CFMIP

Cloud Feedback Model Intercomparison Project

2017 CFMIP meeting on Clouds, Precipitation, Circulation & Climate Sensitivity

25-28 September 2017, University of Tokyo, Tokyo, Japan

<u>Session Report</u>

Session 1 - Cloud feedbacks and emergent constraints
Chair: Chris Bretherton

Clouds respond quickly to environmental factors. Thus, the factors controlling how clouds respond to and feed back on climate change should be the same as those controlling clouds on interannual and shorter time scales, though the weighting of those factors will depend on the time scale. Thus, we should be able to use present-day climate and its natural variability to determine these factors and quantitatively estimate how clouds respond to them. We can then use climate models together with these estimates to observationally constrain the global climate change feedback of clouds. The seven science talks of Session 1 explored steps in this chain in diverse ways.

Steve Klein presented a recently-published synthesis of results from five studies of low-cloud controlling factors based on satellite and surface observations on monthly, seasonal and interannual time scales. When extrapolated to climate change, the studies agree that overall warming of the atmosphere-ocean column is the most important cloud controlling factor, and that in response, low cloud will decrease (positive low cloud feedback). This is corroborated by high-resolution models that explicitly simulating low clouds and the turbulent motions that sustain them.

Axel Lauer discussed a sample of four diverse 'emergent constraints' on equilibrium climate sensitivity (ECS), based respectively on present-day tropical observations of SE Pacific double-ITCZ precipitation bias, relative humidity, lower-tropospheric mixing, and clouds. The original papers introducing each these constraints suggested that they implied an $2xCO_2$ ECS of around 4 K, consistent with the upper half of estimates from CMIP5 models. Using alternate datasets, Lauer finds they individually suggest ECS of 2.7-4.1 K, and all four ECS estimates include the range 3.3-3.6 K.

Andrew Dessler noted that monthly anomalies ΔR of global TOA net radiation are surprisingly weakly correlated with global mean surface temperature anomalies, due to decoupling between the surface and the overlying atmosphere, especially at higher latitudes. He showed that ΔR is better correlated with 30S-N mean 500 hPa temperature anomalies, so that the latter provides a less noisy proxy for atmospheric temperature trends over the last 50 years, when it can be reliably constrained by upper-air observations. During the questioning, he noted that surprisingly, this correlation is mainly driven by shortwave rather than longwave variability.

Mark Webb proposed a physical argument for why models with a larger double-ITCZ precipitation bias tend to have a smaller ECS. It is based on uncoupled aquaplanet AGCM simulations, which tend to have a single ITCZ if the atmospheric column longwave radiative cooling is a strongly decreasing function of the precipitation (which also promotes positive longwave cloud feedback and higher ECS), and a double ITCZ if this sensitivity is weaker.

Gregory Cesana compared G20OCCP analysis of CALIPSO satellite lidar observations with CMIP5 models in low-latitude subsidence regions where low clouds are particularly challenging to simulate. He showed that in these regions, there are correlations between the observed mean and variability of low cloud amount (LCA) and CRE and the response of LCA and CRE to climate change. Observed cloud fraction profiles can be broken down by cloud controlling factors (warming, inversion strength, subsidence) and compared with GCMs.

Rob Colman compared interannual and decadal variability of several global climate metrics with their sensitivity to climate change. The intermodel variation of lapse rate and water vapor feedbacks, like cloud feedbacks, are correlated across these time scales. Models have a broad spread of decadal-scale global-mean surface temperature variability, mostly below observational estimates.

Tianle Yuan used satellite observations to look at the dominant spatial patterns of interannual variability of SST and low cloud. Because warm SSTs tend to reduce low cloud cover, allowing more sunlight to further warm the ocean, the low cloud feedback on these patterns was found to be strongly positive, enhancing their persistence.

Consensus

Observations and LES simulations suggest that tropical low-cloud feedback is positive and of order 1W/m2/K.

Use of current (monthly/seasonal/interannual/decadal) climate variability to constrain feedbacks and thus ECS is very promising, but more remains to be done with emphasis on understanding physical processes.

Emerging issues

The dependence of cloud response on SST is less clear away from the tropics. Emphasis so far has been on tropical and stratocumulus regimes. We need to extend this emphasis to shallow cumulus and higher latitude regimes, and determine appropriate controlling factors in the context of physical mechanisms.

Emergent constraints are highly sensitive to observational dataset and length of record. We need to utilize the full spectrum of available observational datasets and carefully account for uncertainty.

Session 2 - Forcing, feedbacks and climate sensitivity
Chair: Mark Webb, Rapporteur: Tomoo Ogura

Jonathan Gregory: "Can we estimate the future climate sensitivity from the historical period?"
Climate feedback parameter α is estimated with (1)AOGCM historical runs and (2)AGCM amipPiForcing runs. The results are compared with the estimates from (3)abrupt 4xCO2 runs. The α from (2)amipPiForcing is larger than that from (3)abrupt 4xCO2 runs in all three AGCMs examined, suggesting that historical forced α may not give an accurate estimate of the parameter for elevated CO2. The α from (1)AOGCM historical runs may give an accurate estimate of the parameter for elevated CO2, if we have an accurate estimate of radiative forcing. However, the estimates from (1) is sensitive to historical changes in SST that is not well-simulated by AOGCMs.

Levi Silvers: "The diversity of cloud responses to Twentieth-century Sea Surface Temperatures"
Climate feedback parameter α is estimated with amipPiForcing runs using 3 versions of GFDL AGCMs. Large decadal variation in α in the amipPiForcing runs originates from changes in low cloud amount, which is related to changes in static stability (EIS). The decadal changes in α are decomposed into contribution from different regions. Results indicate that tropical subsidence regions dominated by stratocumulus clouds cannot explain the variation in α; it is rather due to contribution from broader tropics.

Mark Zelinka: "On the time dependence of climate feedbacks"
Time-dependence in climate feedback parameter λ is quantified in abrupt4xCO2 runs with 28 AOGCMs. Cloud, albedo, and lapse rate feedbacks all become more positive / less negative with time in the vast majority of models, which contributes to the change in net climate feedback λ. Both cloud and lapse rate feedbacks become more positive in regions of delayed warming, consistent with the hypothesis that evolving pattern of surface warming is responsible for the change in λ. Large inter-model variance is found with respect to cloud, albedo, and lapse rate feedbacks, which is partly explained by the amount of delayed warming in different AOGCMs.

Hideo Shiogama: "Reconciling estimates of the Earth's climate sensitivity"
The best estimate of equilibrium climate sensitivity (ECS) based on the Earth's energy budget and observation data is 2°C, which is more than 1°C lower than the averaged estimate from CMIP5 AOGCMs of 3.1°C. The difference between the two estimates can be explained by three factors, namely, (1)systematic underestimation of ECS by the energy budget approach, which originates from the assumption that climate feedback does not change over time, (2)changes in radiative forcing in the last 10-15 years due to decline of solar activity and volcanic eruptions, and (3)biases in observed surface air temperature due to limited spatial coverage and blending with SST data.

Thorsten Mauritsen: "Towards a theory for Earth's Climate Sensitivity (ECS)"
This study discusses the best estimate for the Earth's Climate Sensitivity (ECS), referring to previous studies estimating ECS. The argument starts with a hypothesis that ECS is 2.6K (2.0-

3.5) based on robust understanding of climate feedbacks, and then checks the consistency of the hypothesis with other multiple lines of evidence. The hypothesis is corroborated under the following conditions, namely, (1)ECS rises in a warmer climate, (2)feedback is highly time-dependent, and/or (3)aerosol cooling is strongly negative, and (4)climate models miss negative feedback(s).

Bjorn Stevens: "The climate sensitivity parameter over a wide range of forcings"
This study explores responses of an AGCM coupled to a slab ocean in RCE configuration under a wide range of forcing due to atmospheric CO2 increase and decrease. For present day forcing, the climate sensitivity remains stable at about 2K. However, 16-fold increase in CO2 induces oscillations in global surface temperature with amplitude as large as 10K, which last for years to decades. Strong radiative forcing of 16xCO2 increases the static stability and stratiform clouds in the non-convective area, which cool the surface and eventually ventilate (cool) the convecting area with a time-scale dependent on surface heat capacity.

Xin Qu: "On the interconnection of climate feedbacks"
An Energy Balance Model (EBM) is used to better understand the anti-correlation between cloud and surface albedo feedbacks found in CMIP5 GCMs. The EBM runs reproduce the anti-correlation between the two feedbacks as in GCMs. In both EBMs and GCMs, the anti-correlation is largely attributed to the high/low latitude warming contrast associated with one degree increase in global-mean temperature. The results suggest that the inter-connection between the two feedbacks is an artifact of the way we define the feedbacks.

Michael Byrne: "Atmospheric dynamics feedback: concept, simulations and climate implications"
Changes in TOA radiation induced by atmospheric CO2 increase are decomposed into dynamic, thermodynamic, and nonlinear terms using the abrupt4xCO2 and piControl runs of CMIP5 AOGCMs. The dynamic term is smaller than the thermodynamic term at all latitudes, although the former turns out relatively important in the tropics. The study shows that (1)conservation of atmospheric mass, and (2)quasi-linear dependence of TOA radiation on omega, in combination, constrain the dynamic term to be small on large scales.

Daniel Feldman: "Rigorous and comprehensive greenhouse gas and aerosol radiative forcing calculations for CMIP6"
Overview of greenhouse gas (GHG) and aerosol radiative forcing estimates is presented. GHG forcing from CO2 and CH4 are well-understood, but parameterization error and forcing dependencies needs to be addressed. Aerosol radiative forcing is a work-in-progress and still has large uncertainty. New diagnostics are requested for RFMIP/CMIP6 to better understand the uncertainty and reduce errors. Global benchmark calculations with line-by-line or band-model are conducted. Evaluation of GFDL AM4 and CESM 1.2.2 suggest that debugging efforts specific to each model are needed to reduce spread in aerosol forcing.

Jean-Louis Dufresne: "The contribution of emission height and total absorptivity to the greenhouse effect"
This study discusses why greenhouse effect of the atmosphere increases for a CO2 increase, even though the absorptivity of the atmosphere almost saturates. A framework is proposed to quantify contribution to the change in TOA radiative flux due to CO2 increase from changes in

(1) total absorption and in (2) emission height of the atmosphere. Two test cases, namely $2xCO_2$ and $1.2xH_2O$ are considered in the calculation. The results show that changes in emission height play a major role, even for the H_2O increase.

Discussion
Question was posed as to whether there is a consensus that estimates of ECS based on fixed feedback interpretation of historical warming is likely to be biased low. There seemed to be increasing support for this view, although some concerns remained over a lack of understanding as to exactly how the effect works. The discussion underlines the importance of diagnostic studies to better understand changes in climate feedback according to SST pattern. There was a comment that Xin Qu's talk was a very nice example of using idealized modelling to test a well posed hypothesis. It offers hope for dealing with feedback anticorrelation elegantly rather than lumping terms together. There was a discussion on the mechanism of the iris effect. Many papers refer to the narrowing ITCZ as an iris effect although the original iris argued by Lindzen et al.(2001) was a cloud fraction effect.

Consensus

Time dependence of feedback parameter. Estimates of ECS based on fixed feedback interpretation of historical warming is likely to be biased low.

Emerging Issues

Importance of diagnostic studies to better understand changes in climate feedback, including use of idealized modeling and wide range of forcings.

Session 3: Low cloud feedbacks and adjustments

Chair: Jen Kay, Rapporeteur: Bill Frey

C. Roberto Mechoso: Sensitivity of climate simulations to low-level cloud feedbacks

C. Roberto Mechoso analyzed low level cloud feedbacks and tropical-extratropical connections. The talk started with a thought experiment – What happens when you cool sea surface temperatures over the Southern Ocean (SO)? The anomalously cool SSTs are advected into the stratocumulus regions by subtropical gyres. Thus the question becomes -- How will stratocumulous clouds respond to cooler SSTs? C. Roberto used two GCMS - UCLA CGCM and NorESM to imposed cool SST anomalies in the S. Ocean. The result was large impacts on the TOA radiation that were model dependent and depended on the low cloud response. Over the Southern Ocean, the UCLA model increased cloud amount in subtropical stratocumulous regions. In contrast, there was a very small low cloud response in NorESM. Subsidence increased in the Southern Hemisphere subtropics of both models, but more so in the UCLA model. The magnitude of the low cloud feedback is important. The cloud pattern mimics SST and EIS patterns and affects the amplitude of modes of variability.

Chris Bretherton: Cloud feedbacks in ultraparameterized (UP) CAM5

Chris Bretherton motivated high resolution modeling stating that climate feedbacks controlling ECS result from interactions between clouds and circulation at small scales. Boundary layer clouds which are most important for ECS are only resolved at LES scale but LES is too expensive in a global model. With UP, Chris is able to run an eddy permitting 2d cloud resolving model in each GCM grid cell. The UP model also has high vertical resolution in troposphere. The model simulations are 500x more expensive than conventional GCM but much cheaper than global LES (See Marchand and Ackerman 2010). Chris presented the cloud response to +4K SST using multiyear UP simulations at 4x5 degree horizontal resolution. In a superparameterized model (CCSM4 with $4xCO_2$), the ECS is 2.8K and there is a weak positive cloud feedback which mimics standard models. The UP model has more realistic clouds and PBL struction compared to the low resolution model. For example, SE Pacific stratocumulous region, a standard model has too little cloud too low, increasing the horizontal and vertical resolution in the SP model gives a deeper cloud at the right level.The UP model shows PBL turbulence with a diurnal cycle**.** Chris next analyzed the cloud feedbacks with different tuning. Mixed phase cloud partitioning affected the shortwave feedbacks, but not the longwave feedbacks. All model versions had reduced mid level and more high level clouds (FAT), and "probably" a shallower PBL. In summary, Chris found UP is computationally feasible in GCMs and that the UP global cloud feedback is positive, which is consistent with CMIP5 consensus. UP is good, but does not solve all cloud problems. For example, UP model did not have coastal SC decks.

Hajime Okamoto: Cloud-feedbacks from CloudSat/CALIPSO to EarthCARE

Hajime Okamoto introduced three cloud products from the CALIPSO satellite produced at Kyushu University (KU): 1) Cloud mask, 2) Cloud particle type, 3) Ice and water microphysics. To motivate interest in the KU products, he reminded us that EarthCARE (Earth clouds aerosol Radiation explorer) should launch in 2019 at a 393 km orbit (lower than CALIPSO). EarthCARE has a doppler cloud radar at 94 Ghz (like CloudSat), a 355nm LIDAR (CALIPSO 532

nm), visible imager, and a broadband radiometer. He then presented examples from the KU products including the mask product and the ice-water partition product and for model evaluation of MIROC. Next, large differences between GOCCP product, NASA ST product, and the KU product in both ice and water cloud fractions were discussed. All three products purportedly measure the same quantities but there are differences due to their retreival algorithm. Specifically, the differences are due to different treatment of ice, clouds/aersrol partitions, resolution,treatment of fully attenuated pixels, and multiple scattering (Cesana et al 2016 JGR). Ground based instruments can be used to refine and improve algorithms and products.
Question from Mark Webb: Will a GCM simulator be available for the new KU products?
Answer: Yes

Youichi Kamae: Increase in the northeastern Pacific low cloud cover in the rapid adjustment to CO2
Youichi Kamae discussed the subtropical cloud adjustment that occurs in all CMIP5 models. There is a decrease in cloud amount leading to positive SW CRE - But is it really low cloud? Actually, he found the total cloud reduction is mostly from mid and high clouds. Low clouds shift westward in subtropical stratocumulous regimes as shown by a dipole East-West pattern in low cloud amount in stratocumulous regions. The factors controlling low cloud cover include: SST, EIS, subsidence, humidity profiles. In rapid adjustment SST is constant, so some or all of the other factors must dominate. Youichi looked at several possibilities for rapid adjustment of low cloud coverage. First, there was a dynamic mechanism: Increased CO2 increases atmospheric temperature even when SSTs are fixed. This enhances inversion strength and should give increased low cloud coverage. Second, there was a thermodynamic Mechanism: CO2 warms troposphere. The result of this warming is a shallower PBL, increased boundary layer moisture, increased moisture gradient with free troposphere, and decreased low cloud coverage. But -- Neither of these mechanisms explain westward shift: What does? A possibility: Land warms due to CO2, this changes atmospheric circulation and shifts (reduced wind speed along coasts, reduced clouds right on the coast). Youichi tested this mechanism with different configurations of MIROC5, aquaplanet, aquaplanet with a bit of land, and a realistic model. He saw the westward shift in models with land, not in aquaplanet. This comparison helped him arrive at increased understanding. When SST is fixed, the land surface warms which gives lower pressure over land and produces a wind anomaly which weakens the trade winds over the western coastal regions. In summary, land-sea temp contrasts explains westward shift in subtropical low cloud coverage.
Question from Robert Pincus - What controls the scale of the westward shift?
Answer: The magnitude of the change in circulation due to land-sea contrast

Andrew Gettleman: The interaction of cloud forcing and feedabacks from the global scale to the process level
Andrew Gettelman motivated his talk by stating that aerosols may play a large role in forcing and the role in feedbacks is uncertain. There are forcing differences between models, and these differences are related to ECS. There is also a relationship between adjusted forcing and ECS in CMIP5 models, a relationships that is strongest among CMIP5 models which reproduce historical forcing. Andrew's simulations have interactive aerosols i.e., Aerosols are affected by climate state (ie sea salt emissions depend on wind speed). So in these simulations climate

change can cause aerosol feedbacks. Aerosol feedbacks contribute to spread in diagnosed cloud feedbacks because aerosols may directly alter cloud feedback. Feedbacks were analyzed in three ensembles: Large ensemble (LE) with RCP8.5 forcing, medium ensemble (ME) with RCP4.5 forcing, fixed aerosol ensemble (FE) with RCP8.5 forcing and fixed 2000 aerosols. He calculated. The LE has largest change in Aerosol optical depth, but FE also has changes even though aerosols are fixed. Differences are largest over the SO, where there are no anthropogenic emissions. He found the FE changes are due to changes in climate over the Southern Ocean. He then asked: Can we factor this aerosol change out in cloud feedback calculations? Yes, we can come up with an aerosol kernel and factor it out. When you use a kernel to remove aerosol impacts it makes the cloud feedback more positive. The northern hemisphere feedbacks look the same between models after aerosol feedback is removed. Southern Ocean differences remain because aerosol kernel is due to anthropogenic aerosols, which are less important over the Southern Ocean. In summary, understanding in forcing limits our ability to understand feedbacks. Different aerosols give different cloud feedbacks (50% of cloud feedback in CESM, which equates to a 0.5K in ECS). We need to factor in aerosols when comparing models. Now we can can remove aerosol impacts with an aerosol kernel.

Consensus

Additional support for positive SST-driven low cloud feedback.

Strong dependence of high latitude optical depth feedback on ice-liquid transition

Use of model heirarchies in addressing cloud-climate feedback questions is very helpful

Emerging Issues

How important are interactive aerosols for cloud feedbacks?

Importance of simulators for comparisons to observational data products with large retrieval algorithm differences

Interesting that the high resolution modeling is largely supporting the positive cloud feedback consensus established in the last IPCC – What are we learning from high resolution modeling of clouds and circulations?

Session 4: Precipitation and Hydrological Sensitivity
Chair: Rob Chadwick, Rapporteur: Youichi Kamae

The session on Precipitation and Hydrological Sensitivity began with a presentation by *Hui Su*, on *"Changes of the Hadley Circulation under global warming and their linkage with climate sensitivity and hydrological sensitivity"*. Inter-model differences in Hadley circulation change were shown to be correlated with inter-model differences in climate sensitivity, suggesting a link between the two. A physical mechanism was proposed for this connection, whereby stronger circulation change is associated with greater boundary layer drying, and larger reductions in low cloud. Tightening of the Hadley cell ascent regions and a subsequent reduction in high cloud area may also be important.

Next was *Masahiro Watanabe, on "Equilibrium climate sensitivity tied to hydrological sensitivity by temperature-mediated low cloud feedbacks"*. An inverse relationship between climate sensitivity (ECS) and global hydrological sensitivity (HS) was proposed, based on energetic considerations. This was demonstrated through idealised experiments, where the response of evaporation to SST was systematically varied. With greater evaporation sensitivity, ECS increases but HS decreases, and this effect was traced to an increase in low and mid-level clouds and the contrasting effect this has on the TOA (relevant to ECS) and atmospheric (relevant to HS) radiation budgets. An observational constraint using the surface LW cloud radiative effect exploits this connection between atmospheric and TOA radiation budgets to suggest that ECS is likely to be towards the top end of GCM estimates.

Angie Pendergrass discussed *"Precipitation variability increases in a warmer climate"*. The standard deviation of precipitation in GCMs increases at a faster rate than mean precipitation change, but never greater than the rate of increase of moisture, suggesting that the Clausius-Clapeyron relationship provides an upper bound on precipitation variability change. Variability change appears to have a robust magnitude of change across different timescales, and there is also evidence of a small increase in variability in the observational record over recent decades.

Rob Chadwick presented analysis on "*The influence of land warming on precipitation and atmospheric circulation change*". A series of idealised experiments were used to isolate the influence of land warming on precipitation and circulation change from other factors such as SST warming, the direct CO_2 effect, and the plant physiological effect. Land warming is important, particularly in determining the overall circulation response to the plant physiological effect. However in the case of the direct CO_2 radiative effect, both land warming and atmospheric warming are responsible for driving precipitation increases over land.

Finally, *Toshihiko Takemura* presented "*Temperature responses of anthropogenic aerosols assessed with coupled-ocean general circulation models*". Decadal variations in the rate of warming over the historical period in GCMs are strongly linked to aerosol emissions. PDRMIP has a series of multi-model experiments to examine the response of precipitation to aerosol and other forcings, and some initial results were presented. The model intercomparison is a powerful framework for quantifying uncertainty in fast and slow components of precipitation responses to the forcing factors on global and regional scales. Improved monitoring of aerosol emissions over recent decades may allow improved constraint on model responses to aerosol forcing.

Discussion focused mainly on the narrowing of the ITCZ in observations and projections. It was suggested that the use of zonal mean diagnostics could be inappropriate for representing changes in the structure and size of convergence zones, given the importance of zonal circulations in determining ascent and descent regions. However, there was general consensus that convergence zones are likely to narrow and that this could have important consequences for several aspects of the climate, including climate sensitivity. Later in the meeting, it was proposed that a model Intercomparison project focused on the consequences of changes in the ITCZ, ITCZMIP, could be useful.

Consensus

Changes in the strength, shape or width of convergence zones could have important consequences for several aspects of the climate, including climate sensitivity. Connection to climate sensitivity appears to be through cloud responses to ascent/subsidence changes.
A "Hydrologic sensitivity' constraint appears to favor higher sensitivity models in a single model PPE, and this should be explored in other models.

Emerging Issues

Need to move beyond zonal-mean framework in examining dynamic influences on cloud and precipitation.
Most studies to date on regional precipitation change have focused either on long-term mean changes, or daily-scale intensity/frequency changes, so more work is needed on intermediate timescales and linking processes across timescales.

Session 5: Coupling of Clouds with Circulation

Chair: Bjorn Stevens

This session featured talks on how clouds, and cloud feedbacks coupled to circulations. Both tropical and extra-tropical cloud-circulation couplings were discussed, as well as there response of tropical clouds to extra-tropical perturbations. Based on the talks a relatively clear picture of the cloud coupling to extra-tropical circulation emerged, as presented by *Paolo Ceppi and Oliver Watt-Meyer*. Here there was a consistent picture of a southern hemispheric jet shift the was associated with an overly strong phase change response (ice to liquid) implying an exaggerated cloud feedback at high-latitudes. Ceppi looked at ghost forcing experiments to explore the role of surface temperature effects, doing so by modifying the solar insolation in latitude bands. Here the insolation gradient led to changes in surface temperature gradients and changes in cloudiness, but there were opposing effects of the albedo and cloud response, so that the strong negative signal emerges from a tug of war of two effects. This theme of opposition was further explored by Watt-Meyer who shoed that the jet-shift dependence on cloud radiative effects is differentially driven by tropical versus extra-tropical cloud radiative effects. In a different take on the problem the question as to controls on precipitation from extra-tropical storms was explored in high-resolution NICAM simulations of a present day fixed SST experiment, and a future (patterned) SST experiment, each ran for thirty years (*Chihiro Kodama*). The simulations, and two years of GPM Precipitation Radar data suggest that the most extreme storms in both hemispheres share a temperature precipitation scaling relationship that follows Clausius-Clapeyron, also into the future. All in all there seems to be robust mechanisms of compensation that damp extra tropical changes, but the cloud circulation coupling mechanisms showed signs of being robust and well understood, but given the strength of polar amplification, indicative of large future precipitation changes in a warmer world. It would be helpful to know if this impression was correct.

The coupling of clouds to circulation in the tropics was less straighforward. Here evidence (*George Tselioudis and Bernard Lipat*) was presented for a stronger expansion of the Hadley Cell than predicted by the models favouring stronger negative feedbacks and models with a weaker equilibrium climate sensitivity. In the discussion we tried to reconcile this picture with earlier talks (e.g., Hui Su) that show models robustly narrowing the ITCZ. Contributing to the difficulty in reconciling these effects was the different implications of mean-state versus sensitivity biases. For instance is the ITCZ too broad in models, and do they narrow too much, and is this related to not enough broadening of the descent regions, or are these dynamics not strongly linked. An attempt to provide a coherent narrative of the model behaviour and its implications would be helpful in this area, as the link between ITCZ narrowing in models and observations provides an indication that models with a stronger ECS are easier to reconcile with the data. These would be good themes to follow up on in the context of the planned TRAC-MIP workshop in July and again at our next meeting.

Making the picture potentially more confusing was the question of how extra-tropical forcing affects tropical circulation. In idealised forcing experiments *Sarah Kang* showed that only forcing that persists on decadal scales penetrates into the tropics. As temperature perturbations begin to be felt in the tropics they are accentuated by positive cloud feedbacks, but these same feedbacks damp the response of the circulation within the tropics once the signal emerges there. These results came from aqua-planet simulations with and without cloud radiative effects and would be good to further explored in the proposed CFMIP3 COOKIE experiments. Kang also introduced a framework for looking at cloud radiative effects in coupled simulations, as part of what she calls ENT-MIP, something for which there was a lot of interest within CMIP.

The session was lively and involved presentations from some of the intellectual leaders of the early career scientist community. This is a very strong activity within CFMIP and CFMIP should focus on strengthening and supporting these individuals and their science. One way to do this is to make ENT-MIP a success and give the theme some prominence in the forthcoming CFMIP meetings. This community also most naturally touches on the main drivers of regional precipitation changes, see also the talk by *Yen-Ting Hwang*, and should be seen in this context, i.e., as compared to research that is more trivially related to precipitation climatologies but that do not link to circulation.

Consensus

Southern hemispheric jet shift is associated with an overly strong phase change response (ice to liquid) implying an exaggerated cloud feedback at high-latitudes.

Emerging Issues

Understanding the diverse cloud/precipitation effects of ITCZ strengthening/tightening and Hadley cell expansion and the resulting climate feedbacks.

Session 6, Convective organization and role of clouds in climate variability
Chair: Thorsten Mauritsen, Rapporteur: Paulo Ceppi

Adrian Tompkins, Organization of convection in low vertical wind shears: Impact of boundary conditions
This talk seems to have slightly different content than announced. He first talked a bit about organization in general, and in particular how large lateral entrainment was important for convection to getting organized. This is also the case in cloud resolving models, where often clouds are just a few grid-boxes wide. If one uses the typical vertical diffusion only schemes then the lateral diffusion is handled by the dynamical core, and so depending on how diffusive that is one may or may not get organization. In the second part of the talk he looks at the two-layer convection model of Emanuel et al. (2014). This model has a threshold behavior such that below a certain critical temperature only one solution exist, interpreted as disorganized convection, and above two solutions which can be interpreted as organization. By introducing a different form of the lateral entrainment, though, it is found that it always produces organization.

David Coppin, Role of convective aggregation and ocean-atmosphere coupling in climate sensitivity and internal variability: Insights from radiative-convective equilibrium simulations
David studies radiative-convective equilibrium in the LMDZ climate model on a global spherical grid, coupled to a mixed-layer ocean. He finds that there is a mode of variability in this model setup. It has to do with how low-level clouds in non-convecting regions that come and go, and how that couples to shortwave radiation impacting the surface temperature. It is suggested that this has some similarities with El Nino. It is further argued that the negative cloud feedback from organization is somewhat compensated by low-level clouds.

Shuhei Matsugishi, Uncertainties of high-cloud responses in a global cloud-resolving model found in aquaplanet SST+4K sensitivity tests
A particularly interesting behavior of the NICAM global cloud resolving model is that in global warming in AMIP Cess-type experiments it increases the coverage of upper-level thin cirrus, which implies a positive longwave cloud feedback. Shuhei found that this behavior is also replicated in the aquaplanet configuration. He therefore set up a series of experiments with 14, 7 and 3.5 km resolution, finding that the positive longwave feedback increases with higher resolutions in particular in the tropics. At 3.5 km it is so strong that when warming the surface the outgoing longwave radiation decreases. Still the NICAM aquaplanet exhibits a relatively low climate sensitivity of about 0.414 K/Wm-2, or about 1.5 K for a doubling of CO_2. This is due to strong negative shortwave cloud feedback.

Leo Donner, Feedback connections between deep convection and shallow cloud systems
This talk reviewed how deep convection in the tropics affects low clouds in the sub-tropics. The key is that diabatic heating from deep convection affects the Hadley circulation, thereby controlling the properties of the lower atmosphere in the subsidence regions, refers to Holton. For the diabatic heating in particular lateral entrainment is important, and it has been shown that lowering the entrainment rate leads to a more top-heavy heating profile, which in turn is more effective in driving the Hadley circulation than a bottom-heavy heating profile. It is finally argued that we need to keep the Hadley circulation in mind when

considering low-cloud feedbacks in models.
Comment: related arguments have recently been posed also for the Walker-circulation affecting cloudiness in the east Pacific, Zhou et al. (2016).

Ping Huang, Cloud–radiation feedback as a leading source of uncertainty in the tropical Pacific SST warming pattern in CMIP5 models
This study analyses dynamic feedbacks to El Nino in CMIP5 models. Theses feedbacks include mainly cloud shortwave feedback, surface turbulent flux feedbacks, and ocean transport- and upwelling. It is found that models underestimate all the components of the both positive and negative feedbacks, thus obtaining reasonable ENSO variability for the wrong reasons. In a second, apparently more speculative part, an emergent constraint on the El Nino patterns is conducted. The constraint suggests that East Pacific should warm faster than the West Pacific in global warming, contrary to the current trend. It is therefore suggested that the current warming pattern is an expression of internal variability.

Consensus
Convective processes affecting cloud feedback through changes in subsidence and low cloud amounts.

Emerging Issues
Contrasting effects of cirrus and low cloud changes resulting from changes in convection/aggregation.

Session 7: Observations and model evaluation for process-level understanding of clouds

Chair: Mark Zelinka

This session highlighted several observationally-based approaches for increasing the process-level understanding of clouds and precipitation and for evaluating and improving their representation in models. It included talks on novel techniques for diagnosing and evaluating models, use of tools for facilitating apples-to-apples comparison of modeled and observed fields, new observational datasets, and a field campaign.

Yi Huang has developed a new set of radiative kernels using ERA-Interim atmospheric fields as input to RRTM, allowing for a detailed decomposition of radiative feedbacks. Applying them to observed climate variations associated with ENSO reveals the complex evolution of cloud-induced radiative anomalies at the TOA, in the atmosphere, and at the surface, with clouds generally heating the tropical surface but cooling the tropical atmosphere over the course of a typical El Nino warm event. Biases in models' evolution of these terms are revealed through these advanced diagnostics, and are especially pronounced in low cloud regions. One such region is the site of a proposed field campaign described by *Bjorn Stevens* – the Elucidating the Role of Cloud-Circulation Coupling in Climate (EUREC4A) Experiment. This campaign seeks improved understanding of what controls the macro and micro structure of trade-cumulus clouds. It is envisioned that the experiment will provide insights into controls on convective mass flux, mesoscale organization, and depth of shallow-cumulus clouds, how trade-cumulus cloud fraction varies with turbulence, convective mixing, and large-scale circulations, and the impact of these variations on radiation. Bjorn noted that it will provide opportunities to test our understanding of cloud circulation coupling and evaluate long-standing biases like the "too few too bright" bias.

Complementary to highly detailed process-level measurements are long-term global cloud property measurements from space. However, large differences are present in satellite-based measurements of cloud liquid water path (CLWP), as were highlighted by *Matt Lebsock* in a comparison of MODIS and MAC, an updated and enhanced version of the University of Wisconsin satellite microwave-based CLWP product. Issues with passive infrared retrievals of liquid water path include fixed sample times that prevent sampling throughout the diurnal cycle and problems with cloud detection and cloud phase identification, while passive microwave CLWP retrievals are subject to contamination by precipitation. After carefully accounting for these issues, Matt showed that MODIS and MAC largely agree in inter-annual, seasonal, and diurnal variability and on relationships with large-scale meteorology.

Just as observation-specific quirks and biases must be accounted for in order to compare observational datasets with each other, so too must care be taken when comparing observed and modeled fields. Specifically, *Jen Kay* performed a scale-aware and definition-aware model evaluation of near-surface precipitation frequency, which showed that CESM1 rains and snows too frequently when compared to CloudSat observations. Similarly, *Johannes Mulmenstadt* showed that many models overestimate warm rain fraction, which is itself a useful constraint on parameterized precipitation owing to the fact that it can be unambiguously diagnosed in both models and observations and is not already a tuning target. He showed that reducing autoconversion in the ECHAM–HAM model (while also increasing accretion to maintain TOA balance) reduced warm rain fraction, bringing the model into better agreement with the satellite climatology. To the extent that CESM1's projections of 21st Century precipitation change are trustworthy, Jen Kay showed that many changes -- including increased light rain in sub-tropics and more snow in high Arctic and over Greenland -- would be detectable by a future CloudSat launched in 2080.

Consensus

Importance of scale-aware and definition-aware model evaluation, especially for precipitation. Model overestimation of precipitation frequency.

Emerging Issues

- Need to understand cloud processes and radiative effects in trade-cumulus regions.
- Need to improve models' representation of cloud and precipitation characteristics and the cloud-radiative response to observable climate variations (e.g., ENSO) using insights gained from process-level diagnostics.
- Need for continued elucidation of the causes of differences among relevant observational datasets such that they can be utilized in the most appropriate and optimal fashion, both individually and in synergy with each other.

Session 8: Extratropical cloud feedbacks and cloud-aerosol interactions

Chair: George Tselioudis, Rapporteur: Bernard Lipat

Advances in understanding the response of cloud microphysics to aerosols and temperature were presented in this session. *Ivy Tan* showed that at high latitudes, the microphysics of cloud phase are especially sensitive to increasing temperature. The cloud optical depth feedback; i.e. the increase in cloud reflectivity with increasing temperature, is time-scale invariant, so that present observations bear much relevance to constraining projections of future climate. The cloud optical depth feedback cools too strongly in CMIP5 models over the Southern Ocean, so that future warming is likely toward the higher end of estimates.

Xiyue Zhang showed that the Arctic cloud cover, though high all year, exhibits a clear seasonal cycle; however, CMIP5 models exhibit large spread in the phase of the seasonal cycle of Arctic clouds. Experiments with an LES suggest that with warming, Arctic low cloud cover will decrease but cloud liquid water will increase, with mixed implications for clouds' shortwave radiative effect.

Brian Soden pointed out that aerosols, while having a well-known microphysical effect on the radiative effects of clouds, they also affect clouds through dynamics. In fact, about half of the inter-model spread in the aerosol-mediated cloud response to GHG is due to aerosol-mediated cloud microphysical changes and half due to the aerosol-induced circulation effect on clouds. Models with stronger microphysical and dynamical cloud-aerosol interaction agree better with observed hemispherically-asymmetric warming.

Kentaroh Suzuki presented evidence that aerosol loading, cloud microphysics, and the coupling between aerosol direct and indirect effects also shape the precipitation change with temperature. Climate models precipitate too much, cleaning out the atmosphere of aerosols, which leads to the wrong historical simulation. This may be the results of an aerosol indirect forcing that too sensitive to the auto-conversion process.

Daniel McCoy showed that biased microphysical processes in CMIP5 models may also explain why the observed increase in liquid water path over the Southern Ocean has been faster than that predicted by GCMs. Cyclone compositing reveals that the warm conveyor belt moisture flux predicts the liquid water path as well as the rainfall rate, but this is "clogged" by more cloud condensation nuclei. This understanding is to key for correcting GCMs over-representation of the mixed phase cloud feedback.

Wrapping up and tying together the session's themes, *Romain Roehrig* overviewed the many known problems with models' representations of clouds, chiefly: the "too few, too bright" problem; accurately simulating Arctic clouds; and modeling the three-dimensional structure of clouds. These have been addressed in CNRM through a new boundary scheme, a new large-scale microphysics scheme, and a new convective scheme. Yet, some challenges remain: the high cloud bias had not changed even after dynamical nudging; and, stratocumulus-cumulus transition had not been well captured.

Consensus
Cloud particle phase transition the dominant process in high latitude cloud optical depth feedback. Observational constraints indicate that models overestimate this negative optical depth feedback and therefore cool the region too strongly.

Previously noted overprediction of precipitation frequency in models strongly biases aerosol indirect forcing.

Emerging Issues
Need to better observe and constrain cloud particle phase transitions.

Need to quantify aerosol effects on atmospheric dynamics, as well as aerosol role in overprediction of precipitation frequency and the resulting biases in aerosol indirect effect.

Session 9 Climate model development toward better representation of clouds
(Chair: Masahiro Watanabe, Rapporteur: Tomoo Ogura)

Brian Medeiros: "Climate response across three generations of CAM physics packages in aquaplanet configurations"
Effective climate sensitivity and climate feedback are estimated with three versions of AGCM CAM 4, 5, and 6 in aquaplanet configurations. The three AGCM versions employ different parameterizations for shallow convection, turbulence, clouds, and radiation. Results show that ECS estimates in aquaplanets tend to be lower than the one in Earth configuration, presumably related to the difference in albedo feedback. Large difference in ECS estimates is also found among the three versions in aquaplanets.

Ming Zhao: "Simulation of clouds and cloud feedbacks in GFDL new generation atmospheric model AM4"
GFDL new generation AGCM AM4 has been developed and frozen for use in CMIP6. The AM4 produces better quality than the earlier GFDL models and most CMIP5 models in simulations of TOA radiative fluxes, clouds, and precipitation. Compared to AM3, AM4 has a lower Cess climate sensitivity and a lower aerosol radiative flux perturbation, which help the simulation of historical temperature trend in coupled AOGCM. Model cloud feedbacks and aerosol forcing are dependent on parameterization details including the treatment of cloud liquid drop number and aerosol activation scheme.

Joao Teixeira: "Unified boundary layer and convection parameterization: The EDMF approach"
A new parameterization, Eddy-Diffusivity/Mass-Flux (EDMF), has been developed which represents vertical mixing induced by turbulent eddy and convective mass flux in a unified way. The EDMF is updated to a new version which diagnoses updraft mass flux from multiple plumes based on PDF of thermodynamic variables in the surface layer. The new EDMF version in a single column model can simulate shallow and deep convection well when compared with LES results. The new EDMF is also tested in global WRF aquaplanet simulation and the results are similar to other WRF versions.

Yoko Tsushima: "Use of a perturbed parameter ensemble to understand model errors in clouds and their impact on cloud feedbacks"
Perturbed Parameter Ensemble (PPE) simulations are conducted with HadGEM3 in the AMIP and AMIPfuture settings. Results from the PPE as well as from the Emulator are analyzed to explore how changing different parameters have an impact on cloud feedbacks. The study shows that important parameters for net cloud feedbacks are different from those for the present day CRE. The results imply that different parameter settings can give similar representation of CREs of the present day climate, but can give very different cloud feedback.

Peter Caldwell: "Impact of physics parameterization order in the EAM v0 model"
There is arbitrariness in deciding sequential order of processes calculated in AGCMs at each timestep. This study evaluates impact of the process ordering on simulated climate by conducting ensemble simulations with different process orderings in an AGCM, EAM v0. Results demonstrate that process order has a big impact on simulated climate. Changing process order induces changes in climate feedback which are about 50% the size of the CMIP5

inter-model range. Placement of macrophysics, microphysics, and radiation are the main determinants of the model behavior. Impact of process ordering is expected to be smaller with shorter timestep.

Consensus

Climate model development is continuously in progress, not only by updating physics parameterization schemes but also by devising a unified scheme for multiple processes. Also, experiments with various types of ensemble (e.g., MME and PPE) and with different generations (e.g., CMIP3, 5, and 6 version models) are useful for identifying model errors and understanding sources of the model spread.

Emerging Issues

While CMIP6 data are not yet ready, we'll soon need to evaluate improvements of climate simulations as well as change in the inter-model spread compared to CMIP5. This will be done in parallel to further model development beyond CMIP6 in individual modeling centers.

<u>Session 10: CFMIP Experiments and CFMIP-related Activities:</u>
Chair: Steve Klein, Rapporteur: Peter Caldwell

In this session, the major activities of the CFMIP community were reviewed and opportunities for new efforts were discussed. One major thrust is design of experiments and output requests for the most recent set of CMIP experiments. Process-oriented output (COSP, tendencies, and CFSites info) are requested for DECK simulations in addition to CFMIP-specific experiments. CFMIP experiments include “tier 1” experiments reminiscent of previous CFMIP ensembles as well as optional new “tier 2” experiments and several more “informal” intercomparisons. A number of these optional experiments are aimed at understanding the state dependence of feedbacks (amip minus 4K, amip_piForcing, nonlinMIP, regional single-change AMIP experiments, hotMIP 8x and 16x abrupt CO_2 change, and AMIP pattern warming with fast, slow, or observed warming) while others are aimed at elucidating the role of particular processes in climate change (LW-COOKIE, common simple cloud scheme, abrupt-solar, Extratropical Interaction-MIP, RCE-MIP, SPOOKIE-II, Aqua-Walker, and polar-amplification AMIP). A number of lines of inquiry presented at this meeting suggested that the position and strength of the ITCZ may have an important role in controlling clouds and circulation and their changes. This led to the proposition in this session that we create a new ITCZ-MIP aimed at clarifying this relationship.

In addition to identifying and guiding model intercomparisons and output requests, the WGCRP Grand Challenge effort on clouds, circulation, and climate sensitivity has acted to focus CFMIP attention towards potentially-tractable issues related to clouds and climate change. A talk on the Grand Challenge described ongoing activities. Particular emphasis was placed on the WCRP effort on assessing climate sensitivity and on an upcoming field campaign, entitled EUREC^{4}A, that aims to measure the relationship between shallow cumulus convection and large-scale circulation and thermodynamics. The limited duration of the Grand Challenge effort was emphasized – we are currently in the execution stage, with wrap-up expected by 2022.

The session concluded with a discussion of new prototype experiments to follow CFMIP3. Currently termed ‘informal’ experiments. *Yen-Ting Hwang*, *Thorsten Mauritsen*, and *Tim Andrews* are servicing as contact points to support, advise, and facilitate the development of these new experiments. Nine experiments were discussed:
1. SST pattern experiments (coordinator: *Tim Andrews*).
2. Non-linear aspects of climate change (*NonlinMIP, Peter Good*).
3. The sensitivity of climate sensitivity to the mean temperature (*hotMIP, Thorsten Mauritsen*).
4. The interactions between the extra-tropics and tropics (*ETIN-MIP, Sarah Kang*).
5. Adding a Walker Cell to the Aqua-Planet (*Tapio Schneider*).
6. Aspects of climate change related to polar-amplified warming (*Steve Sherwood*).
7. Further experiments specifying various physical processes across models (*SPOOKIE-II, Jessica Vial*).
8. Radiative-convective equilibrium (*RCEMIP, Masaki Satoh*).
9. The role of the Inter-tropical Convergence Zone in climate (*ITCZ-MIP, Mike Byrne*).
Please feel to get contact the coordinator directly to get involved.

Consensus

Current suite of CFMIP experiments should increase our understanding of the state dependence of feedbacks and elucidate the role of particular processes in climate change. We agreed that the CFMIP committee will act as facilitators for the people running the informal intercomparison experiments, helping them in whatever way perceived appropriate on a case by case basis. This seemed more attractive than coming up with a one-size-fits-all endorsement process like the one used by CMIP. This procedure places the main responsibility at the leaders of each informal MIP, and further reflects the emergence of facilities for easily exchanging output data.

Emerging Issues

An emerging issue is that CFMIP may be trying to manage too many experiments and modeling centers may be overwhelmed and unable to take part in all of the CFMIP3 Tier 1 and 2 experiments plus these new informal experiments. A consequence may be that there may be too few models available for each experiment. Care will need to be taken to manage the execution of experiments so that the scientific potential of each experiment be maximized.