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Report from a Workshop
Clouds, Circulation and Climate Sensitivity: A Grand Science Challenge

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Authors: Bjorn Stevens, Sandrine Bony, Dargan Frierson, Christian Jakob, Masa Kageyama, Robert Pincus, Ted Shepherd, Steven Sherwood, Pier Siebesma, Adam Sobel, Masahiro Watanabe, Mark Webb

Contributors: Dorian Abbot, Peter Bauer, Michela Biasutti, Hervé Douville, Jean-Louis Dufresne, Anthony Del Genio, Kerry Emanuel, Qiang Fu, Julia Hargreaves, Sandy Harrison, Isaac Held, Cathy Hohenegger, Brian Hoskins, Sarah Kang, Hideaki Kawai, Stephen A. Klein, Norman Loeb, Thorsten Mauritsen, Brian Mapes, Martin Miller, Caroline Muller, Colin Prentice, Camille Risi, Masaki Satoh, Courtney Schumacher, Bruce Wielicki, Masakazu Yoshimori, Paquita Zuidema[1]

Observers: Michel Rixen (WCRP), Michael White (Nature Publishing)

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Executive Summary

Ever since scientists began thinking about Earth's energy balance they recognized the role of clouds in controlling the planetary albedo; but it took a surprisingly long time for the idea to emerge that changes in cloudiness might determine how this energy balance responds to perturbations. Likewise, even before the development of synoptic meteorology, clouds had been recognized as harbingers of changing circulation patterns, but only recently has it become appreciated how clouds influence these circulation patterns. Even so, when it comes to clouds and climate, much focus still remains on cloud feedbacks or the ways in which clouds determine the aerosol forcing. But clouds are deeply connected to the dynamic atmosphere, and understanding how climate changes, both on regional and global scales, requires a deeper understanding of how clouds couple to circulations. An appreciation of this need, combined with a maturing capacity to study the interplay between clouds and circulation systems, motivates the Grand Science Challenge on Clouds, Circulation and Climate Sensitivity — the Cloud-GC.

Since the initiation of the Cloud-GC in late 2012, a process of broad community consultation gave rise to the idea of shaping the grand challenge around the articulation of a handful of scientific questions. The process of identifying these questions culminated in a workshop dedicated to this purpose, which this report summarizes. *Four Questions* were identified for further articulation:

1. How will storm tracks change in a future climate?

2. What controls the position and strength of tropical convergence zones?

3. Is convective aggregation important for climate?

4. Does convection determine the strength of cloud feedbacks?

By focusing on these *Four Questions*, each intellectually compelling in its own right, the community would be better placed to attract the brightest young minds to work on important problems, which, together with more focus and coordination, would lead to substantial progress in key areas of climate science over the coming decade.

Additionally the workshop highlighted a number of other issues that should be addressed in developing the Grand Science Challenges. Three issues stood out: (i) The need to support model development by linking it strongly to all the activities organized by the Cloud-GC; (ii) The importance of better understanding the water budget across scales, and advancing and sustaining empiricism on this issue, perhaps through the initiation of an experimental initiative across the whole of the WCRP; and (iii) the value of looking at the key scientific issues across the full climate record, and thereby more closely integrating paleoclimate activities within the Cloud-GC, but also throughout the core projects of WCRP.

Preface

It is widely accepted that Earth has warmed over the last century, and that this warming is principally due to increasing concentrations of greenhouse gases. In the absence of action mitigating against a further rise of greenhouse gases, continued warming appears inevitable. But what does this mean, and how should society react?

Many important questions remain unsatisfactorily answered. How quickly will Earth warm in the coming century, and what types of circulation, and hence regional, changes will accompany such warming? The lack of satisfactory answers limits the quantitative prediction of many aspects of climate change, ranging from how changes will manifest themselves regionally, to how changes on all scales might respond to attempts to deliberately manage the climate system. To better answer these questions and reduce uncertainty in future projections, it is necessary to address fundamental gaps in understanding. So doing poses basic questions that stir the intellect. Foremost among these is the question as to how water, particularly in the form of clouds, couples to atmospheric circulation systems and in so doing determines basic properties of the climate system, and their propensity to change. By articulating the Grand Science Challenge of advancing understanding of clouds, circulation and climate sensitivity, it thus becomes possible to link questions that stimulate the human intellect, with the very tangible needs of a human society struggling with the uncertain implications of climate change.

To develop this link a workshop was organized, under the auspices of the WCRP *Grand Science Challenge Initiative on Clouds, Circulation and Climate Sensitivity*. The four and a half day workshop brought together about forty scientists from across the community to discuss the shape of this Grand Science Challenge by identifying key, or guiding, questions. This goal arose from the belief that science progresses through its ability to articulate compelling questions, as so doing attracts brilliant minds, guides the application of technological advancements, and secures support by the society at large.

The Grand Science Challenges

In 2012 the Joint Scientific Committee of the WCRP capped a multi-year process based on consultation with WCRP sponsors, stakeholders and affiliate networks of scientists by identifying six *Grand Science Challenges.* The 'Grand Challenges' were chosen to help articulate major areas of scientific research, modeling, analysis and observations for WCRP and its affiliate Projects in the ensuing decade. The WCRP further announced the intent to promote these Grand Science Challenges through community-organized workshops, conferences and strategic planning meetings. Their aim is to identify important and exciting topics, which with additional research focus, would disproportionately advance the field, particularly in areas that could yield "actionable information" for decision makers. Although it was envisioned that the particular content of the Grand Science Challenges will evolve with time, their form should:

- be specific and focused on identifying a specific barrier preventing progress in a critical area of climate science;
- enable the development of targeted research efforts with the likelihood of significant progress over 5-10 years, even if its ultimate success is uncertain;
- enable the implementation of effective and measurable performance metrics;
- be transformative, a Grand Challenge should attract the best minds, building and strengthening communities of innovators that are collaborative, perhaps also extending beyond in-house expertise; and

- capture the public's imagination: teams of world-leading scientists working to solve pressing challenges can offer compelling story lines to capture the interest of media and the public.

Six Grand Science Challenges were identified. One of these was on *Clouds, Circulation and Climate Sensitivity*, hereafter the Cloud-GC.

To develop the Grand Science Challenge, coordinators were selected and asked to prepare a white paper that would define a particular Grand Challenge and its place within the WCRP as a whole. Sandrine Bony (LMD, Paris France) and Bjorn Stevens (MPI, Hamburg Germany) were asked to organize the Cloud-GC, which was the focus of the workshop. Their white paper on the Cloud-GC (Bony and Stevens, 2012)[2] incorporated extensive input from the community and outlined the initial structure and scope of the Cloud-GC. The structure was crafted to respond to three perceived barriers to progress, as well as the community sense of opportunities. The barriers being: (i) an inability to constrain the effects of clouds on climate sensitivity estimates; (ii) a lack of understanding of regional circulation and precipitation changes, especially over land; (iii) unreliable representations of the coupling between cloud-processes and larger-scale circulations. The major opportunities include advances in coordination (as represented by CMIP), a golden age of cloud observations, and breakthroughs in simulation. By leveraging these in an attempt to answer a handful of specific scientific questions, it was anticipated that significant progress could be achieved in a ten-year timeframe. This framework encouraged the structuring of the Cloud-GC around five initiatives, each led by a pair of coordinators, which together with Bony and Stevens would form the coordination team of the Cloud-GC as a whole.

These initiatives are as follows:

1. **Climate and Hydrological Sensitivity** (Sherwood & Webb). This initiative would maintain a focus on the big picture of narrowing uncertainty in estimates of different measures of climate sensitivity, including the hydrological sensitivity.

2. **Coupling Clouds to Circulation** (Frierson & Siebesma). This initiative in some sense encapsulates the parameterization problem as it pertains to diabatic processes in the atmosphere, but does so by thinking of it in the context of circulations.

3. **Changing Patterns** (Shepherd & Sobel). This initiative was designed to link understanding of circulations and factors causing changes in circulations, to regional responses, thereby giving more of a dynamic impetus to the Cloud-GC.

4. **Leveraging the Past Record** (Kageyama & Pincus). This was thought of as a cross cutting activity to link the modern instrumental record and indicators of the past to the central question of the Cloud-GC, and also inform future planning.

5. **Toward more reliable models** (Jakob & Watanabe). This is also intended as a cross cutting initiative that would help energize model development and connect it to the ideas being developed through the Cloud-GC.

The first three deal with specific questions directly related to the Cloud-GC, the latter two have a more cross cutting character.

[2] Bony, S. and B. Stevens, 2012: Clouds Circulation and Climate Sensitivity, *White Paper on WCRP Grand Challenge*.

Workshop Structure and Themes

***Figure 1**: Participants on the way to town.*

The goals of the workshop were:

- to articulate and build consensus around a handful of scientific questions around which initial efforts within the Cloud-GC would coalesce; and
- to answer a small list of specific questions related to the proposed organization of the Cloud-GC.

The first and main goal sought to identify particular and compelling questions which could give shape to the Grand Challenge. Broad and important questions were sought, questions which (in the spirit of the guidelines of the Grand Challenge as a whole) would stir the imagination of the community on the one hand, and benefit from additional coordination of efforts on the other hand. Toward this end a particular emphasis was placed on identifying gaps, which often brought us to old questions, but from new angles. Moreover, it was further emphasized that the handful of questions identified need not be exclusive, nor static, but (in their more specific articulation) stood a chance of being answered in the ten-year time-frame of the Grand Science Challenges and which, as targets of inquiry, would propel the field as a whole forward.

Themes and Issues

The more organizational questions that the workshop aimed to answer during the course of the workshop were:

Should the Cloud-GC work toward major new observational programs? Various ideas had been discussed in meetings leading up to the workshop. These include a proposal for a new, very ambitious, tropical experiment, in the mold of GATE; a more focused experiment designed to test ideas coming out of the study of radiative-convective equilibrium (RCE); new initiatives to close the energy and water budgets; or develop better indicators of paleo-climate?

Should the Cloud-GC work toward its own assessments? SPARC has long organized its own assessments on particular important science questions, which subsequently feed into the governmental assessments (IPCC but also the quadrennial WMO/UNEP Ozone Assessments). Should a similar approach be adopted by WCRP as a whole, and if so, should this be done in the context of the Grand Challenge?

Should the Cloud-GC advocate for specific facilities, and if so, what are they? For example, does the Cloud-GC require a new world climate modeling center with access to very high performance computers and a better institutionalization of model development? Is there a need to develop other specific facilities?

Should an educational component be added as a sixth initiative? If not, then how should the Cloud-GC organize educational activities?

What is the publishing strategy? What will be the contours of an article describing the Grand Challenge? How long should it be, what journal should it be in, and who would be the target audience? . . . What, if any, other papers should be written to help stimulate activity in the field?

But most of the time was spent on articulating another set of more general questions, with the **goal of developing a handful of questions for the Cloud-GC as a whole.** To help move this discussion forward, the Cloud-GC team used a series of workshops held during the year[3] prior to the Ringberg meeting to begin articulating the outline of possible themes. Through an exchange of emails some of these ideas were developed further and presented to the workshop participants on the first day. These being: (i) do cloud processes (e.g. cloud-radiation interactions, convection-humidity interactions, convection/cloud-surface flux interactions, cloud-aerosol interactions) contribute to the large-scale organization of cloud systems (e.g. self-aggregation), particularly the MJO and the ITCZ? (ii) Are the storm tracks, and storminess, sensitive to the representation of clouds and convective processes, and if so, how? (iii) What is the best strategy for linking GCMs to very high-resolution cloud-resolving modeling? (iv) Is there evidence of out-of-sample climate behavior in the real-world compared to current GCMs, and if so, what is missing in the GCMs (stochasticity, organization, aerosol or water vapor effects)? (v) How do we understand and constrain the variety of different modeled cloud feedbacks?

These questions served as the starting point for the first round of breakout-group discussions, but participants were asked to supplement them with their own ideas, and the breakout groups were free to linger on the questions or introduce and discuss others as they saw fit. In the second round of breakout-group discussions the cross cutting themes were addressed and two further questions were posed:

- What would be metrics for progress?
- Given a particular question, how do we link to observations, model development, experimental (e.g., CMIP6) and educational activities?

[3] Formal discussions of the Cloud-GC were organized at the ISCCP 30th Anniversary workshop, the WGNE workshop on systematic errors, the CFMIP workshop, an MIT Lorenz Center workshop, an Aerocomm workshop, a Royal Society workshop, the annual WGCM meeting, as well as informally through the planning for the sixth phase of CMIP by individual modeling centers.

Meta-Themes

Workshop participants were also asked to be mindful of three meta-themes. These themes were connections that the coordination team thought should be strengthened irrespective of what scientific question was being posed. They are illustrated as connected circles in Fig. 2. The first meta-theme emphasized the importance of linking clouds to circulation, circulation to climate, and clouds and climate. Although the link between clouds and climate is well established, the links between clouds and circulation and climate and circulation are much less well established and lie at the heart of the Cloud-GC, encompassing in one fashion or another the first three initiatives. The remaining themes focused on the cross cutting initiatives. For instance, the question of how to link modeling to the development of specific ideas, and how to connect ideas, often developed on the basis of modeling, through a critical dialog with data. As the apparent sophistication of climate models and the needs of the policy community increasingly encourage prognostication, extra effort needs to be devoted to this critical dialog which is the underpinning of scientific work. The third meta-theme was chosen to help maintain a focus on how the paleo-record could be developed to better link to understanding of the present, instrumental record, and at the same time constrain projections of future changes.

Figure 2*: Three meta-themes that should be developed in the articulation of scientific questions for the Grand Science Challenge on Clouds, Circulation and Climate Sensitivity. Note that here the word data is meant to refer to that what is collected through observations of what we presume to be an objective reality.*

Four Questions

The main goal of the workshop was achieved through the identification of *Four Questions* which can help guide the further development of the Cloud-GC:

How will storm tracks change in a future climate? Storm Tracks are extensively studied, and basic processes well understood, but the persistence of anomalous storm track structure is not, and little research has explored the role of moist processes, the mix of which will change with a changing climate. How will the changing energetics of the storm track regions, a different mix of remote forcing, and possibly cloud radiative interactions influence the strength, position and stability of the storm track? What can be learned from the analysis of indicators and simulations of past climates?

What controls the position and strength of tropical convergence zones? Many of the most important climate patterns can be interpreted in terms of the position and strength of the tropical convergence zones. How does the tropical circulation depend on the state of the climate system, including more pronounced changes in the distant past? What is the relative role of remote versus local influences such as aerosol forcing, cloud radiative interactions, the diurnal cycle, or the mesoscale circulations?

Is convective aggregation important for climate? Are processes leading to self-aggregation important for large-scale properties of the climate system? The MJO, the position of the ITCZ, the Northward Extent of the African Monsoon? Is aggregation paced by temperature and can this influence the climate and hydrological sensitivity of the planet?

Does convection determine the strength of cloud feedbacks? Clouds, particularly low clouds, are well understood to underlie differences in model based estimates of climate sensitivity, but is this a proximate cause? How much of this response ultimately depends on the representation of convective processes, both remotely (through circulation changes) and locally? Is a distorted representation of convective processes obscuring our ability to envisage other effects, i.e., high- thin, or mid-level clouds? How much do convective cloud feedbacks influence hydrological sensitivity?

Further outcomes of the workshop

Recap of Presentations and General Points

Some general points also arose in the discussions, partly in response to some themes that emerged in several of the presentations. Namely, that

- computational advances are bridging scales and breaking down long-standing obstacles – true multi-scale simulations are now possible and LES simulations are beginning to overlap with general circulation studies (for instance, at the workshop the very first sub-kilometer global simulations were presented (Satoh), which represents a major milestone in numerical modeling);
- observational records are advancing rapidly on all time-scales (e.g., the paleo record is becoming increasingly multivariate and new observational systems are advancing the phenomenological study of the present climate, particularly as relates to clouds and precipitation – the very first data from the Global Precipitation Mission were presented, also by Satoh);
- richer and more extensive model and experimental hierarchies are being developed (RCE, APE, process diagnostics; mechanism denial experiments, and idealized forcing experiments like Easy Aerosol[4]), deepening our understanding of climate and climate models; and
- a proliferation of coordinated modeling approaches, such as CMIP, have enabled new insights by exploring the responses that arise from the collective behavior of model systems.

These advances implicitly and generally posed the question as to how to synthesize all of this information into knowledge. More specifically, and pressingly,

> How can understanding be translated into practical improvements of existing climate models?

The other such question to be raised, being:

> If one accepts that the climate system is changing, and that present understanding informs the outline of the ways in which the system will change, do we have the observing system in place to help us detect these changes,

[4] Easy Aerosol is the first coordinated activity of the Cloud-GC. Led by Aiko Voigt of Columbia University it explores robust circulation responses to imposed aerosol forcing. RCE stands for radiative convective equilibrium and APE denotes the Aqua Planet Experiments that were featured for the first time in CMIP5.

particularly early indicators of the most dangerous changes?

Both of these questions merit follow up by the Cloud-GC, but also by WCRP as a whole.

Practical Questions

Additionally discussions through the workshop provided the following feedback on the practical questions related to the organization of the Cloud-GC.

Should the Cloud-GC work toward a field experiment? There was considerable support for the idea of a major, WCRP or Grand Challenge sponsored, field experiment. Several related, but competing initiatives were identified, one planned for the Southern Oceans, another being thought about in the vicinity of the Maritime Continent, both in the 2017 time frame. The idea of a very large, and long, experiment that focused on the tropics in the manner of GATE, was positively received, as the idea of understanding the tropical water budget was identified as a key issue in many realms, for reanalysis (NWP talks, e.g., Bauer), for process understanding (RCE talks, e.g., Emanuel, shallow convection, e.g., Schumacher), and for the energy budget (e.g., Loeb). This scale of activity would need to be taken up by the WCRP as a whole but could give commonality to all of its projects. At the Cloud-GC level, discussion focused on the more immediate possibility of a smaller scale experiment, focused on the interplay of water and convection, in so doing this could: help evaluate the ability of closing the tropical water budget over a variety of scales; test ideas being developed in the context of idealized studies (for instance of RCE); and evaluate processes thought to underlie apparent constraints that emerge from analyses of the CMIP5 ensemble (e.g., Sherwood, et al., *Nature* 2014).

Should the Cloud-GC work toward its own assessments? The Cloud-GC should encourage scientific assessments on specific issues (as do some of the WCRP core projects, e.g., SPARC) as this might be a way to involve a broader community in a more timely manner than is possible within the framework of the IPCC. More broadly, there is the sentiment that the WCRP as a whole should become more proactive in supporting and initiating scientific assessments. To assess the Cloud-GC itself, it was felt that it is important to articulate performance metrics (as discussed in the next section), which could then serve as a basis for others to evaluate the success of our efforts.

Should the Cloud-GC be advocating for its own facilities? The discussion touched on a number of possible facilities, and there was a consensus that climate research needs access to the highest performance computing available, and the development of a climate observing system. For the computing there was *not* the strong feeling that this would be best accomplished by a single or small number of scientific institutes, in which resources were concentrated, although some concentration of resources for model development was recognized as important. In particular, given the shortage of model developers and the need of having a critical mass of model developers to maintain and improve models on the long term, the Cloud-GC and WCRP can do more to support model development within the existing institutional landscape. For the observations, the discussion reinforced the first point that a major WCRP emphasis should be on better measurements of the global water and energy budgets and that the Cloud-GC should help in this regard.

Should the Cloud-GC adopt a sixth initiative focused on education? There was not support for this idea, but there was strong support for educational activities within the existing initiatives. For instance, the idea was proposed to support the WCRP Model Advisory Council Model development summer school by aligning it with key questions of the

Cloud-GC. In addition, an extended discussion arose regarding the idea of WCRP (through the activities of the GC) supporting the development of a repository of tools and models, which would be written in a consistent fashion and made available to the broader community.

Particularly interesting was the idea of supporting a repository containing a hierarchy of models, from one-dimensional energy budget models through comprehensive climate models, with all things (QG models, shallow water models, dry dynamical cores, simplified GCMs) in between.

What will be the contours of an article, or articles, describing the GC? There was support for writing an article that articulated the *Four Questions* (see above) of the Cloud-GC in a way that captured the attention of the community. The general idea was an article of about 4000 words, with perhaps 700 words devoted to each of the *Four Questions*. The article would be authored by the Cloud-GC coordinators and Initiative leaders (the authors of this report) and would try on the one hand to articulate the intellectual attraction of the *Four Questions* (for a scientific audience, including prospective scientists) and on the other hand it should make the social relevance of these issues clear for policy makers, science managers, and the general public at large. These articles could nicely be complemented by review articles, each of which would focus on individual questions.

Recommendations and Implementation

Presented below are seven recommendations distilled by the authors from the workshop discussions. These recommendations were circulated among all the participants to ensure that they accurately reflected the workshop discussions. In this sense they are recommendations of the workshop itself.

1. The Cloud-GC should maintain its current organizational structure of five initiatives, but use these to collectively coordinate and guide work related to the *Four Questions* in ways that help the community sharpen and advance its priorities, and attract a greater pool of talent to climate science.

2. As a next step, workshops should be organized with WCRP and Cloud-GC support on each of the *Four Questions*. Ideally within the coming two years. Given the focus on convective aggregation at the recent workshop on “Water in the Climate System” organized by MIT’s Lorenz Center[5], workshops on the other questions should be pursued first. M. Biasutti, S. Kang and D. Frierson expressed an interest in organizing a workshop on tropical convergence zones and the green Sahel. A. Sobel and T. Shepherd expressed interest in supporting efforts rooted in SPARC (see Table 1 for an explanation of acronyms) to initiate a workshop on the storm tracks.

3. A concerted effort should be made to link the Four Questions to both model development and observational activities; for instance, through dedicated sessions at meetings, wherein model developers are invited to present results relating to how their work relates to a specific issue, or discussions of analyses, or observational campaigns initiated with the purpose of linking emerging ideas to data. Individual labs, and modeling/observation groups in particular, could also consider initiating such discussions, to explore the extent to which the Four Questions can be used to prioritize and facilitate model development and

[5] Understanding Atmospheric Water and Climate *Eos, Transactions American Geophysical Union* Volume 95, Issue 19, page 162, 13 May 2014

observational activities.

4. The connection between the Cloud-GC and the paleo-community should be nurtured and strengthened, for instance by encouraging the use of isotopic information in models, or more forward operators/CFMIP-like output in PMIP simulations. Efforts to develop indicators and story lines as to how cloudiness (or sunshine), storm tracks, and tropical convergence zones changed over the pre-instrumental record should be strongly encouraged and supported, as should Past4future like efforts, which interpret present day models in light of their representation of past climates.

5. The Cloud-GC should approach Nature, Nature Geoscience, or the Bulletin of the American Meteorological Society as to their interest in publishing articles related to the Cloud-GC, for instance through a presentation of the *Four Questions,* both collectively and individually. S. Bony agreed to take the lead on an overview article. Leaders of workshops on specific questions should consider using these workshops to help develop review articles that explain each individual question in more depth.

6. Regarding coordinated modeling activities, the Cloud-GC should work with CMIP to incorporate the *Four Questions* in the experimental design of CMIP6. WGCM should also encourage more idealized modeling activities, not the least because these help maintain and advance a hierarchical model infrastructure. For example, the Easy-Aerosol Project, which looks at the consistency of modeled dynamical responses to a heterogeneous aerosol forcing, can help bridge a gap between the forcing and the dynamic/response communities, but requires flexibility in model design (i.e., the ability to run models with prescribed aerosols).

7. WCRP can play a more important role in the community by: (i) initiating discussions of a new major field initiative, and programmes for sustaining and improving ongoing measurements, linking the different WCRP projects around the topic of water, for instance as part of the forthcoming Climate Symposium; (ii) becoming more proactive in the scientific assessment process, for instance on questions related to understanding of feedback processes, climate sensitivity, aerosol forcing, sea-level rise, etc; (iii) investing more in its website development for dissemination activities, for instance to distribute community tools.

Performance Metrics The most effective performance metric will be to clearly articulate the current state of knowledge, particularly as pertains to the *Four Questions* and what one would like to know. By precisely identifying what one does not know, but thinks is knowable, the success of the Cloud-GC can be measured by the degree to which these knowable unknowns can be addressed over the coming years. The key to this strategy being successful is to be specific in the articulation of the *Four Questions*. As an example, consider the statement: Climate models presently do not include parameterizations capable of representing the effects of mesoscale organization. If such effects are incorporated, even in a very crude manner, do they systematically change the way in which the models respond to perturbations? Hopefully statements of this sort are of the type that can be used to measure progress through the life of the Cloud-GC. Although the group proposed mostly qualitative metrics, it was pointed out that it might be possible, and beneficial, to develop more quantitative metrics through the process of articulating the *Four Questions*.

Implementation within WCRP

The Cloud-GC is hosted by WGCM through which it has strong ties with the CMIP, CFMIP, and PMIP projects of this working group (acronyms are spelt out in Table 1). It also has strong links to the GEWEX GASS project, for the process related questions, e.g., the role of convective mixing, and the DynVar activity within SPARC for the question of the storm tracks. Some of the recommendations can be implemented through these connections; however, the implementation of the Cloud-GC within WCRP should focus both on the specific recommendations enumerated above, as well as by encouraging WCRP working groups and core projects to explore ways of contributing to answering the *Four Questions* by exploiting and leveraging links as outlined below.

The first two questions, on storm tracks and convergence zones, are the most cross cutting. Both questions intersect strongly with activities within GEWEX and CLIVAR, but also overlap to some extent with CliC and SPARC, the remaining two core projects of WCRP. For instance, connections between storm track changes and sea-ice provide a link to the WCRP CliC core project, as well as WWRP projects such as T-NAWDEX. WGSIP could also contribute to understanding to what extent anomalies in the Storm Tracks (like the unusual zonal persistence of the Atlantic Storm track in the winter of 2013-2014) can be anticipated ahead of time. Here the challenge will be to bring groups together, including the palaeo-community whose link to the core projects could be strengthened in a way that best advances each research related to each of the *Four Questions.*

Links to specific activities within the working groups and core projects should also be strengthened. For instance, CLIVAR activities such as IMILAST (The intercomparison of mid-latitude storm diagnostics) as well as ASOF (arctic and sub-arctic ocean fluxes) are intimately related to the question as to how the Storm Tracks will change in a warming climate. GEWEX projects such as the Vertical Structure and Diabatic Processes of the Madden-Julian Oscillation (with links to the MJO task which reports to WGNE) can make important contributions to the process related aspects of the Four Questions. This is particularly relevant for the last three questions, which overlap with tropical processes to a greater degree. CLIVAR's Atlantic panel and AMMA activities also relate closely to the present posing of the tropical convergence zone question, as does its focus on monsoon predictability.

Finally, the emphasis on model development, and the idea to more strongly link this to the *Four Questions*, also provides a basis for stronger interaction with WGNE. By using the *Four Questions* to give new impetus to different activities related to model development, it should be possible to strengthen efforts to reduce systematic biases across the WCRP core projects. One strategy for doing, so would be to focus efforts within the Cloud-GC on the identification of idealized problems or analysis approaches that help identify model biases and articulate their relation to one or more of the *Four Questions*. In so doing the idea would be to help energize (and raise resources for) model development.

National and International Funding Activities

With the active involvement of the JSC, the WCRP and its core projects could use the impetus of the *Four Questions* to help design national and international (e.g., the European Union or the Group of Eight (G8) forum of leading industrialized countries) programmes to target aspects of the *Four Questions*. Specifically the WCRP and the core projects should use their national and international contacts to organize meetings of funding groups to discuss possibilities for coordinated programmes and research calls.

Appendix A: Organizational Acronyms

***Table 1**: Brief overview of the acronyms mentioned in the implementation plan. Most projects live within the WCRP organizational structure, the exceptions being THORPEX and its daughter programme T-NAWDEX, both of which are organized by the WWRP.*

Acronym	Brief Descripition
AMMA	African Monsoon Multidisciplinary Analysis
CFMIP	Cloud-feedback model intercomparison project
CLiC	Climate and Cryosphere
CLIVAR	Climate Variability and Predictability CMIP
	Coupled Model Intercomparison Project
GEWEX	Global Energy and Water Exchanges Projects
GASS	Global Atmospheric Systems Studies
PMIP	Paleoclimate Modelling Intercomparison Project
SPARC	Stratospheric-Tropospheric processes and their role in climate
T-NAWDEX	THORPEX N. Atl. Waveguide and Downstream Impact Experiment
THORPEX	The Observing System Research and Predictability Experiment of WWRP
WGNE	Working Group on Numerical Experimentation (joint WCRP-CAS)
WGSIP	WCRP Working Group on Seasonal and Interannual Prediction
WGCM	WCRP Working Group on Coupled Modeling
WCRP	World Climate Research Programme
WWRP	World Weather Research Programme (analog to WCRP)

Appendix B: Workshop Organization

Schloß Ringberg is a facility owned and maintained by the Max Planck Society for the Advancement of Science, and was chosen as a venue for the meeting. The facility provides an intimate setting for a modestly sized (thirty to forty) group of participants to discuss specific issues in more depth at an affordable price and in an attractive setting. Logistical support for the workshop was provided by the Max Planck Institute for Meteorology, in Hamburg Germany, through the services of Ms Angela Gruber and Ms Bettina Diallo. In addition, two PhD candidates, Mr Tobias Becker (MPI) and Mr David Coppin (LMD) helped with technical organization and participated in the scientific discussions. Part of the workshop was also subsidized by WCRP.

Invited participants were identified by the Cloud-GC coordination team (i.e., the twelve authors of this report). A variety of factors including geographic origin, scientific interests, and career stage were accounted for when identifying possible participants (Table 2). In targeting scientific disciplines, a specific interest in bridging the gap between the large-scale dynamics and small, cloud-scale processes as well as between the palaeo-indicator and modern instrumental record, guided the selection of workshop participants. The enthusiastic response of the selected participants (thirty-seven of forty invited participants attended the workshop), the overall level of scientific quality, and the fact that the vast majority of participants covered all of their own costs, was taken as an indicator of the resonance of the Cloud-GC with the broader scientific community. The setting, the participants, and the topic all worked together to lend the meeting the sense of a very special event.

In addition to addressing the workshop goals, the agenda of the workshop was crafted so as to permit individuals to introduce themselves, scientifically speaking, to the other participants. To provide a scientific introduction, each participant was allotted a short (12 min) timeslot

***Table 2**: Scientific participants and presentation titles. In addition, three overview talks (not listed below) were presented at the beginning of the workshop: one by Sandrine Bony on the Grand Science Challenges as a whole, another by Bjorn Stevens on the specific goals of the workshop, and a third by Michael White (Nature Publishing) on how Nature might support the Grand Science Challenges.*

Name	Institution	Title
Abbot, Dorian	U. Chicago	Convective self-aggregation in a cloud resolving model at very low temperature.
Bauer, Peter	ECMWF	Model error assessment methods in NWP.
Biasutti, Michela	Columbia Univ	Changes in the seasonality of tropical rainfall under global warming: lessons from idealized simulations.
Bony, Sandrine	LMD	On the interplay between clouds, circulation and climate
Douville, Hervé	CNRM	Bridging the gap between CMIP and CFMIP experimental strategies.
Dufresne, Jean-Louis	LMD/IPSL	Patterns of precipitation changes and Cloud heterogeneity.
Del Genio, Anthony	NASA GISS	What do we need to know about convection?
Emanuel, Kerry	MIT	Radiative-convective Instability.
Frierson, Dargan	U. Washington	Remote cloud influences on the double ITCZ problem.
Fu, Qiang	U. Washington	The coupling of stratospheric H2O and TTL thin cirrus clouds to atmospheric circulations: Implication to climate sensitivity
Hargreaves, Julia	Bluesky Research	The Power of Paleo: identifying climate model biases . . . ?
Harrison, Sandy	U. Reading	Reconstructing palaeoclouds: potential ways forward.
Held, Isaac	NOAA, GFDL	Non-stationary relationship between tropical TOA fluxes and surface temperatures in a model.
Hohenegger, Cathy	MPI-Meteorology	What determines the coupling strength between convection and the land surface? Hoskins,
Brian	Imperial College	Potential vorticity perspectives on (a) the output from parameterizations and (b) the Hadley Cell.
Jakob, Christian	Monash Univ.	The future of cumulus parameterization - no deadlocks in sight!
Kageyama, Masa	LSCE IPSL	Methodologies, targets and analyses in the context of the grand challenge on Clouds and circulation.
Kang, Sarah	UNIST	Dependence of climate response on meridional structure of thermal forcing.
Kawai, Hideaki	MRI	Importance of minor treatments in parameterizations in GCMs for the cloud representations and the cloud feedbacks.
Klein, Stephen A.	DOE, LLNL	Emergent constraints and cloud trends.
Loeb, Norm	NASA	Observing clouds and Earth's radiation budget from CERES: Recent progress.
Mauritsen, Thorsten	MPI-Meteorology	What if the Earth had an adaptive infrared iris?
Mapes, Brian	U. Miami	Anomaly physics to isolate moisture coupling and its rectified climate signatures.
Miller, Martin	ECMWF (emeritus)	Clouds and the global circulation: a model developers experience.
Muller, Caroline	École Polytechnique	Organization of convection in the tropical atmosphere, and implication for the large scales.
Pincus, Robert	NOAA	Seeking a consistent view of energy and water flows through the climate system.
Prentice, Colin	Imperial College	Representation of carbon-water cycle coupling through land plants.
Qiang, Fu	U. Washington	Tropical cirrus
Risi, Camille	LMD	How can we make use of water isotopic observations to better evaluate the representation of moist processes in climate models.
Satoh, Masaki	U. Tokyo	Clouds, Circulation and Climate sensitivity simulated by NICAM.
Schumacher, Courtney	Texas A&M	The role of low-level convective heating in tropical weather and climate.
Shepherd, Ted	U. Reading	How predictable is the atmospheric circulation response to climate change.
Siebesma, Pier	KNMI	How large domain LES can inform cloud-circulation interactions in GCMs.
Sherwood, Steven	U. New South Wales	Seeking systematic model failures.
Sobel, Adam	Columbia Univ	Radiative feedback mechanism denial experiments for MJO +
Stevens, Bjorn	MPI-Meteorology	Stratocumulus, the root of unrealistic cloud feedbacks.
Watanabe, Masahiro	U. Tokyo	How can we identify, attribute, and effectively use climate model biases?
Wielicki, Bruce	NASA	The three laws of climate change: accuracy, accuracy, accuracy
Webb, Mark	Met Office, UK	De-Evolving climate models.
Yoshimori, Masakazu	U. Tokyo	An overall perspective on constraining uncertainty in climate sensitivity from the last glacial maximum
Zuidema, Paquita	U. Miami	The Southeast Atlantic and its place within the global circulation - Inferences from observations.

and asked to present something related to their perception of the Grand Challenge that they are currently excited about. These talks (Table 2) were all at the beginning of the week. To satisfy the second purpose, the remainder of the time (mostly on Wed-Fri) was allocated to breakout groups, plenary discussion, and common social events directed toward the workshop goals. The social events included an evening sing-along and a midweek walk to the neighboring town of Tegernsee, as 30 cm of fresh snow enhanced the setting, but prevented the planned hike.

Two series of breakout groups were organized, one after the other. One group of three breakout groups focused on the first three initiatives; the other followed thereafter and addressed the latter two cross-cutting themes. In both cases, two sessions of individual breakout groups were complemented by two plenary sessions; one at the mid point to summarize the status, another to summarize at the end. This gave all participants an opportunity to contribute to every question. Participants were free to sign up for whichever breakout group they chose, with each session led by an initiative team. Some coordination was provided by asking individuals to openly identify which breakout group they planned to attend, so that participants could adjust their plans based on what others were doing. This ensured a relatively balanced participation in all of the breakout groups.