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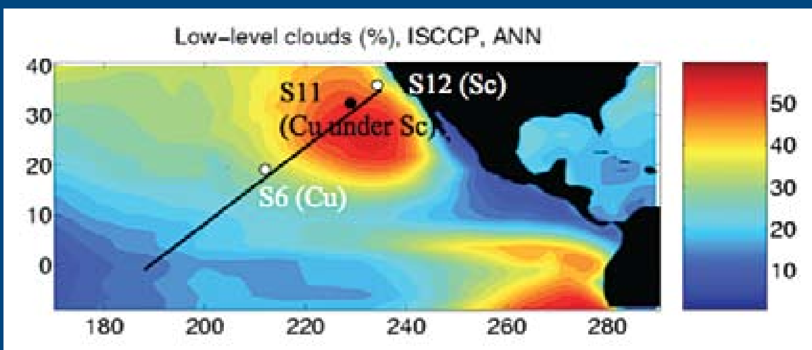
GCSS Teams with CFMIP to Understand the Physical Mechanisms of Low Cloud Feedbacks in Climate Models



The CGILS intercomparison transect overlaid on the Northeast Pacific annual-mean low cloud amount. Initially, CGILS focused on location S11 (32°N, 129°W) near the northern end of the GCSS Pacific Cross-Section Intercomparison study region. The other two locations are S6 and S12. S11 is near the climatological summertime maximum of low-level cloud cover. S6 is characterized by shallow cumuli, and S12 by shallow coastal stratocumulus.

CFMIP-GCSS Intercomparison of Large Eddy Models and Single Column Models (CGILS)

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Despite progress in recent years in understanding cloud processes and feedbacks in General Circulation Models (GCMs; Bony et al., 2006; Stephens 2005), knowledge is lacking about the physical mechanisms of cloud feedbacks and the causes of model-to-model variation in simulated cloud feedbacks. These issues are related to several factors: (1) the transient and spatial variability of clouds is typically much larger than the small signal of cloud feedbacks; (2) clouds are highly interactive with atmospheric dynamical circulations; and (3) in a GCM, clouds are simulated with an interactive web of physical parameterizations of subgrid structure, microphysics, turbulent mixing, cumulus convection, radiation and surface fluxes, which are poorly resolved by the model grid.

The World Climate Research Programme (WCRP) Working Group on Coupled Modelling (WGCM) **Cloud Feedback Model Intercomparison Project (CFMIP)** and the **GEWEX Cloud System Study (GCSS)** Boundary Layer Cloud Working Group have initiated a joint project—the CFMIP-GCSS Intercomparison of Large Eddy Models and Single Column Models (CGILS)—that uses idealized large-scale dynamical conditions to evaluate subtropical marine boundary layer cloud feedback processes in GCMs. The working hypothesis of CGILS is that the model

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diversity of simulated cloud feedbacks can mainly be explained as model-dependent cloud responses to the same warming and warming-induced change in large-scale conditions. The CGILS objectives are: (1) to understand the physical mechanisms of cloud feedbacks in GCMs by using Single-Column Models (SCMs); and (2) to assess the physical credibility of low cloud processes in the SCMs by using cloud-resolving models (CRM) and large eddy simulations (LES).

The approach of carrying out idealized simulations has advantages and limitations. The advantages are: (1) it isolates the model physics from dynamics, thus dramatically simplifying the problem; (2) it allows the use of LES, whose fine grids provide a considerably more realistic description of subgrid scale processes in the GCMs, to be compared with SCMs forced under identical conditions; and (3) it allows the sensitivity of the simulated clouds to various aspects of the changed large-scale dynamical conditions to be isolated. A major limitation of this approach is that the cloud response to climate change cannot be determined or constrained by current observations. However, this is a fundamental property of cloud feedbacks in climate models, not specific to CGILS, and is a part of the motivation for using LES models. In CGILS forcings used for the control climate are very close to observed large-scale conditions in July, allowing the clouds simulated by the SCMs and LESs to be tested against observations in the control climate.

CGILS focuses on the marine stratus, stratocumulus, and shallow cumulus clouds in the subsidence regions of the subtropics because these clouds have been identified as the main cause of model discrepancies (Bony and Dufresne, 2005). The study region is the northern half of the GCSS Pacific Cross-Section Intercomparison (GPCI) cross section, which traverses the northeast subtropical Pacific from California to Hawaii, and across the central Pacific Intertropical Convergence Zone (Siebesma et al., 2004). The large-scale forcing data is derived starting with the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis for July 2003 (courtesy of Martin Kohler). GCM simulations from the NCAR CAM3 and GFDL AM2, as well as simulations from the super-parameterized CAM were used as a guide to how forcings will change if sea surface temperature (SST) is uniformly warmed to 2K as a representative climate perturbation. In summary, as the climate warms, changes in free-tropospheric temperature are assumed to follow moist adiabats, relative humidity is assumed constant, profiles of horizontal heat and moisture advection are treated as invariant, and vertical motion is derived so as to balance advective warming and radiative cooling above the boundary layer. The dynamical conditions emulate the large-scale forcing in the control and warmer climate in the GCMs, but they are independent of any physical parameterizations. The derivation procedure follows Zhang and Bretherton (2008) with further refinements described at: *http://atmgcm.msrc.sunysb.edu/cfmip_figs/Case_specification.html*. Our initial hypothesis is that the clouds respond mostly to time-mean forcing changes. Thus, for simplicity, we use time-independent forcing.

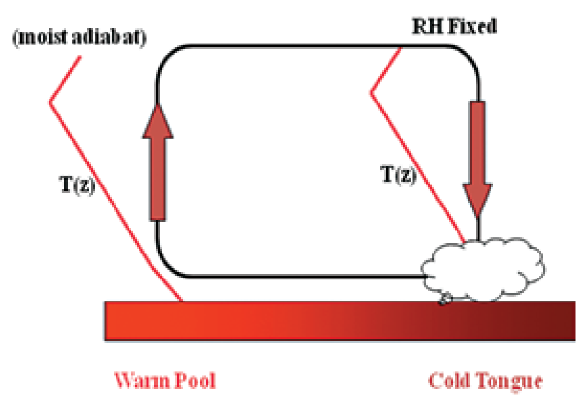
The figure below shows the schematic design of the study, where the key underlying variable is SST. For each set of SSTs (control climate and warmer climate), the corresponding large-scale subsidence is calculated. The SST and the subsidence rate are then used to force the SCM and LES. Simulation results from the control case are used to understand the physical processes in the models that generate the clouds, while the changes of clouds from the control SST to warmer SST are used to understand the cloud feedbacks in the same spirit as the Cess-type experiments (Cess et al., 1990).

Initially, CGILS focused on location S11 (32°N, 129°W) near the northern end of the GPCI cross-section. The figure on page 1 shows that this is near the climatological summertime maximum of low-level cloud cover. Physical properties of observed clouds (derived from satellite data) in July near this location are shown in the figure in the next column (Lin et al., 2009). Other CGILS study locations are S6 (characterized by shallow cumuli) and S12 (characterized by shallow coastal stratocumulus).

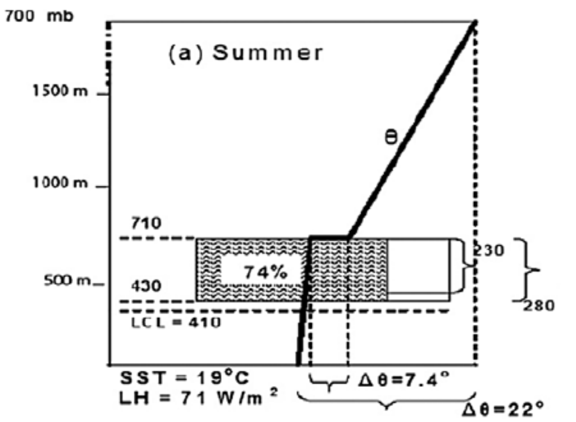
Table 1 lists the models that have submitted results and includes 16 SCM and five LES models. Other groups have expressed interest in participating and will be added.

Preliminary SCM Results

Many SCM simulated low clouds at S11 are similar to those in the parent GCM. In some models a constant forcing at a single point can represent GCM cloud processes, while in other models this is not the case. This feature depends upon the mechanism used for cloud generation in the models. An interesting result obtained by LMD/IPSL was that when a random transient component is added to the large-scale forcing, SCM simulated clouds and feedbacks are more representative of their GCM. Other CGILS groups will explore the importance of time-varying forcing to reproduce GCM clouds using their SCMs.



Schematic of the experiment. Low clouds in the subsidence region are the subject of the CGILS study.



Synthesis of observed low clouds near S11 in July. The numbers correspond to: (i) cloud amount in percentage in the shaded box; (ii) cloud top and base heights, as well as lifting condensation level (LCL) to the left of the shaded box; and (iii) cloud thickness. The adiabatic liquid water thickness (to the right of the cloud box) is calculated from the in-cloud liquid path. The thick lines represent schematic vertical profiles of potential temperature. Shown at the bottom are: SST, latent heat flux, lower-tropospheric stability (LTS), and inversion strength (adapted from Lin et al., 2009).

Cloud feedbacks simulated by the SCMs show two distinct groups of large negative and positive feedbacks. Two models with relatively large negative cloud feedbacks are CAM4 and CSIRO, and two with relatively large positive cloud feedbacks are GFDL and GISS. The mechanism of negative feedbacks in the SCMs tends to be similar to those in well-mixed boundary layer models (Caldwell and Bretherton, 2009) and the LES results of Blossey et al. (2009). In the SCMs, the reduced subsidence leads to a deeper and stronger trade inversion and supports a thicker cloud layer. SCMs with positive cloud feedbacks tend to have more decoupled boundary layers with more frequent episodes of cloud break up in the warmer climate due to activation of shallow cumulus convection, and in some cases (e.g., UKMO), more efficient cloud-top entrainment.

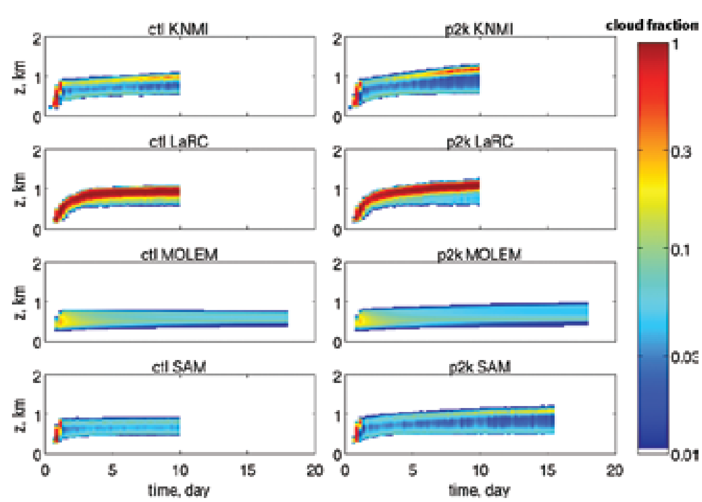
Preliminary LES Results

The 3-dimensional LES models have 25-m vertical and 50-m horizontal grid spacing and a double-periodic domain of 6.4 km per side. This vertical resolution is relatively coarse for stratocumulus simulations, a compromise that makes very long 10-30 day simulations computationally cheaper. The figure below shows a time-height plot of the simulated evolution of cloud fraction for the LES models. In the control climate, three of the four LES models that had submitted results by late February 2010 produced broken cloud layers whose area-mean albedo is much thinner than observed. This bias may occur because the specified vertical resolution of 25 m is too coarse and leads to spurious numerical mixing of dry warm air down through the inversion that quickly evaporates clouds. The fourth LES simulated too thick a cloud, even at this resolution. These strikingly different results are being investigated and may be due to a setup issue rather than the LES formulation.

All the LES models exhibit slightly increased cloud albedo in the specified warmer climate. This increase seems to be driven mainly by the weaker subsidence in the warmer cli-

Table 1: CGILS Participating Models and Investigators

Models	Model Institution	Participants
SCM 16		
CAM4	National Center for Atmospheric Research (NCAR), USA	Minghua Zhang, Chris Bretherton
CAM5	NCAR, USA	Cecile Hannay, Minghua Zhang
CCC	Canadian Climate Center, Canada	Phil Austin
CSIRO	Australian Commonwealth Scientific and Research Organization	Charmaine Franklin
ECHAM5	Swiss Federal Institute of Technology, Switzerland	Colombe Siegenthaler-Le Drian, Isotta Francesco, Ulrike Lohman
ECHAM6	Max-Planck Institute of Meteorology, Germany	Suvarchal Kumar, Bjorn Stevens
ECMWF	European Centre for Medium-Range Weather Forecasting	Martin Koehler
GFDL	Geophysical Fluid Dynamics Laboratory, USA	Chris Golaz, Ming Zhao
GISS	Goddard Institute for Space Studies, USA	Tony DelGenio, Audrey Wolf
GSFC	Goddard Space Flight Center, USA	Andrea Molod, Max Suarez, Julio Bacmeister
JMA	Japanese Meteorological Center, Japan	Hideaki Kawai
KNMI	Royal Netherlands Meteorological Institute, The Netherlands	Roel Neggers,Pier Siebesma
LMD	Laboratory of Dynamic Meteorology, France	Florent Brient, Sandrine Bony, Dufresne Jean-Louis
SNU	Seoul National University, Korea	Sing-Bin Park, In-Sik Kang
UKMO	Met Office, United Kingdom	Adrian Lock, Mark Webb
UWM	University of Wisconsin at Madison, USA	Vincent Larson, Ryan Senkbeil
DALES	Technical University Delft, The Netherlands	Stephan de Roode, Pier Siebesma
SAM	System for Atmospheric Models-University of Washington/Stony Brook University, USA	Peter Blossey, Chris Bretherton, Marat Khairoutdinov
UCLA	University of California at Los Angeles, USA	Irina Sandu, Bjorn Stevens
UCLA/ Langley	NASA Langley Research Center, USA	Anning Cheng, Kuan-man Xu



Time-height sections of cloud fraction from four LES with identical boundary forcing and resolution for a control simulation using mean conditions from point S11 (left) and from a simulation with boundary conditions adjusted to reflect a +2K overall low-latitude warming (right). The models have diverse control clouds, but all show boundary layer deepening and a slight albedo increase in the +2K climate.

mate, which allows the inversion to deepen and fill in with clouds. Thus far, the LES cloud biases limit their usefulness as a benchmark for the LES, but the consistency between their cloud responses to the climate change (except LaRC) is quite encouraging. The LES models will repeat the CGILS simulation with 5-m vertical resolution, which should increase the simulated cloud cover and thickness and decrease the LES biases.

In the near-term the LES models will run cases using forcings from two additional locations (the shallow cumulus and stratus at S6 and S12), where almost all SCMs have already submitted results. The SCMs will be run with slightly modified large-scale forcing data to match slight improvements made during the LES study. In additon, systematic testing will be conducted of the sensitivity of an S11 simulation to vertical grid resolution with the SAM LES to identify a fine enough LES grid spacing to achieve approximate convergence of cloud characteristics.

Longer-term plans include separating out the effects of the different climate-related changes to large-scale forcings (vertical motion, free tropospheric temperature and relative humidity, advection, and CO_2 changes) in both SCM and LES simulations; more careful use of the observations and LES results to improve the SCM physical parameterizations; and use of a common set of time-varying advective forcings for a more realistic comparison with observations and GCM simulations. New results from CGILS will be published in the future.

References

Blossey, P. N., C. S. Bretherton, and M. C. Wyant, 2008. Subtropical Low Cloud Response to a Warmer Climate in a Superparameterized Climate Model. Part II: Column Modeling with a Cloud Resolving Model. *J. Adv. Model. Earth Syst.*, Vol. 1, Art. #8, 14 pp.

Bony, S., and J.-L. Dufresne, 2005. Marine boundary layer clouds at the heart of cloud feedback uncertainties in climate models. *Geophys. Res. Lett.*, 32, L20806, doi:10.1029/2005GL023851.

Bony, S., and coauthors, 2006. How well do we understand climate change feedback processes? *J. Clim.*, 19, 3445–3482.

Caldwell, P., and C. S. Bretherton, 2009. Response of a subtropical stratocumulus-capped mixed layer to climate and aerosol changes. *J. Clim.*, 22, 20–38.

Cess, R. D. et al., 1990. Intercomparison and interpretation of climate feedback processes in 19 atmospheric general circulation models. *J. Geophys. Res.*, 95, 16601–16615.

Lin W., M. Zhang, and N. Loeb. 2009. Seasonal variation of the physical properties of marine boundary layer clouds off the California coast. *J. Clim.*, 22, 624–2638.

Siebesma, A. P., and coauthors, 2004. Cloud representation in general circulation models over the northern Pacific Ocean: A EUROCS intercomparison study. *Quart. J. Roy. Meteor. Soc.*, 130, 3245–3267.

Stephens, G. L., 2005. Cloud feedbacks in the climate system: A critical review. *J. Clim.*, 18, 237–273.

Zhang, M., and C. S. Bretherton, 2008. Mechanisms of low cloud climate feedback in idealized single-column simulations with the Community Atmospheric Model (CAM3). *J. Clim.*, 21, 4859–4878.