggested other better diagnostics of cloud feedbacks, CRF is used for simplicity, which should not affect the results of this paper.

The SCMs and LES are integrated to quasi-equilibrium states by using the same steady large-scale advective tendencies and subsidence as forcing data. Each model ran six simulations: CTL and P2S at the three locations of S6, S11 and S12. Since the forcing is fixed, a model may eventually drift if its radiative cooling rate in the free atmosphere differs from the rate used in the derivation of the prescribed large-scale subsidence. To prevent models from similar drifting, at pressure less than 600 hPa, temperature and water vapor mixing ratio are relaxed to their initial conditions with a time scale of 3 hours. In LES models, they are relaxed at altitudes above 4000 m for S6, 2500 m for S11, and 1200 m for S12, respectively to reduce computational costs and allow for high vertical resolutions in shallow domains. Some LES models did not complete all six simulations.

Most of the SCMs are integrated for 100 days. Based on a visual inspection of statistical equilibrium, the averages of their last period of about 50 days are used. Most LES simulations reached quasi-equilibrium states after 10 days, in which case the last two days are used in the analysis. Zhang and Bretherton (2008) analyzed the transient behavior of the Community Atmospheric Model.
(CAM) under constant forcing and showed that the interaction of different physical parameterization components can create quasi-periodic behaviors of model simulation with time scales longer than a day. Since LES models contain fewer parameterization components, the impact of this type of interactions is reduced. This likely explains why LES models reach quasi-steady states in shorter time than SCMs. To our knowledge, CGILS is the first LES intercomparion study to investigate clouds by integrating them to quasi-equilibrium states.

3. Models and Differences in Physical Parameterizations

Fifteen SCMs and eight LES models participated in this study. Many parent GCMs of the SCMs also participated in the Coupled Model Intercomparison Project 5 (CMIP5). Table 2 lists the model names, main references, and CGILS contributors. It also gives the number of total vertical model layers and number of layers between the surface and 700 hPa in SCMs. The SCM vertical resolution in the boundary layer (PBL) is generally not sufficient to resolve observed thin clouds. No attempt is made to make them finer since our objective is to understand the behavior of operational GCMs. For the LES models, however, because they are intended as benchmarks, much higher resolutions are used. The horizontal resolutions of LES models are 100 meter, 50 meter and 25 meter respectively at S6, S11 and S12. The vertical resolutions of the majority of LES are 40 meter, 5 meter and 5 meter respectively at the three locations. More detailed descriptions of the CGILS LES models are given in a recent paper by Blossey et al. (2013).

The physical parameterizations in the SCMs relevant to the present study are the PBL, shallow convection, and cloud schemes. Cloud schemes include a macrophysical and a microphysical component. For PBL schemes, the generic form can be written in terms of turbulent flux at the model interfaces:
\[
\bar{w'}S' = -K_c \left( \frac{\partial S}{\partial z} - \gamma_c \right)
\]

where \( z \) is height; \( w \) is vertical velocity; \( S \) is a conservative model prognostic variable. Prime represents the turbulent perturbation from the mean that is denoted by the overbar. \( K_c \) is the eddy diffusivity, and \( \gamma_c \) is the counter-gradient transport term. In addition to resolution, the differences in PBL schemes among the models are in their formulations of \( K_c \) and \( \gamma_c \). For \( K_c \), some models parameterize it by using local variables at the resolved scales, such as local Richardson number in the so-called first order closure models, or local turbulent eddy kinetic energy (TKE) such as the Mellor-Yamada higher order closure models (Mellor and Yamada 1974). Other models use non-local empirical parameterization of \( K_c \) as function of height relative to the boundary-layer depth on the basis of previous LES simulations. Another \( K_c \) difference is its parameterization at the top of the PBL. While some models have explicit parameterizations of turbulent entrainment based on parameters such as cloud-top radiative and evaporative cooling; others do not consider entrainment. For the counter-gradient term \( \gamma_c \), some models calculate it based on surface buoyancy fluxes, while others do not have this term. Table 3 categorizes the PBL schemes in the SCMs according to the above attributes. Cloud-top entrainment in Table 3 refers to explicit parameterization. PBL schemes formulated using moist conservation variable and TKE closure (ECHAM6) may implicitly contain cloud-top entrainment. As can be seen, a wide variety of PBL parameterizations are used in the SCMs. Because of coarse vertical resolutions, however, some of these differences do not make as much an impact on cloud simulations as they would if higher vertical resolutions were used.

The majority SCMs used mass-flux shallow convection schemes. The generic form of convective transport for a conservative variable \( S \) in these schemes is
\begin{equation}
\bar{w'S'} = M(z)(S_e - S_c) \tag{4}
\end{equation}

where the prime denotes deviation of the bulk properties of clouds from the mean; \(M\) is the convective mass flux; subscripts \(c\) and \(e\) represent values in the parameterized cloud model and in the environment air respectively. The convective mass flux is calculated from parameterized rates of entrainment \(\lambda\) and detrainment \(\delta\):

\begin{equation}
\frac{1}{M} \frac{\partial M}{\partial z} = \lambda - \delta. \tag{5}
\end{equation}

Some models do not separately parameterize shallow and deep convections, but because CGILS uses large-scale subsidence as forcing data, deep convection schemes also simulate shallow convection. The schemes can differ in their entrainment and detrainment rates, the closure that determines the amount of cloud base mass flux, and convection triggering condition as well as origination level of convection. Table 4 categorizes the convective schemes in the SCMs based on the their main attributes. Among the SCMs, CLUBB and RACMO use a single scheme to parameterize PBL turbulence and shallow convection.

Cloud macrophysical schemes parameterize cloud amount and grid-scale rate of condensation and evaporation. These schemes can be generically described by assuming that the total water in the air, \(q_t\), obeys a probability distribution function (pdf) \(P(q_t)\) within a model grid box. The cloud amount is then

\begin{equation}
C = \int_{q_{c}}^{\infty} P(X) dX. \tag{5}
\end{equation}

where \(q_s\) is the saturation vapor pressure at cloud temperature. Cloud liquid water \(q_l\) is then

\begin{equation}

\end{equation}
Therefore, cloud fraction and cloud liquid water are often proportional to each other in individual models of the cloud fraction is less than 100%. The cloud microphysics scheme treats how condensed water is converted to precipitation. Models differ in their assumptions on the pdf of $q$, and number of hydrometer types as well as their conversion rates. Even though clouds are the subject of this study, cloud schemes actually play a secondary role in inter-model differences of simulated clouds in CGILS. They are not categorized here.

4. Simulated Clouds and Associated Physical Processes

Before investigating cloud feedbacks, we first examine the simulated clouds in CTL. Figure 4 shows the time-averaged cloud profiles in all 15 SCMs and all LES models, with S6 in the top row and S12 in the bottom row. SCMs results are in the left column; LES models in the middle column; observations from C3M for the summers of 2006 to 2009 in the right column. Note that the observations may have categorized drizzles as clouds, therefore having a different definition of clouds from that in the models. The blue lines denote the ensemble averages or multi-year averages; the red lines denote the 25 and 75 percentiles. Figure 5 shows examples of the time-pressure cross sections of these cloud amount from a sample of three SCMs (JAM, CAM4, GISS), which are selected because they span the range of model differences as will be shown later, and from one LES (SAMA).

Despite large differences among the models, they generally simulated the correct change of cloud types from shallow cumulus, stratocumulus, and coastal stratus at the three locations. The spread in the LES models is much smaller than that in the SCMs. At S11, LES models simulated
shallow cumulus under stratocumulus. The use of the steady forcing for all models may have amplified the inter-model differences, since in both GCMs and the real atmosphere the large scale circulation can respond to local differences in the inversion height by partially compensating them (Blossey et al. 2009; Bretherton et al. 2013).

We find it instructive to use the following moisture budget equation to probe the physical parameterizations responsible for the simulated clouds in the SCMs. It is written as:

\[
\frac{\partial q_m}{\partial t} = \left( \frac{\partial q_m}{\partial t} \right)_{\text{turb}} + \left( \frac{\partial q_m}{\partial t} \right)_{\text{conv}} - (c-e)_{\text{stra}} - \left[ (\vec{V} \cdot \nabla q)_{LS} + \alpha_{LS} \frac{\partial q_m}{\partial p} \right]
\]

(7)

where the variables are as commonly used, and the tendency terms have been separated into three physical terms representing PBL turbulence (turb), convection (conv), large-scale stratiform net condensation (c-e), plus the 3-dimensional large-scale forcing. Figure 6 shows the time averaged profiles of these three terms for the selected SCMs at S11 in CTL. The dashed lines are the simulated cloud liquid water. The solid dots on top of the dashed lines donate the mid-point of model layer.

Figure 6a shows that in JMA only two physical terms are active: The PBL scheme moistens the boundary layer; the large-scale condensation dries it. The residual is balanced by the drying from the large-scale forcing. The peak altitudes of the “turb” and “c-e” are the same as that of the cloud liquid water. Since the PBL scheme is always active, the stratiform condensation scheme responds to the PBL scheme. Figure 6b shows that in CAM4, shallow convection is active in addition to the “turb” and the “c-e” processes. The shallow convective scheme transports the moisture from the boundary layer to the free troposphere. Figure 6c shows that in the GISS model, shallow convection is also active, but unlike CAM4, the maximum drying of the “conv” term is at the same level as the maximum level of “turb”, in the middle of the cloud layer. These differences will be shown later as
causes of different cloud feedbacks in the models. In Figure 6, the stratiform condensation term is the direct source of cloud water.

The inter-model differences in Figure 6 are examples of how different parameterization assumptions can affect the balance of the physical processes and associated clouds. The JMA model used the relaxed Arakawa-Schubert convection scheme (Moorthi, 1992) with a specified minimum entrainment for convective plumes (Kawai, 2012). As a result, convection is not easily triggered in this model. CAM4 and GISS both used positive Convective Available Potential Energy (CAPE) of undiluted air parcels as criteria of convection. As a result, shallow convection is more easily triggered in these two models. Nevertheless, the assumptions in their shallow convection parameterizations are different. For example, CAM4 does not include lateral entrainment into the convective plumes (Hack, 1994); while GISS uses a specified value of lateral entrainment (Del Genio and Yao, 1993). The shapes of the moisture tendency due to the convection schemes in the two models reflect these different assumptions. They result in the different clouds shown in Figure 4. Figure 6 reminds us again the inadequate vertical resolution of SCMs in simulating the intended physical processes of convection and turbulence, and so the challenge of physical parameterizations.

5. Cloud Feedbacks

a. SCM results at S11 (stratocumulus)

We first use the stratocumulus regime S11 to interpret the cloud feedbacks in the 15 SCMs. Figure 7 shows the change of net CRF from CTL to P2S. Increase of CRF means positive cloud feedbacks; decrease means negative feedbacks. For simplicity, the change of CRF is referred to as cloud feedback. The 15 SCMs simulated negative and positive cloud feedbacks that span a rather
Because of the simplified CGILS setup, we do not expect the feedbacks here to be the same as in the full GCMs, but they allow us to gain some insight into the physical processes that determine them.

In Figure 7, the character “X” above a model’s name indicates that shallow convection is not triggered in both the CTL and P2S simulations of this model. The character “O” indicates that shallow convection is active in at least of the simulations. PBL schemes are always triggered in all models. Models without these characters about their names had unified schemes of turbulence and shallow convection (CLUBB and RACMO) or did not submit information for convection (ECMWF). One can see that models without shallow convection tend to simulate negative cloud feedbacks, while models with active convection tend to simulate positive cloud feedbacks.

Without convection, as discussed above for the JMA model, the water vapor balance is achieved by a competition between the moistening effect of the “turb” term in (7) and drying effect of the “c-e” term and large-scale forcing; clouds are caused by the moistening term from the PBL scheme. Therefore, the response of the PBL scheme to SST largely determines the change of cloud water, hence, the cloud feedbacks in the models.

Figure 8a shows the change of the PBL moistening term at the altitude of maximum cloud liquid water. It is seen that except for HadGEM2 and CCC, the magnitude of this term is larger in the warmer climate. In HadGEM2 and CCC, the simulated altitudes of maximum cloud water in P2S are much higher than CTL, above the top of the boundary layer (not shown), where the turbulent term is small. We note that it is the enhanced convergence of the turbulent moisture transport, not the moisture itself that can cause increased amount of condensation.
The increased moistening by the PBL schemes is generally consistent with the increase of surface latent heat flux (LHF) in P2S, as shown in Figure 8b. The increase of latent heat flux with SST is consistent with CGILS LES simulations in Blossey et al. (2013, Table 4) and in earlier LES studies under similar experimental setup (e.g. Xu et al. 2011). Also, Liepert and Previdi (2012) showed that in virtually all 21st Century climate change simulations by CMIP3 models, surface latent heat fluxes are larger in a warmer climate over the oceans (their Table 2, column 3).

We use Figure 9a to conceptually summarize the main physical processes that are responsible for negative cloud feedbacks in models without shallow convection. In these models, the warmer climate has greater surface latent heat flux, large turbulence moisture convergence in the cloud layer, and consequently the negative cloud feedbacks. This behavior is similar to the behavior of mixed layer models (MLM), which also have negative cloud feedbacks (Caldwell and Bretherton 2009; Caldwell et al. 2012). Because the warmer climate has weaker large-scale subsidence, the cloud top in MLM is generally higher. This has been also shown using LES models (Blossey et al. 2013). However, the SCMs generally cannot resolve this change due to coarse vertical resolutions.

There are notable exceptions in Figure 7. For example, the convective schemes in CAM5 and ECHAM6 are also not active in the simulations, but they simulated small positive cloud feedbacks. These may be related with cloud-top entrainment, included explicitly and implicitly in these models, that acts like shallow convection.

We now turn to models with active shallow convection. Figure 7 shows that these models tend to have positive cloud feedbacks. As discussed in the previous section for CAM4 and GISS, shallow convection acts to dry the cloud layer. It is a moisture sink that has the same sign as the stratiform condensation sink in (7). The enhanced moistening from the PBL scheme in the warmer
climate should be approximately balanced by enhanced drying from the sum of the stratiform condensation and shallow convection. When the rate of drying from the shallow convection is greater than the rate of moistening from the PBL scheme, the stratiform condensation can decrease in a warmer climate. This tends to reduce cloud water and clouds, thus causing positive cloud feedback.

The enhanced rate of convective drying in the warmer climate may be explained by applying (4) immediately above the top of the boundary layer. The convective transport of total water out of the top of boundary-layer clouds depends on the moisture contrast across the cloud top and the convective mass flux. The moisture contrast is larger in the warmer climate, since the subsiding free tropospheric air remains dry but the total water in convective plumes increases with SST. The convective mass fluxes, for reasons unknown to us, generally increase in the warmer climate (not shown). Therefore the role of active convection tends to cause positive cloud feedbacks.

We use Figure 9b as a schematic of the positive cloud feedbacks in the models. We can interpret the net cloud feedbacks as due to two opposing roles of surface-based PBL turbulence and shallow convection, with the latter dominating in most of the models in which convection is active. Figure 9b also applies to models with parameterizations of significant cloud-top entrainment. The PBL scheme can also be dominant over the shallow convection scheme in some models, such as in CAM4. In this model, as discussed in the previous section, the peak drying of shallow convection occurs below the cloud layer instead of within the cloud layer.

Why does shallow convection often play the dominant role? We offer a plausible explanation here. If the convective mass flux does not change, the upward moisture flux immediately above the PBL cloud top described in (4) should change with SST approximately at the rate of the Clausius-Clapeyron relationship (7% per degree). This flux is a measure of the convective drying of the cloud
layer. The surface latent heat flux, on the other hand, generally increases with SST at a smaller rate of about 3% calculated from Figure 8b, which is also consistent with previous studies (e.g., Held and Soden, 2005). This flux is a measure of moistening by the PBL scheme. The sum of the two effects therefore tends to follow convection. Brient and Bony (2012) used the larger moisture contrast between the free troposphere and boundary layer in the warmer climate to explain the positive cloud feedbacks in the LMD SCM and GCM; while Kawai (2012) used the increased surface flux to explain the negative cloud feedback in the JMA SCM and GCM. These are consistent with the present interpretation. In GCMs or in the real atmospheres, the changes in the frequency of convection and convective mass fluxes would also matter.

We need to point out that the separation of the effects of PBL turbulence and shallow convection in the framework of Figure 9 is an artifact. However, this is what the current generation of climate models used. This separation helps to provide a baseline of interpreting cloud feedback behaviors in the models.

**b. SCM results at S6 (shallow cumulus) and at S12 (coastal stratus)**

We next show SCMs results at the other two locations. Before proceeding, we need to supplement our schematics with another scenario, shown in Figure 9c, in which the depth of convection is large and mixing of cloudy air with dry air can occur laterally. This scenario also includes regime change of clouds from stratocumulus to shallow cumulus as exhibited by some models (e.g., HadGEM2 at S11, not shown). If the cloud-scale dynamical fields are the same, larger drying is expected in P2S than CTL because of the larger moisture contrast across cloud boundaries. But other factors such as lateral mixing, cloud depth, and cloud microphysics can also affect the feedbacks. These factors may lead to either positive or negative cloud feedbacks.
Figure 10a shows the SCM cloud feedbacks at S6. The models are ordered in the same sequence as in Figure 7. Almost all models simulated convection at S6. Partially due to the complications described above, convection at S6 does not necessarily correspond to positive cloud feedbacks. In all simulations, surface latent heat flux is greater in the warmer climate (not shown). We may therefore use the same framework as for S11 to think that the larger surface latent heat flux alone is a factor for more clouds in a warmer climate, but the other factors from shallow convection such as lateral mixing favor more dilution of clouds and a positive cloud feedback. The two effects compensate each other differently in the models because of the different assumptions in the specific parameterizations.

Figure 10b shows SCM results at S12, where SST is colder and subsidence is stronger than at S11. Clouds are restricted to within the boundary layer. The simulated cloud feedbacks also span a wide range. Three models simulated no clouds at this location (GFDL AM3, EC-ETH, CAM5) (because of the constant forcing). Most models simulated the same cloud feedback signs as at S11. Some simulated opposite signs, one of which is the GISS model. As indicated by the “X” character in Figure 10b for this model, shallow convection is not active at S12, in contrast to active convection at S11. In all models except for ACCESS, surface latent heat flux is larger in P2S at S12 (not shown).

The conceptual framework in Figures 9a and 9b can be generally applied to describe the behavior of cloud feedbacks in the SCMs at S12.

c. LES results

Figures 11a to 11c show the LES cloud feedbacks at the three locations of S6, S11 and S12 respectively. The LES results are more consistent with each other than SCMs. At the shallow cumulus location S6 (Figure 12a), LES models simulated a small positive cloud feedback except for
DALES and WRF that had negligible feedbacks. At the stratocumulus location S11 (Figure 12b), all models except for SAM simulated positive cloud feedbacks. At the coastal stratus location S12 (Figure 12c), all except for DALES simulated positive cloud feedback.

There is therefore consensus, but not uniform agreement, among the LES models with regard to simulated cloud feedbacks. We point out that this degree of convergence of the LES models in CGILS is the result of four-years of iterations among the participating groups to refine and standardize the experimental set up, including the use of same horizontal and vertical resolutions, number of cloud droplet numbers, radiation codes, and exchange coefficients of the surface turbulent fluxes. The remaining differences in the LES models are in numerical schemes, subgrid-scale turbulences, and the cloud microphysics. Without the standardization and the refinement as well as the 5 meter vertical resolution, the LES models do not produce consensus cloud feedbacks. This illustrates the challenges of correctly simulating cloud feedbacks in global climate models. It also implies the need to understand the problem at the process level in order to improve model parameterizations. We point out that the consensus among the LES model does not necessarily mean they simulated the correct cloud feedbacks. Nevertheless they give plausible answers for SCMs to target for. Eventually, they need to be validated by observations under more realistic experimental setups.

Detailed analyses of the LES turbulence and cloud simulations from the CGILS experiments have been described in Blossey et al. (2013). A companion paper by Bretherton et al. (2013) investigated the sensitivity of LES results to large-scale conditions. The LES results tend to support the framework we proposed in Figure 9: In regimes where the PBL is relatively well mixed, cloud feedback is negative, while in regimes where shallow convection is active, cloud feedback tends to be positive.
6. Summary and Discussion

We have described the experimental setup of CGILS. Shallow cumulus, startocumulus and coastal stratus are simulated, which allowed the investigation of physical mechanisms of cloud feedbacks under idealized climate change. We have reported that in models where shallow convection is not activated or plays minor role in drying the cloud layer, cloud feedbacks tend to be negative. In models when convection is active, cloud feedbacks tend to be positive in the stratocumulus and coastal stratus regime, but uncertain in the shallow cumulus regime. We have provided a framework to interpret the SCM cloud feedbacks by using the two opposing effects of increased moistening from PBL scheme and drying from the convection in a warmer climate, with the PBL schemes causing negative cloud feedbacks while the convective schemes causing positive cloud feedbacks. The latter plays a more dominant role at times when it is active. We offered a simple explanation by using the relative change of the moisture contrasts between the cloud layer and surface and between the cloud layer and the free troposphere.

LES models simulated overall consistent cloud feedbacks. They are positive in the shallow cumulus and stratocumulus regimes, but negative in the coastal stratus regime. The same framework used to interpret the SCM cloud feedbacks is shown to be applicable to the LES results.

The relevance of CGILS results to cloud feedbacks in GCMs and in real-world climate changes is not clear yet. Several recent works have started to address this question (Brient and Bony 2012; Kawai 2012; Webb and Lock 2012). How to use LES results to improve GCMs is also an open question. The CGILS experiments are limited to constant forcing. When transient forcing is used, convection will likely be triggered in all models during time periods of upward motion. The role of convection is expected to depend on the frequency and intensity of these convective events. In the
present study, we also did not change the concentration of greenhouse gases in the experimental set up. This will be the subject of a follow-up study. Additionally, it would be worthwhile to treat SST interactively as a response to greenhouse forcing and cloud feedbacks.

Regardless of the limitation of the simple idealized set up, CGILS results have provided us some insights into low cloud feedbacks in models. It is hoped that these physical understandings can help to reduce the cloud feedback uncertainties in models. For example, because of the opposing roles of the turbulence scheme and shallow convection scheme in causing cloud feedbacks, it is desirable to parameterize them in the future as a single system rather than as separate components.
Acknowledgements

We wish to thank the two anonymous reviews whose comments have led to significant improvement of the paper from its original version. Sing-bin Park of the Seoul National University (SNU) participated in the initial phase of the CGILS project. His tragic death disrupted the submission of results from the SNU model. This paper serves as an appreciation and memory of him. Zhang’s CGILS research is supported by the Biological and Environmental Research Division in the Office of Sciences of the US Department of Energy (DOE) through its FASTER project, by the NASA Modeling and Analysis Program (MAP) and the US National Science Foundation to the Stony Brook University. Bretherton and Blossey acknowledge support from the NSF Center for Multiscale Modeling and Prediction. Del Genio is supported by the NASA MAP program. Wolf is supported by the DOE ASR program. Webb was supported by the Joint DECC/Defra Met Office Hadley Centre Climate Programme (GA01101) and funding from the European Union, Seventh Framework Programme (FP7/2007-2013) under grant agreement number 244067 via the EU CLoud Intercomparison and Process Study Evaluation Project (EUCLIPSE). Franklin was supported by the Australian Climate Change Science Program, funded jointly by the Department of Climate Change and Energy Efficiency, the Bureau of Meteorology and CSIRO. Heus was funded by the Deutscher Wetter Dienst (DWD) through the Hans-Ertel Centre for Weather Research, as part of the EUCLIPSE project under Framework Program 7 of the European Union. The simulations with the Dutch LES model were sponsored by the National Computing Facilities Foundation (NCF). The National Center for Atmospheric Research is sponsored by the National Science Foundation.
Appendix A: Large-Scale Forcing

The vertical shape of the large-scale subsidence $\omega_{LS}$ is assumed to be

$$
\omega(p) = \begin{cases} 
A \times \cos\left[\frac{(p_m - p)}{(p_m - 100)} \times \frac{\pi}{2}\right], & \text{for } 100\text{hPa} < p \leq p_m \\
A \times \cos\left[\frac{(p - p_m)}{(p_s - p_m)} \times \frac{\pi}{2}\right], & \text{for } p_m < p \leq p_s
\end{cases}
$$

where $p$ is pressure level in hPa; $A$ is the amplitude; $p_s$ is the surface pressure; $p_m$ is the level where $\omega_{LS}$ has its maximum, set as 750 hPa.

The amplitude of the subsidence profile at S12 is derived by vertically integrating the following clear-sky steady-state atmospheric thermodynamic equation and using the vertically integrated Interim-ERA horizontal tendencies from 900 hPa to 300 hPa:

$$
(\vec{V} \cdot \nabla \theta)_{LS} + \omega \frac{\partial \theta}{\partial p} = Q_R. 
$$

(A1)

$Q_R$ is the radiative heating/cooling rate. It is calculated from the initial atmospheric state for July 15 insolation, a surface albedo of 0.07, and the RRTM radiation code (Mlawer et al., 1997). At the other two locations (S6 and S11), the amplitude of subsidence is scaled by the ratio of the 750 hPa value to that at S12 in the ERA-Interim data.

Once subsidence is derived, profile of the free tropospheric horizontal advective forcing of temperature with pressure less than 800 hPA is then calculated from (A1) again for temperature as a residual of $Q_R$ and the vertical advection at all three locations. The clear-sky moisture continuity is
used to derive the horizontal advective tendency of water vapor. In the boundary layer from the surface to 900 hPa, the horizontal temperature advection is calculated directly by using the spatial distribution of SST and surface winds; the horizontal advection for water vapor is obtained similarly by using the ERA-Interim relative humidity at the surface. Between 900 hPa and 800 hPa, the advective tendencies are linearly interpolated from boundary-layer values to free-tropospheric values.

The above computational procedure completely determines the required forcing data to integrate the SCMs and LES models. In the perturbed climate, SST is uniformly raised by 2°C along GPCI. The same procedure as for the control climate is used to derive the corresponding forcing data.


NCAR/TN 486+STR. Available at http://www.cesm.ucar.edu/models/cesm1.0/cam/docs/description/cam5_desc.pdf


*J. Climate*, 17, 3661–3665.


doi:http://dx.doi.org.libproxy.cc.stonybrook.edu/10.1175/2011JCLI3672.1


Webb, M. J. and A. Lock, 2012: Coupling between subtropical cloud feedback and the local hydrological cycle in a climate model. *Climate Dynamics*


Table 1: Study locations and surface meteorological conditions in the control climate

<table>
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<tr>
<th></th>
<th>S6 Shallow Cu</th>
<th>S11 Stratocumulus</th>
<th>S12 Stratus</th>
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<tr>
<td>Longitude (Degrees)</td>
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<td>125°W</td>
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<td>1020.8</td>
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<td>SST (°C)</td>
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<td>19.3</td>
<td>17.8</td>
</tr>
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<td>Tair_surface (°C)</td>
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<td>17.8</td>
<td>16.3</td>
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<td>U_surface (m/s)</td>
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<td>V_surface (m/s)</td>
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<td>RH_surface (m/s)</td>
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<td>80%</td>
<td>80%</td>
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<td>52.7</td>
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<td>0.539</td>
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<td>0.590</td>
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<td>Eccentricity on July 15</td>
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<tr>
<td>Surface Albedo</td>
<td>0.07</td>
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Table 2: Participating models and contributors

Table 2: Participating models, main references, and contributors. The number of vertical layers and layers between the surface and 700 hPa for SCMs are given in the last column.

<table>
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<tr>
<th>Models Acronyms</th>
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<th>References</th>
<th>Contributors</th>
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<td>SCM (15)</td>
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<td>Charmaine Franklin</td>
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<td>CAM4</td>
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<td>Neale et al. (2013)</td>
<td>Minghua Zhang, Cecile Hannay, Philip Rasch</td>
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<td>Phillip Austin, Knut von Salzen</td>
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<td>Vincent Larson, Ryan Senkbeil</td>
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<td>Schmidt et al.</td>
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<td>Adrian Lock, Mark Webb</td>
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<td>Hideaki Kawai</td>
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<td>Neggers et al (2009a, 2009b)</td>
<td>Roel Neggers, Pier Siebesma</td>
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<td><strong>LES (8)</strong></td>
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<td>LARC (NASA Langley Research Center)</td>
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<td>University of Washington/Stony Brook University, USA</td>
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Table 3: Boundary-layer turbulence schemes in SCMs

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Table 4: Shallow convection schemes. Some models use the same schemes for deep convections

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Figure Captions

Figure 1: Schematics of the experimental setup. The atmospheric temperature and water vapor are constructed based on moist adiabat and fixed relative humidity respectively. The large-scale subsidence is calculated based on the clear-sky thermodynamic equation. These fields change with SST, which is given warming of 2°C in the perturbed climate.

Figure 2: Averaged amount of low clouds in June-July-August (%) from the C3M satellite data. The red line is the northern portion of the GPCI (see text); the symbols “S6”, “S11” and “S12” are the three locations studied in the paper.

Figure 3: (a) Large-scale pressure vertical velocity at the three locations in the control climate (solid lines), and in the ERA-Interim (dashed). (b) Same as (a) except that the dashed lines denote subsidence rates in the warmer climate. (c) Same as (b) except for horizontal advective tendency of temperature. (d) Same as (c) except for advective tendency of water vapor.

Figure 4: (a)-(c) are the averaged profiles of cloud amount (%) by SCMs for S6, S11 and S12 respectively (from top to bottom panels). (d)-(f) are the same as (a)-(c) but by the LES models. (g)-(i) are from the C3M satellite measurements. The blue lines are ensemble averages; the red lines are the 25% and 75% percentiles.

Figure 5: Examples of time evolution of cloud amount (%) simulated by JMA (left column) for S6, S11 and S12 respectively from top to bottom panels; CAM4 (middle column); GISS (third column); SAMA (right column).
Figure 6: Examples of physical tendencies (g/kg/day) of water vapor budget in three SCMs at S11 for the control climate, “turb” for turbulence scheme, “conv” for convection scheme, “(c-e)” for net large-scale condensation. The dashed lines are cloud liquid water (0.1 g/kg). The black dots show the mid-point of model layers. (a) JMA, (b) CAM4, (c) GISS.

Figure 7: (a) Change of cloud radiative forcing ($\Delta$CRF, W/m$^2$) in SCMs at location S11 corresponding to 2$^\circ$K SST perturbation. Character “X” above a model’s name indicates that the shallow convection scheme is not active; “O” indicates that the shallow convection scheme is active. Models without these characters either do not separately parameterize shallow convection and PBL turbulence, or do not submit results with convection information.

Figure 8: (a) Change of moisture tendency in the layer of maximum cloud water (g/kg/day) by the “Turb” term from the control climate to the perturbed climate at S11. (b) Same as (a) but for surface latent heat flux (W/m$^2$).

Figure 9: Schematics of cloud feedbacks. Changes of clouds from the control (left) to warmer (right) climates. Blue arrows denote the term of turbulence parameterization in the moisture budget equation; red arrows denote shallow convection; black arrows denote cloud-top entrainment, lateral mixing and dry turbulence. The sizes of arrows schematically correspond to the magnitude of moisture tendency from the associated processes. (a) Negative cloud feedback, dominated by the increase of surface turbulence. (b) Positive cloud feedback, dominated by the increase of shallow convection or cloud-top entrainment. (c) Cloud feedback from shallow cumulus with sufficient depth, with sign depending on the cloud depth and lateral mixing.
Figure 10: Same as Figure 7, but for (a) S6, (b) S12. The models are ordered in the same sequence as in Figure 7. One model (EC_ECH) did not reach quasi-equilibrium state and it is indicated by “N/A”.

Figure 11: Same as Figure 7 but in LES models. (a) S6; (b) S11; (c) S12.
Figure 1: Schematics of the experimental setup. The atmospheric temperature and water vapor are constructed based on moist adiabat and fixed relative humidity respectively. The large-scale subsidence is calculated based on the clear-sky thermodynamic equation. These fields change with SST, which is given warming of 2°C in the perturbed climate.
Figure 2: Averaged amount of low clouds in June-July-August (%) from the C3M satellite data. The red line is the northern portion of the GPCI (see text); the symbols “S6”, “S11” and “S12” are the three locations studied in the paper.
Figure 3: (a) Large-scale pressure vertical velocity (subsidence) at the three locations in the control climate (solid lines), and in the ERA-Interim (dashed lines). (b) Same as (a) except that the dashed lines denote subsidence rates in the warmer climate. (c) Same as (b) except for horizontal advective tendency of temperature. (d) Same as (b) except for horizontal advective tendency of water vapor.
Figure 4: (a)-(c) are the averaged profiles of cloud amount (%) by SCMs for S6, S11 and S12 respectively (from top to bottom panels). (d)-(f) are the same as (a)-(c) but by the LES models. (g)-(i) are from the C3M satellite measurements. The blue lines are ensemble averages; the red lines are the 25% and 75% percentiles.
Figure 5: Examples of time evolution of cloud amount (%) simulated by JMA (left column) for S6, S11 and S12 respectively from top to bottom panels; CAM4 (middle column); GISS (third column); SAMA (right column).
Figure 6: Examples of physical tendencies (g/kg/day) of water vapor budget in three SCMs at S11 for the control climate, “turb” for turbulence scheme, “conv” for convection scheme, “(c-e)” for net large-scale condensation. The dashed lines are cloud liquid water (0.1g/kg). The black dots show the midpoint of model layers. (a) JMA, (b) CAM4, (c) GISS.
Figure 7: (a) Change of cloud radiative forcing (ΔCRF, W/m$^2$) in SCMs at location S11 corresponding to 2°K SST perturbation. Character “X” above a model’s name indicates that the shallow convection scheme is not active; “O” indicates that the shallow convection scheme is active. Models without these characters either do not separately parameterize shallow convection and PBL turbulence, or do not submit results with convection information.
Figure 8: (a) Change of moisture tendency in the layer of maximum cloud water (g/kg/day) by the “Turb” term from the control climate to the perturbed climate at S11. (b) Same as (a) but for surface latent heat flux (W/m²).
Figure 9: Schematics of cloud feedbacks. Changes of clouds from the control (left) to warmer (right) climates. Blue arrows denote the term of turbulence parameterization in the moisture budget equation; red arrows denote shallow convection; black arrows denote cloud-top entrainment, lateral mixing and dry turbulence. The sizes of arrows schematically correspond to the magnitude of moisture tendency from the associated processes. (a) Negative cloud feedback, dominated by the increase of surface turbulence. (b) Positive cloud feedback, dominated by the increase of shallow convection or cloud-top entrainment. (c) Cloud feedback from shallow cumulus with sufficient depth, with sign depending on the cloud depth and lateral mixing.
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Figure 11: Same as Figure 7 but in LES models. (a) S6; (b) S11; (c) S12.