EUCLIPSE

EU Cloud Intercomparison, Process Study & Evaluation Project

Grant agreement no. 244067

Deliverable D4.1 A developing database and protocol for parameter and structural (numerical) sensitivity studies.

See also: http://www.euclipse.eu/wp4/wp4.html

Delivery date: 24 months

CLOUDS ON-OFF KLIMATE INTERCOMPARISON EXPERIMENT (COOKIE)

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1. Synopsis

Cloud-radiative effects are expected to control many aspects of the current and future climates, ranging from the large-scale circulation of the atmosphere and intra-seasonal variability to climate sensitivity and precipitation projections. However, investigations so far have been carried out using individual models and various methodologies. To identify robust effects and facilitate physical understanding, the role of clouds in climate and climate change needs to be investigated in a more coordinated way and through a wider range of model configurations and complexity. This provides the scientific motivation for the Clouds On Off Klima Intercomparison Experiment (or COOKIE for short) proposed here. This COOKIE proposal, which is based on parameter sensitivities and analysis frameworks explored and developed as part of the EUCLIPSE project, uses simple atmosphere-only simulations, where is some experiments clouds are made transparent to radiation. The experimental protocol is centered around six additional experiments to the CFMIP contribution to CMIP5, three thirty-year AMIP and three five-year Aqua planet Experiments, thus comprising a total of 105 years of atmosphere only simulations. Many of the experiments, and the affordability of the proposed computations, lend themselves to very high-resolution models. In addition to the base experiments, a number of other experiments and model configurations are described, which would complement the main COOKIE experiments, some as optional contributions to the COOKIE protocol, others which we call CREAM (Clouds Radiation, Easy Aerosol and More) extend the framework.

Below some of the background motivation for COOKIE is presented, followed by a description of the COOKIE experiments and extensions to include additional COOKIES and CREAM.

2. Background

2.1. **Parameter Sensitivities & Analysis Frameworks.** Controls on climate sensitivity have been explored using multi-model ensembles (MME) and perturbed parameter ensembles (PPE) by a number of groups. A general finding has been that relationships that emerge from the PPE framework do not generalize to the MME. For example, using a single model Webb et al. (2012) find a very strong relationship between biases in cloud radiative effect, or net top-of-atmosphere radiation, and the climate sensitivity across their PPE. This relationship is not, however, reproduced within the CMIP3 MME. Similarly, using a PPE derived from a different model, Klocke et al. (2011) found

Date: August 31, 2012.

that climate sensitivity is well correlated with root-mean-square errors in cloud-radiative effects in strongly subsiding regions characterized by intermediate values of lower tropospheric stability. However this property of the PPE also did not explain differences in the climate sensitivity of the CMIP3 MME. Brient and Bony (2012) explored a limited PPE using the IPSL model, and in so doing also showed that factors which tended to increase low cloud amount, for instance a change in the formulation of their statistical cloud scheme or a change in their precipitation efficiency, also increased the sensitivity of low clouds to changing surface temperatures.. All three studies studies explored a range of different parameters, and reported on those influencing the climate sensitivity of their models, as summarized in Table 1. An intriguing aspect is the sense that low-cloud feedbacks are related to low cloud amounts in each model, although not in the multi-model ensembles. Could it be that a more robust relationship between low-cloud amount and the sensitivity of low clouds to warming is somehow masked by other changes in the MME?

TABLE 1. Summary of parameters that have been identified as being correlated (r_{CS}) to climate sensitivity.

Parameter		r_{CS}	
	ECHAM	IPSL	UKMO
Cloud Overshoot Parameter	+	n/a	n/a
Low Cloud Amount	+	+	+
Upper Tropospheric Vertical Resolution	−?	n/a	n/a
Entrainment (Convection)	n/a	n/a	+
Ice Fall Speed	n/a	n/a	+
Precipitation Efficiency	n/a	−	−

2.2. **Moist Static Energy Budget.** A framework for thinking about these changes in the moist-static energy, h, budget as analyzed by Brient and Bony (2012). Vertically averaged this takes the form,

$$Q + \langle R^{\mathrm{cld}}_{\mathrm{atm}} \rangle + \overbrace{\langle R^{\mathrm{clr}}_{\mathrm{atm}} \rangle - \langle \omega \frac{\partial h}{\partial p} \rangle - \langle \mathbf{u} \cdot \nabla h \rangle}^{-A} = 0, \tag{1}$$

where Q denotes the net surface flux (latent plus sensible, where the former are an order of magnitude larger), R irradiances, ω the pressure velocity, and $\mathbf{u}$ the horizontal wind. Clear and cloudy sky irradiances are decomposed so that $R^{\mathrm{cld}}_{\mathrm{atm}}$ denotes the atmospheric cloud radiative effect. The equation essentially describes the balance between surface fluxes, radiative fluxes and the dynamics, or circulation, at stationarity. Brient and Bony (2012) argue that the dynamic and clear sky radiative driving is relatively robust in their simulations, such that $\partial_T A = 6\,\mathrm{W\ m^{-2}\ K^{-1}}$. If this holds across models the inference is that

$$\partial_T Q + \partial_T \langle R^{\mathrm{cld}}_{\mathrm{atm}} \rangle = \partial_T A. \tag{2}$$

This equation provides a compelling framework for analyzing models. Are changes in $\partial_T A$ robust. If so what explains how different models partition this change between surface fluxes versus changes in cloud radiative effects? And is, as suggested by Rieck et al. (2012) and Webb and Lock (2012), there a link between $\partial_T Q$ and the changes in cloud radiative effects, $\partial_T \langle R^{\rm cld}_{\rm atm} \rangle$?

By introducing a parameter $\beta \in \{0, 1\}$ Brient and Bony (2012) proposed to control the influence of cloud radiative effects

$$\partial_T Q + \beta \partial_T \langle R^{\rm cld}_{\rm atm} \rangle = \partial_T A. \tag{3}$$

By using idealized experiments with fixed perturbations to the sea-surface temperatures Brient and Bony (2012) explored the $\beta = 0$ limit and found that changes in clouds were substantially damped, suggesting that $\Delta R^{\rm cld}_{\rm atm} \propto R^{\rm cld}_{\rm atm}$ which would also explain the tendency for many models to have changes in low-cloud cloud radiative effects which are proportional to the strength of the cloud radiative effects of their low clouds. This idea, which they called the β feeback can, and should, be tested in a wider class of models.

2.3. **Further Sensitivities.** As part of the ECHAM6 development Mauritsen et al. (2012) explored parameter sensitivities identified by Klocke et al. (2011), and found that the effects of the cloud overshoot parameter, which had a large influence on a low vertical resolution version of the model, did not generalize to a newer version of the model. Vertical resolution is thought to have been decisive, although other changes were also introduced in the new version of the model, as the effect of the cloud overshoot parameter is more pronounced at the very coarse resolution that are often used in many of the PPE experiments. Mauritsen et al. (2012) also took care to ensure that their set of perturbed models satisfied the same strict quality controls on the base climate that were demanded of their standard model. So doing greatly restricted the number of plausible models that they could create, and may also have limited biases that contribute to the differences in climate sensitivity in model versions that arose in some of the earlier studies, where less stringent criteria were employed. They showed that the strategy used to tune ECHAM6 affected the resultant climate sensitivity to the level of about $\pm 10\%$. Similar uncertainty accompanies a small change in the vertical grid in ECHAM6 (Stevens et al., 2012), although because the model version with the different vertical grid also must be retuned, it is not clear how to separate the parameter sensitivities from those associated with the choice of vertical coordinate.

The effect of convective entrainment has also been identified as an important control parameter on the structure of the general circulations. Work with the CNRM and IPSL models by Oueslati and Bellon (2012) and with the MPI-ESM by Möbis and Stevens (2012) show that the amount of convective mixing determines whether the model produces a single or double ITCZ in certain aqua-planet configurations, and that the tendency toward a double ITCZ in an aqua-planet exacerbates the double ITCZ problem in a more realistic planet and dampens intraseasonal variability (cf., Crueger et al., 2012). This is attributed variously to the degree of moisture coupling by Möbis and Stevens (2012) or to the degree to which convection couples to the large-scale dynamics by Oueslati and Bellon (2012). Work with the MPI model further shows that these differences may also influence climate sensitivity. Experiments using ECHAM6 in a radiative convective equilibrium configuration shows that the equilibrium climate sensitivity correlates strongly with changes in the upper troposphere, and that these changes are in turn dependent on the representation of convection (Popke et al., 2012). Additionally, because the choice of convection scheme in ECHAM6 also influences the humidity structure and hence the moist static energy of the lower troposphere, the effects of the representation of deep convection may affect the response of shallow convection through its preconditioning of the moist static energy budget, for instance by influencing $\partial_T A$ in Eq. (1).

2.4. **Simulation Hierarchies.** Methodologically the development of ideas for constraining cloud feedbacks have benefited greatly from the use of a hierarchy of model configurations. These include single column model studies used by Brient and Bony (2011) to isolate the effect of their parameter sensitivities in well constructed single-column analogs (e.g., the CGILS S6 case with random forcing Zhang et al., 2012) as well as aqua-planet simulations, (e.g., Brient and Bony, 2012; Oueslati and Bellon, 2012; Möbis and Stevens, 2012), radiative convective equilibrium (Popke et al., 2012) and cloud resolving modeling (Rieck et al., 2012). To build on these methodological innovations and deepen our understanding of cloud feedbacks EUCLIPSE/CFMIP is proposing a coordinated extension of the CFMIP runs conducted as part of the fifth phase of the Coupled Model Intercomparision Project (Taylor et al., 2012, CMIP5,), which we call COOKIEs and CREAM.

3. COOKIE

COOKIE, the *Clouds On-Off Klima Intercomparison Experiment* is designed to expand on the AMIP and aqua-planet subset of the CFMIP simulations conducted as part of CMIP5. The main COOKIE set of experiments consists of an extension of modelling centers contributions to CMIP5, and involve six additional simulations totaling 105 years of additional simulation time using atmosphere only models. Additional COOKIEs are also identified below but are optional.

The motivation for COOKIE is to better identify robust effects of cloud-radiative interactions, for instance on changes in cloud feedbacks as discussed in the context of Eq. (1) above, but also through the effects of cloud radiative effects on precipitation, and precipitation changes in a warming climate (e.g., Bony et al. (2012). To what extent does the lack of cloud-radiative interactions make other aspects of the changing climate system easier to understand? If clouds do not interact with radiation, how much can we collapse changes in top-of-atmosphere irradiances among models performing AMIP and AMIP4K experiments, or do differences in convection and cloud microphysical schemes still cause large differences in the thermal structure of the atmosphere, and its radiatively important humidity profile? Does the structure of the ITCZ, the atmospheric response to ENSO, and intraseasonal variability behave differently? Do the fast tropospheric adjustments to CO_2 behave differently. How do clouds robustly affect the distribution of precipitation between the land and sea? Initial explorations using the COOKIE framework were formed nearly a quarter century ago (Slingo and Slingo, 1988; Randall et al., 1989; Slingo and Slingo, 1991); in COOKIE we wish to rejoin this intellectual thread, and follow it up more systematically using modern models.

The CLOUDS-ON component of the COOKIEs , is identified in Table 2. Most groups have already performed these experiments through the CFMIP contribution to CMIP5. The cloud-off part of the experiment involves a requirement for new simulations and is

TABLE 2. CLOUDS-ON component of COOKIE

Name	SST	CO_2	Time Period	Minimum Output
AMIP	AMIP	observed	1979-2008	AMON
AMIP4xCO2	"	4×observed	"	"
AMIP4K	AMIP+4K	observed	"	"
aqua	QOBS	348 ppmv	5yr	"
aqua4xCO2	"	1372 ppmv	"	"
aqua4K	QOBS+4K	348 ppmv	"	"

described in Table 3. It makes reference to the base experiments in Table 2. There are two ways to perform this experiment, the easiest and safest would be to simply make clouds transparent in the call to radiation. Another way would be to replace the use of the all-sky irradiances in the heating rate calculation, and the net irradiance into the surface, with clear-sky irradiances. This might be more error prone, but it it can be correctly implemented, it has the advantage that the normal model output diagnostics would give an indication of how the cloud radiative effects change when they are not coupled to the dynamics (heating rates). Either approach is okay, although the second approach is preferred.

TABLE 3. CLOUDS-OFF ($\beta = 0$) component of COOKIE. offAMIP simulations may require a climatological run of as long as twenty years to spin-up soil moisture and provide more balanced initial data.

Name	Base Experiment	Modification
offAMIP	AMIP	$\beta = 0$
offAMIP4xCO2	AMIP4xCO2	"
offAMIP4K	AMIP4K	"
offaqua	aqua	"
offaqua4xCO2	aquaxCO2	"
offaqua4K	aqua4K	"

For groups who did not participate in CMIP5 we note that the AMIP component of these experiments can be intensive, particularly for very high resolution, super-parameterized or global cloud resolving models. For these groups we prefer that simulation resources be focused on the aqua planet COOKIEs. Because they are run in equinoctial conditions even runs of a few months would be interesting, and sampling issues could be assessed using simulation data of more conventional GCMs. If any of these groups would also be interested in performing short AMIP solutions, we recommend the (up to) three year period starting in 2005, because of its overlap with active space borne remote sensing (CALIPSO and CloudSat were launched in mid 2006). For each experiment only a single simulation is requested.

Because sea-surface temperatures are fixed turning clouds off should not dramatically impact the simulations. Nonetheless, for the AMIP simulations the change in clouds will change the surface energy budget over the land. To explore these effects a twenty year AMIP simulation (1979-1999) was performed with ECHAM6. Fig. 1 shows that the

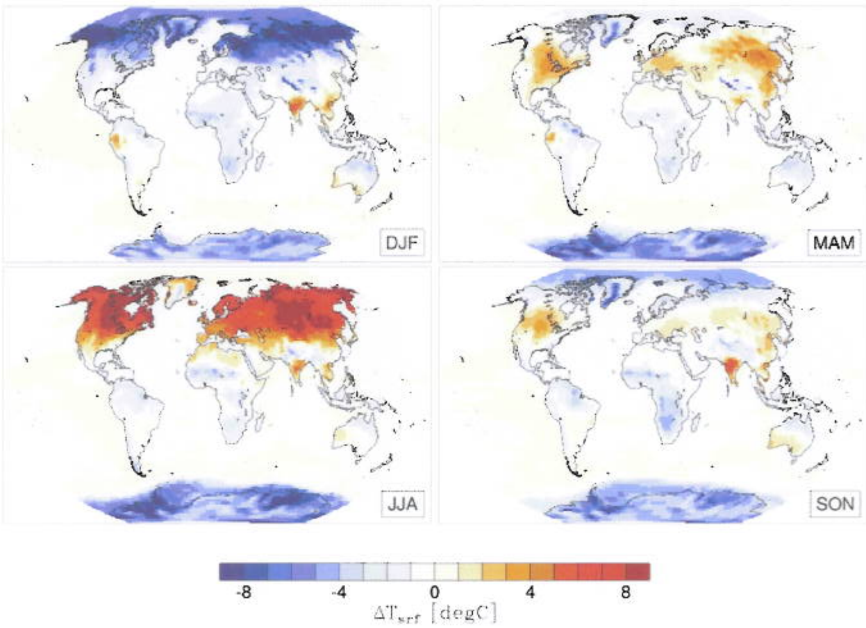

FIGURE 1. Surface temperature changes between Clouds-Off and Clouds-On

seasonal cycle is greatly amplified over land, with much warmer summer temperatures and much colder winter temperatures. This can be expected to substantially alter the land-sea circulations, driving more precipitation over land in the summer season. In ECHAM6 effects on soil moisture are less apparent. A strong seasonal cycle in soil moisture changes is not evident, e.g., as shown in Fig. 2 where the difference between the first and last five years of the twenty year simulation are shown. Soil moisture changes are generally less than 10%, more over arid regions where soil moisture was small to begin with. These results may be sensitive to how soil moisture is modeled, ECHAM6 still has a very simple single layer hydrology. Simulations with the CNRM model suggest a slower adjustment in soil moisture, based on which they recommend a 10-20 year climatological simulation to equilibrate soil moisture for the offAMIP simulations. This would then serve as the starting point for the off AMIP simulations, increasing the total simulation time by the additional time required to spin-up soil moisture in their model. Issues associated with soil moisture highlight one of the advantages of the aqua-planet simulations, which is to help isolate changes that are not dependent on changing land-sea circulations, or slow adjustments in things like soil moisture.

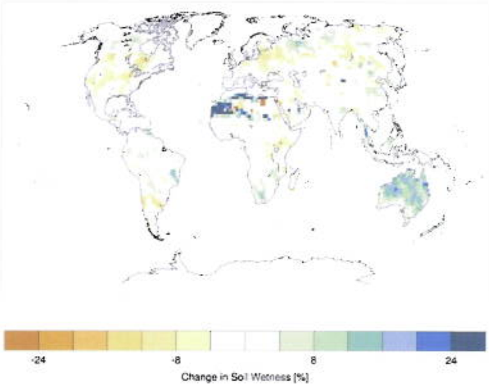

FIGURE 2. Soil moisture changes between Clouds-Off and Clouds-On

3.1. **On Output:** To make the output requirements as simple as possible, for the Clouds-Off component of the COOKIEs, only the AMON (Atmosphere monthly) data is requested, and the provision of CMIP5_day data available is strongly encouraged, particularly for the AMIP runs, where it would allow for studies of intraseasonal variability and extremes. The CMOR2 format is requested, if at all possible, but if this proves too onerous for groups participating for the first time it should not be seen as a requirement. Output data will be archived by the MPI-M, with the help of DKRZ under the support of the EUCLIPSE Project, in a fashion that makes it accessible to the broader community. Please contact the cookie project team (cookie@mpimet.mpg.de) if you have any questions, or if you have data you wish to make available.

3.2. **Notes on Experimental Protocol.** The AMIP and Aqua planet experiments are fully described on the CMIP5 web pages, although supplementary material provided by Brian Medeiros[1]is useful for setting up the aqua-planet experiments for those who have not already done so. Groups should consider starting their offAMIP simulations from a climatological simulation in which clouds are off and soil moisture is allowed to equilibrate. In the clouds-off experiments the only change from the base experiments is for the clouds to appear transparent to radiation (or use the clear-sky irradiances instead of all-sky irradiances for calculating surface and atmospheric heating). Cloud effects should not contribute to the optical properties of the atmosphere. So for instance in the "offaqua" set of experiments this means that there will be no contribution to atmospheric optical properties of the atmosphere from particulate matter whatsoever, as the aqua planets are recommended to be run without aerosols, or at least without aerosol contributions to radiative transfer. Multiple realizations of each experiment are welcome, but not necessary.

[1] http://www.atmos.ucla.edu/~brianpm/cfmip2_aqua.html

3.3. **Submission and Access of Data.** Simulations will be submitted to, and archived by, the German Climate Computing Center (DKRZ) through the support of the EU-CLIPSE project. Simulations will be available to all project participants, and eventually to the broader public.

4. Additional COOKIES

By setting $\beta = 0$ in Eq. (3) only for low clouds, i.e., for $p > 700$ hPa,and recovering the same effect as if β were set to zero everywhere, Brient and Bony (2012) argued that cloud-radiative effects primarily associated with low-clouds dominated the sensitivity of their models β feedback. In a complementary experiment Möbis and Stevens (2012) explored β effects on the ITCZ position, and found that the radiative effects of high-clouds were decisive in determining the structure and position of the ITCZ. Finally, to explore how much of the inter model spread is determined by cloud radiative effects an aqua-planet experiment is proposed for which the cloud component of the radiative forcing will be prescribed as a function of pressure and latitude. These approaches suggest a sequence of additional, optional experiments, which are summarized in Table 4 and which groups are encouraged to performed as time and computational resources permit. The output requirements and protocol are the same as for COOKIE unless otherwise noted.

Table 4. Clouds-Off component of COOKIE

Series	Base Experiment	Modification
offpblAMIP	AMIP	$\beta = 0$ for $p > 680$ hPa
offpblAMIP4K	AMIP4K	"
offpblaqua	aqua	"
offpblaqua4K	aqua4K	"
fixedaqua	aqua	specified mean $R^{\mathrm{cld}}_{\mathrm{atm}}(p, \phi)$

5. CREAM

The CREAM (Convection Radiation Easy Aerosols and More) project is an optional supplement to COOKIE which seeks to use additional idealizations to understand the effects of clouds, convection and the aerosol on basic properties of the atmospheric general circulation.

Preliminary work suggests that radiative convective equilibrium might be a constructive framework to bring together very computational intensive approaches such as large-eddy simulation, global cloud resolving modeling, and conventional simulation for the purposes of understanding water vapor, lapse rate and cloud radiative feedbacks in the tropics. Using ECHAM6 in a radiative convective equilibrium setting, coupled to a mixed layer ocean, Popke et al. (2012) showed that many of the features of the base tropical climate were reproduced, including the detailed vertical structure of clouds. Persistent large-scale circulations developed in response to sea-surface temperature anomalies, which themselves were forced internally through the effect of cloud and water vapor on the surface energy budget. Although the domain as a whole was homogeneous, the circulations and SST anomalies were sufficiently long-lived (correlation timescale of a week) to permit a regime analysis similar to what one performs for simulations of more realistic model configurations. Moreover, and somewhat surprisingly, the range of regimes sampled by such a simple configuration was similar to what is found in the present day tropics. In the ECHAM6 RCE simulations it was also found that the model climate sensitivity was a factor of two smaller than the standard ECHAM6, but reproduced about 70% of the signal seen in ECHAM6 when run in a standard configuration and evaluated over the tropics, and strongly correlated to changes in the upper troposphere which were convection scheme dependent. In a related study Vial et al. (2012) analyzed a large number of CMIP5 models and showed that most of the model spread could be explained by differences in cloud-feedbacks in the tropics, and in circulation regimes (weak vertical motion) that were well sampled by the RCE framework. These results motivate the use of radiative convective equilibrium as a framework for exploring some of the more important tropical cloud feedbacks, and linking GCM results to less parameterized, but much more computationally expensive, approaches. This extension to the COOKIE project we call CREAM (Convection Radiation Easy Aerosols and More).

In addition to radiative convective equilibrium the CREAM experimental suite will also expand on the very simple β model of clouds on or off, to introduce simple parameterizations of clouds that can be used in many models, and thereby provide a more realistic, yet still constrained, framework for exploring cloud effects. One motivation for doing so is to attempt to constrain cloud representations sufficiently to be able to answer the question as to whether differences in possible aerosol effects on clouds is principally dependent on the representation of the aerosol, or the clouds. These simulations also will be complemented by additional simulations designed to explore robust responses to idealized aerosol perturbations.

The experimental configuration for CREAM is still in the process of being defined, but will involve the use of idealized model configurations such as aquaplanes, as well as idealized AMIP or mixed layer ocean simulations, depending on the particular question being posed. Working ideas for different classes of experiments are given below. Groups interested in performing CREAM simulations, should start with the following as suggestions, and iterate with us on the final specification by email (cookie@mpimet.mpg.de).

5.1. **Radiative Convective Equilibrium:** Here we are asking groups to carry out radiative convective equilibrium simulations with their GCMs, Global Cloud Resolving Models, or SuperParameterized GCMs coupled to a 10 m deep slab ocean. These simulations can be performed on any domain size that one wishes, although reference calculations with normal GCMs are preferred on an Earth sized planet. Simulations should have uniform solar insolation and no rotation, so that formally every grid point on the model domain is identical. For this reason, models that preserve an initial symmetry will need a random perturbation to break the symmetry of the configuration (for instance by introducing a small perturbation in the divergence or temperature field at the initial time). A diurnal cycle of radiation should be specified, so that every grid point is in phase, it is solar noon over the whole planet at once. Otherwise the Aquaplanet specifications should be followed, and data that is latitudinally varying in the aquaplaned should be replaced by constant values corresponding to those valid on the equator of the aquaplanet. Two simulations are requested, one with present day CO_2

concentrations of 348 ppmv, another with values concentrations increased by a factor of four.

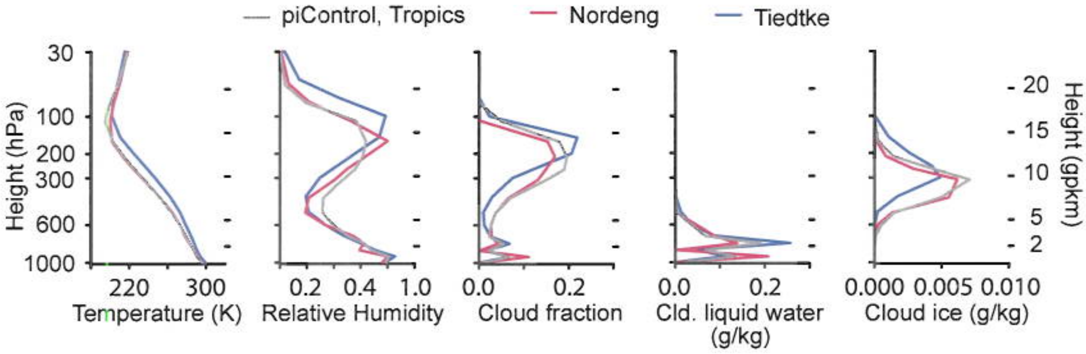

FIGURE 3. Profile of temperature, humidity and clouds over tropical ocean in MPI-ESM piControl experiments, and in RCE using two convection schemes. The Nordeng scheme (red) is the version used in the piControl (grey)

5.2. **Easy (fixed RH) Clouds:** In these experiments we propose to repeat the AMIP CLOUD ON and the AMIP4K simulations using a very simple cloud scheme for the purpose of radiative transfer. These ideas are still in development but involve specifying cloud amount using a simple function of model relative humidity, $f(\mathrm{RH}; \mathrm{RH}_c(T))$ in each model, where the control parameter RH_c is a tunable critical relative humidity which will be adjusted in each model in a way that guarantees a similar balance of top of the atmosphere irradiances.

5.3. **Easy Aerosol:** Several classes of experiments are anticipated. One builds on the $\beta = 0$ experiments to explore the influence of hemispheric anomalies in radiative forcing on the distribution of cloudiness, for instance using idealized aerosol forcing in AMIP or mixed layer ocean simulations. The second will repeat the previous RH_c experiment, but with an update of cloud optics to mimic a possible aerosol perturbation. The goal of these experiments is to help understand to what extent a model's aerosol effect depends on processes wholly unrelated to clouds and convective processes. In addition experiments using AMIP and aquaplanet simulations are planned with idealized aerosol forcing (zonally uniform aerosol optical depth, single scattering albedo and asymmetry factor specified as a function of latitude and pressure) to help explore the response of models to such idealized forcing, and in particular how well aerosol effects are bounded through the use of specified, but idealized aerosol optical properties.

5.4. **More:** Within the CREAM framework we wish to also include specifications for Transpose AMIP experiments, possible single column model studies, and extensions to study the influence of clouds on transient climate sensitivity. But these additional experiments are still in the very early stages of definition.

6. Summary

Cloud-radiative effects are expected to control many aspects of the current and future climates, ranging from the large-scale circulation of the atmosphere and intra-seasonal variability to climate sensitivity and precipitation projections. However, investigations so far have been carried out using individual models and various methodologies. To identify robust effects and facilitate physical understanding, the role of clouds in climate and climate change needs to be investigated in a more coordinated way and through a wider range of model configurations and complexity.The Clouds On Off Klima Intercomparison Experiment (COOKIE) proposes a simple set of atmosphere only experiments designed to better understand the impacts of clouds on climate and climate change. Groups who wish to participate in the COOKIE are requested to perform an additional six experiments with fixed sea-surface temperatures, totaling 105 years of simulation time. In addition to the base COOKIE an number of other COOKIES and an extension called CREAM expands the project into a tiered set of experiments designed to better isolate the effects of clouds, convection, and eventually aerosols on equilibrium climate sensitivity. The ultimate idea behind COOKIEs and CREAM is to control the representation of cloud radiative effects (clouds on-off) in a hierarchy of models so as to better identify large-scale constraints that might be controlling the basic factors through which changes in temperature, and radiative fluxes associated with different distributions of greenhouse gases or aerosols, influence cloudiness.

Acknowledgments

This project is supported by funding from the European Union, Seventh Framework Program (FP7/2007-2013) under grant agreement no 244067. Gilles Bellon, Hervé Douville and Pier Siebesma are thanked for their comments on a draft form of this proposal.

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