CFMIP: Towards a better evaluation and understanding of clouds and cloud feedbacks in CMIP5 models

Sandrine Bony[1], Mark Webb[2], Christopher Bretherton[3], Stephen Klein[4], Pier Siebesma[5], George Tselioudis[6] and Minghua Zhang[7]

1: Laboratoire de Météorologie Dynamique, IPSL, CNRS, UPMC, Paris, France
2: Hadley Centre for Climate Prediction and Research, Met Office, Exeter, UK
3: Department of Atmospheric Sciences, University of Washington, Seattle, WA, USA
4: PCMDI/LLNL, Livermore, CA, USA
5: KNMI, de Bilt, The Netherlands
6: NASA GISS, and Department of Applied Physics, Columbia University, NY, USA
7: ITPA, MSRC, State University of New York at Stony Brook, Stony Brook, NY, USA

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As first emphasized 30 years ago by A. Arakawa and J. Charney (Charney 1979), the simulation of cloud processes and feedbacks by general circulation models remains one of the most critical aspect of climate modelling. In particular, cloud-radiative feedbacks remain the primary source of uncertainty for transient and equilibrium climate sensitivity estimates (Soden and Held 2006, Randall et al. 2007, Dufresne and Bony 2008), and play a critical role in anthropogenic aerosol-induced climate forcing (Lohmann and Feichter 2005). In addition, clouds play a key role in the hydrological cycle and in the large-scale atmospheric circulation, at both planetary and regional scales. By affecting precipitation and atmospheric dynamics, uncertainties in cloud and moist processes remain a major concern for virtually all aspects of climate modelling and climate change research. In a context where the climate modelling community is increasingly focusing its efforts on regional climate change impacts and biogeochemical (e.g. carbon and aerosols) climate feedbacks, improving our understanding of cloud-climate interactions and assessing our confidence in the simulation of cloud processes and feedbacks in climate models is imperative.

For this purpose, the WGCM Cloud Feedback Model Intercomparison Project Phase-2 (CFMIP2, www.cfmip.net), in collaboration with the GEWEX Cloud System Study (GCSS) and the WCRP/CAS Working Group on Numerical Experimentation (WGNE), has elaborated a strategy to better assess and understand clouds and cloud-climate feedbacks in climate models. This strategy has been implemented in CMIP5 in several ways.

1. CMIP5 idealized experiments

Model Inter-comparison projects, including CMIP3, have always exhibited a large range of cloud-climate feedbacks (Soden and Held 2006, Bony & Dufresne 2005, Webb et al. 2006). There are so many factors or physical processes that may potentially contribute to this spread, that interpreting the origin of inter-model differences has turned out to be difficult, and designing specific observational tests to assess the different feedbacks has remained elusive. This is one reason why no-one as yet been able to determine which of the model cloud feedbacks seem the most credible. To make progress on this issue, a pre-requisite is to better understand the reasons why complex climate models behave the way they do and why they differ from one another. This requires the comparison of models across a large variey of configurations, from the most complex to the simplest. For this purpose, a series of idealized experiments have been advocated by CFMIP for CMIP5.

Gregory and Webb (2008) found that changes in atmospheric structure induced by the direct CO2 radiative effect can lead to a "rapid cloud response" (not mediated by the global mean surface temperature response) that can explain a significant fraction of the inter-model spread in cloud feedbacks. Experiment 6.5 of CMIP5 consists of an atmospheric simulation using observed sea-surface temperatures (SSTs) while quadrupling the CO2 concentration in the atmosphere. By analyzing the results of this experiment, it will be possible to examine the fast response of clouds to CO2 increases and thus to assess the role of this response in the spread of cloud feedbacks accross models. It will also be possible to assess the validity of the traditional forcing/feedback diagnostics used so far to interpret inter-model differences in climate sensitivity.

Two complementary experiments (6.6 and 6.8) will allow us to examine the cloud response to a +4K SST (in the absence of CO2 changes), either spatially uniform or associated with a scaled spatial pattern typical of coupled model SST responses in CMIP3 model projections at time of CO2 quadrupling. It will then be possible to examine the effects of local and remote changes in SST on cloud feedbacks, and to better assess the influence of large-scale atmospheric dynamical changes on cloud feedbacks.

Finally, a series of short, idealized aqua-planet experiments (6.7) will make it possible to compare models and their predicted climate response to different types of perturbations (a globally uniform surface warming or a quadrupling of CO2), in a simpler and more idealized context. These experiments use the protocol proposed by Neale and Hoskins (2001) and Medeiros et al. (2008). They will be useful to better interpret the origin of inter-model differences in cloud feedbacks (as shown for instance by Medeiros et al. 2008), but also in many other aspects of climate change (e.g. large-scale atmospheric circulations). These idealized simulations will also facilitate the comparison between general circulation models (GCMs) and the new generation of computationally-demanding climate models such as global Cloud Resolving Models (Miura et al. 2005) or Super-Parameterizations (Khairoutdinov et al. 2005), as well as between GCMs and theoretical or conceptual models.

By comparing climate models through this series of realistic and idealized experiments (Figure 1), the hope is to better identify the physical processes that play a predominant role in inter-model differences of particular simulated climate features. Hopefully, such an identification will then help to propose critical observational tests for assessing the relative credibility of the different models regarding these features.

2. CMIP5 model outputs from the CFMIP Observations Simulator

Several instruments observe clouds from space, including those onboard the A-Train constellation of satellites (Stephens et al. 2002). However, there is no unique definition of clouds or cloud types, in models or in observations. For instance, some cloud may be detected by some satellite instruments but not by others, depending on the viewing geometry, the sensitivity of instruments, or the attenuation of the remote signals. In addition, some cloud layers might not be observed from space if they are obscured by thick upper-level cloud layers. Therefore, to compare models with satellite observations, and even to compare models with each other, it is necessary to use a consistent definition of clouds.

For this purpose, WGCM has recommended that the climate models that participate in CMIP5 use COSP, the "CFMIP Observations Simulator Package" (Bodas-Salcedo et al. 2011): this community software tool, developed in collaboration among several research centers, allows the diagnosis from model outputs of various quantities (e.g. brightness temperatures at specific wavelengths, radar reflectivities and lidar scattering ratios) that would be measured by different satellite-borne instruments if satellites were flying above an atmosphere similar to that simulated by the model. Through this approach, models and satellites "speak the same language", and observations and model outputs may be compared quantitatively in a consistent manner (Klein and Jakob 1999, Webb et al. 2001, Haynes et al. 2007, Chepfer et al. 2008).

In CMIP5, it will be possible to evaluate 3-hourly, daily and monthly statistics of model cloud properties against observations from the International Satellite Cloud Climatology Project (ISCCP, Schiffer and Rossow 1983), from the Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL), and from the cloud-profiling lidar instrument on board the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO, Winker et al. 2009) and the Cloud Satellite CloudSat (Stephens et al. 2002). It will then be possible to assess, for the first time, the ability of climate models to reproduce the observed vertical structure of clouds over the whole globe (Figure 2), from the tropics to high latitudes, including over icy polar regions (the A-Train observes the Earth up to about 80 degrees of latitude). It will also be possible to unraveal compensating errors in the simulation of top-of-radiative fluxes between cloud areal coverage, cloud vertical structure and cloud optical thickness.

Note also that to facilitate the access to satellite diagnostics consistent with COSP simulator outputs, CFMIP has set up the "CFMIP-Obs" website (http:// climserv.ipsl.polytechnique.fr/cfmip-obs.html).

3. Process-oriented diagnostics

To better understand the behavior of climate models, their dependence on model formulation, it is necessary to analyze the simulations not only at the large-scale level and on long time scales, but also at the process level. For this purpose, two categories of process-oriented diagnostics have been included in CMIP5: high-frequency outputs and physical tendency terms.

The high-frequency outputs include 3-hourly global instantaneous outputs for a short period (the year 2008), and half-hourly or timestep outputs over a selection of 119 sites (Figure 3) for several years (1979-2008). The 119 sites have been selected either because they correspond to the location of instrumented sites (e.g. those from the Atmospheric Radiation Measurement Program or the european CloudNet network), of past field campaigns (e.g. AMMA transect, VOCALS, ASTEX, RICO, etc), or to regions of the globe where inter-model differences in climate-change cloud feedbacks were particularly large in CMIP3 and thus deserve enhanced scrutiny. The list of 119 locations can be found at http://www.cfmip.net -> CMIP5information.

As the internal variability simulated by CMIP5 models will be different from that associated with observations, the comparisons between pointwise model outputs and observations will be necessarily of statistical nature, using for instance compositing methodologies. It will be possible to evaluate in particular the diurnal cycle of meteorological and cloud variables predicted by climate models, physical relationships among dynamical, thermodynamical and cloud variables, and the role of different physical processes on the vertical distribution and time evolution of various geophysical quantities.

The CMIP5 experiments also include a set of tendency terms which diagnose the increments to clouds, temperature and water vapour from different physical schemes such as convection, boundary layer, radiation, dynamics, etc (Williamson et al. 2005, Ogura et al. 2008). These, along with upwelling and downwelling radiative fluxes throughout the atmoshere will provide a wealth of information with which to understand cloud feedback mechanisms.

Our hope is that these outputs will encourage the scientific community involved in process studies to analyze model results in the light of their particular expertise and by taking benefit of the wealth of available observations.

4. Further coordinated analyses and inter-comparisons of cloud processes and feedbacks among CMIP5 models

As part of CFMIP, GCSS and WGNE, several coordinated analyses of cloud processes and feedbacks in CMIP5 models will be carried out in parallel to CMIP5.

In CMIP3, the response of marine planetary boundary-layer (PBL) clouds to climate warming had been identified as a leading source of inter-model discrepancies in climate change cloud feebacks (Bony and Dufresne 2005, Webb et al. 2006). To better understand the physical processes responsible for this response, and assess their dependence on model formulation, CFMIP and GCSS have jointly organized a project examining the response of several PBL cloud types to an idealized climate change simulated by single-column versions of CMIP5 models on the one hand, and by Large-Eddy Simulation (LES) and Cloud Resolving Models (CRMs) on the other hand. This project, referred to as CFMIP-GCSS Intercomparison of Large Eddy Models and Single Column Models (CGILS, Zhang and Bretherton 2008, Zhang et al. 2010), will allow us to examine and to interpret the part of the PBL cloud feedbacks spread across CMIP5 models that results from differences in model formulation (the large-scale forcing will be identical in all models), and to compare the physical processes at work in single-column models with those at work in LES models forced in identical conditions. Three case studies will be examined, that correspond to three different PBL cloud types (stratus, stratocumulus and shallow cumulus). The large-scale forcing associated with current climate conditions is an idealization of the forcing actually found at three locations over the GCSS Pacific Cross-Section Intercomparison (GPCI) cross-section that extends from California to the central Pacific Inter-Tropical Convergence Zone (ITCZ). The change of large-scale conditions (sea surface temperature, large-scale vertical velocity, etc) associated with an idealized climate change is derived from Zhang and Bretherton (2008) and described at http://atmgcm.msrc.sunysb.edu/cfmip_figs/Case_specification.html. Currently, 16 single-column models and 5 LES models are participating in this inter-comparison.

In parallel to CMIP5, WGNE in collaboration with WGCM have organized an inter-comparison of climate models run in "weather forecasts mode" referred to as "Transpose-AMIP" (Philipps et al. 2004, http://www.metoffice.gov.uk/hadobs/tamip/index.html). Running weather forecasts (or more correctly hindcasts, as they are run retrospectively) with climate models enables detailed evaluation of the processes operating through a comparison of the model with a variety of observations for particular meteorological events, and makes it possible to examine the model biases associated with 'fast-processes' (e.g. clouds, Williams and Brooks 2008, Xie et al. 2008, Hannay et al. 2009). These simulations will be run with model versions similar to those used in CMIP5, using COSP and extracting CFMIP process-diagnostics over the 119 point locations discussed earlier. By assessing the models' errors in their depiction of clouds (using both satellite observations and ground-based observations) in these simulations, and by comparing these errors with those found in the same models run in climate mode (in CMIP5), it will be possible to investigate how much commonality there is between model errors on short and long timescales, and then how much the correction of cloud errors in CMIP5 models may be investigated by testing model developments in a "weather-forecasts mode".

5. Conclusion

Since CMIP3, considerable efforts have been deployed in the scientific community interested in clouds and clouds feedbacks to define strategies and to develop tools aiming at better assessing and understanding cloud processes and feedbacks in climate models. By implementing COSP into their model and by extracting process-oriented CFMIP outputs, these efforts have been largely echoed and relayed by the different climate modelling groups participating in CMIP5. The numerous opportunities of cloud evaluation and analysis permitted by these efforts should make CMIP5 very special compared to previous CMIP exercises, and hopefully a source of substantial scientific progress for climate modelling and climate change studies.

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Figure 1

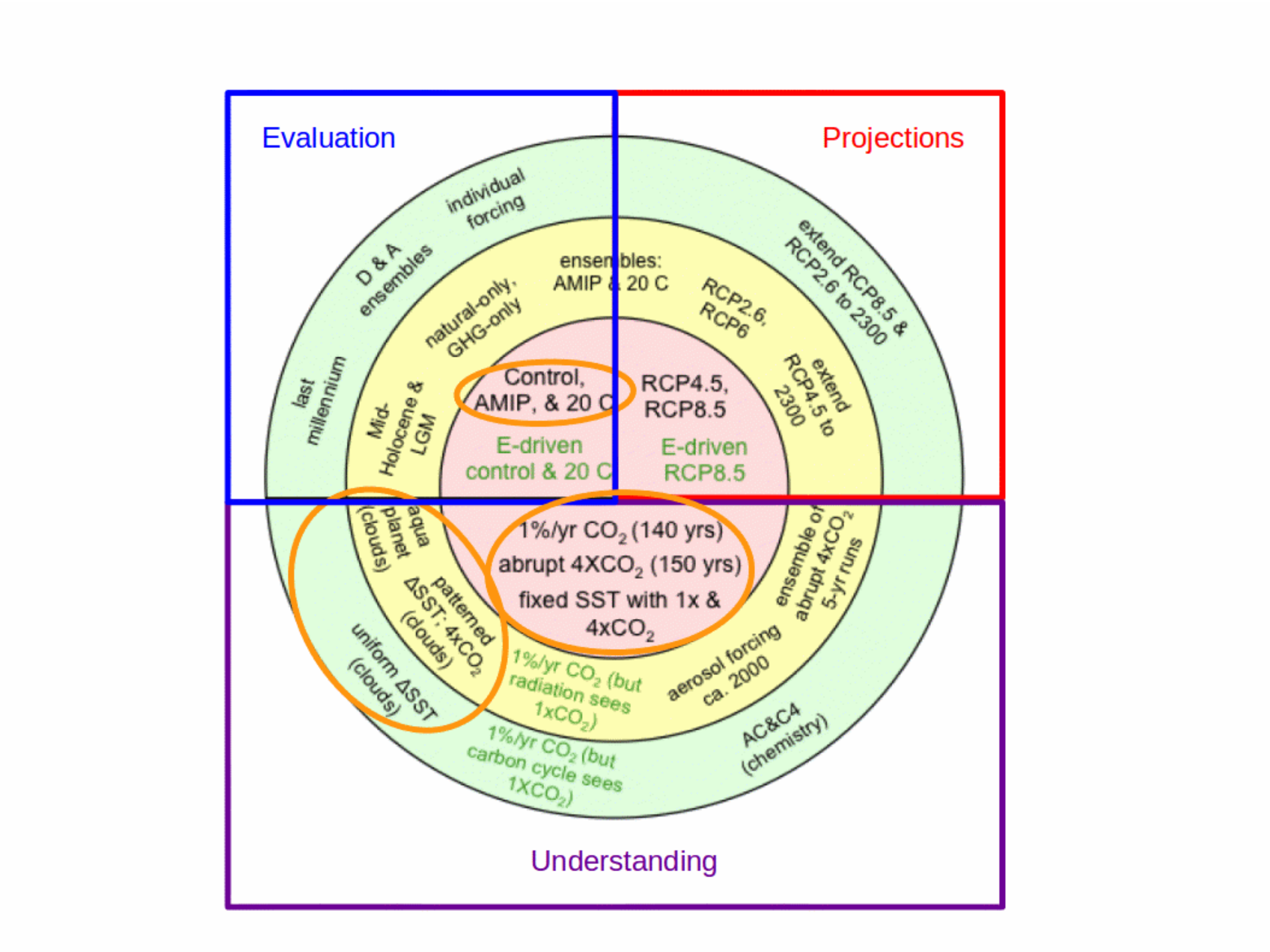

Figure 1: CMIP5 long-term experiments (described in Taylor et al. 2011) will aim at evaluating the realism of climate models on the recent and longer-term past, at providing climate projections for the 21st century and beyond, and at understanding inter-model differences in their simulation of the current climate and of climate change. CFMIP evaluations and analyses of cloud processes and feedbacks in CMIP5 will focus on the experiments highlighted by orange circles.

Figure 2 :

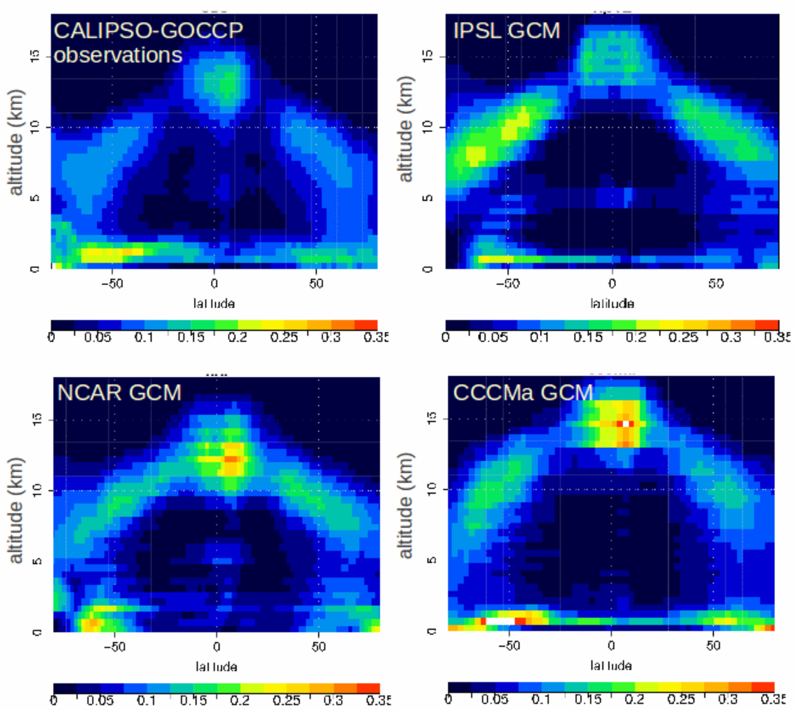

Figure 2: Comparison of the annually, zonally-averaged vertical distribution of the cloud fraction derived from the CALIPSO-GOCCP satellite observational dataset (Chepfer et al. 2010) and from several general circulation models using the CFMIP Observations Simulator Package (COSP) during the model development process.

Figure 3 :

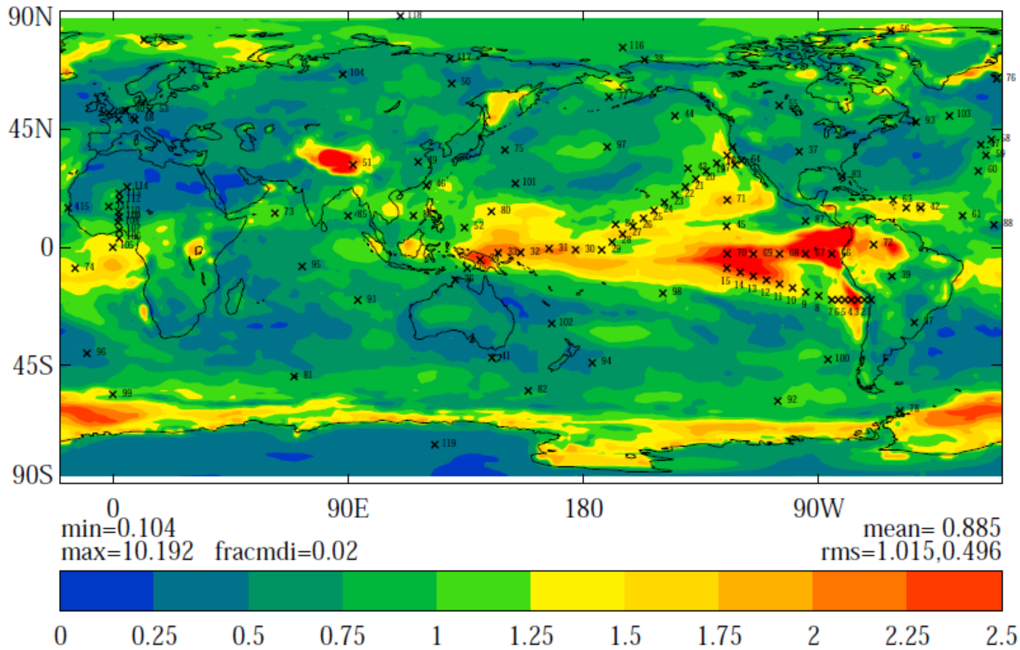

Figure 3: To facilitate the detailed evaluation and analysis of cloud processes simulated by CMIP5 models over a large range of climatic conditions, high-frequency (half-hourly) process-oriented model outputs (CMIP5 output table referred to as cfSites) will be provided by modelling groups over an ensemble of 119 sites. Each black cross represents a site, corresponding either to the location of an instrumented site (ARM and CloudNet stations, Dome C, etc), of a past field campaign (VOCALS, ASTEX and AMMA transects, TOGA-COARE, RICO, etc), or a region where the CMIP3 inter-model spread of the shortwave cloud radiative forcing response to climate change (indicated by the background color shading) was particularly large.