White Paper on WCRP Grand Challenge #4

Clouds, Circulation and Climate Sensitivity:

Or how the interactions between clouds, greenhouse gases and aerosols affect temperature and precipitation in a changing climate

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Context

Earth has warmed over the last century owing to increasing concentrations of greenhouse gases. In the absence of mitigating action, further warming will be inevitable over the next decades and centuries. Sufficiently predictive, accepted and understandable climate information at global and regional scales is required to inform adaptation and mitigation strategies. However, a large uncertainty remains about how much, or how quickly, Earth will warm in response to a given increase in the greenhouse gas concentration, and what types of circulation changes will accompany such warming. The Climate Sensitivity measures the amount of warming that results from a given increase in greenhouse gases. Uncertainty in estimates of the magnitude of the climate sensitivity has hardly changed in thirty years. This uncertainty compounds the effect of persistent biases in modelled large-scale circulations, and limits the quantitative prediction of many aspects of climate change, such as our ability to predict the future occurrence of heat waves, regional rainfall changes and other impacts of climate change on societies and ecosystems. This uncertainty also hinders efforts to design climate stabilization scenarios.

Limited understanding of clouds is the major source of uncertainty in Climate Sensitivity, but also contributes substantially to persistent biases in modelled circulation systems: how do clouds couple to circulations in the present climate, how will clouds respond to global warming or other forcings, and how will they feed back on it through their influence on Earth's radiation budget? As one of the main modulators of heating in the atmosphere, clouds control many other aspects of the climate system. As recognized at the dawn of the climate modelling enterprise (Arakawa 1975), clouds play a central role in the large-scale circulation of the atmosphere and thus in the regional distribution, frequency and intensity of precipitation. Climate models simulate very different patterns of precipitation, which is a major barrier for decadal prediction. Model based projections of precipitation changes on the regional scale also differ substantially, and here understanding remains insufficient to allow an assessment of the plausibility of different projections. A better physical understanding of the coupling between diabatic and adiabatic processes in the atmosphere and of the role of clouds in this coupling would provide a foundation for improving future assessments of temperature, precipitation and the atmospheric circulation and is necessary to improve the predictive capabilities of climate and weather models over all time and space scales.

Improvements in understanding cannot be limited to the effect of greenhouse gases alone, but must consider a wider range of forcing agents, including natural variability associated with solar activity and volcanoes, as well as anthropogenic influences on the atmospheric aerosol and the land surface. The close coupling of clouds and aerosols, wherein aerosol forcing depends strongly on cloud and precipitation processes, makes their treatment a special challenge, as does the very regional nature of aerosol forcing.

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The Grand Challenge

Over the next 5-10 years, the grand challenge will be to overcome three main barriers that prevent progress in assessing Climate Sensitivity and future precipitation changes:

Barrier 1: Inability to constrain the effects of clouds on climate sensitivity estimates.

The spread of climate sensitivity estimates is unacceptably large, mostly as a result of uncertain changes in clouds. This uncertainty can be thought of as the ‘cloud problem’. The cloud problem contributes to an inability to usefully constrain the upper bound, and the relative reliability, of differing estimates of climate sensitivity.

Defining Questions: What are the origins of inter-model differences in climate sensitivity, radiative feedbacks and adjustments? What are the physical processes responsible for cloud feedbacks and adjustments in models? Can critical tests be designed to assess the relative reliability of model-based representations of such processes? Can estimates of possibly extreme climate sensitivity and feedbacks be constrained by observations and proxy data from past climates?

Barrier 2: Lack of understanding of regional circulation and precipitation changes, especially over land.

Regional precipitation projections remain very uncertain, and most of this uncertainty stems from an inability to quantitatively predict how large-scale atmospheric circulation systems will respond to climate change.

Defining Questions: What are the primary factors that control the strength, the regional patterns, temporal trends, and the modes of variability of the large-scale atmospheric circulation? What is the role of clouds in particular and to what extent is the coupling between aerosols and clouds important? How do these factors link to large-scale patterns of precipitation? Can projections of future precipitation changes at the regional scale be made more robust through advancements in physical understanding, or improved analyses of observations and simulations? Can paleoclimate reconstructions help assess the ability of climate models to predict large-scale circulation and precipitation patterns under climate change?

Barrier 3: Unreliable representation of the coupling between cloud-processes and large-scale dynamics.

Long-standing model biases limit the reliability of climate model predictions/projections on all time and space scales. But model development is hindered by a lack of understanding of how processes contributing to model biases couple to large-scale circulation features and influence future projections.

Defining Questions: Can the physical origin of major model biases (double ITCZ, Madden-Julian Oscillation, extended equatorial cold tongue, diurnal cycle of convection and surface temperature biases over continents, etc.) be identified? How much do these biases hinge on the representation of cloud and moist processes and what is their dependence on model resolution? How do model biases at the process level translate into model biases at the climate scale and vice-versa? How do they affect simulations of past and future climate changes?

Opportunities for rapid progress

Establishing the extent to which clouds will undergo changes in response to warming can be thought of as the Higgs Boson of the theory of climate, and climate change. It is the intellectual and experimental challenge of our lifetime. Fortunately, over the past decades the community has invested in a number of ‘accelerators’ that allow us to examine this idea in more depth, and thereby advance progress. They include:

- ***CMIP5 and other Model Intercomparison Projects (or MIPs***): The range and richness of experiments and outputs made available through many MIPs (including specialized projects focused on cloud feedbacks, short-term and medium-term biases, paleoclimate, geo-engineering, aerosol effects and the carbon cycle) provide a basis for unravelling the causes of inter-model differences in the simulation of current, past and future climates.

- ***Qualitatively new types of models:*** A new generation of models has been developed, which makes it possible to simulate clouds more explicitly than in traditional climate models. These include global cloud resolving models and yet finer-scale models on large domains, and hybrid approaches (super-parameterization), models which makes it possible to address the cloud problem on a more nearly ab initio basis, but also decadal prediction systems, which make it possible to design qualitatively new tests.

- ***A golden age of Earth observations***: The present may well be looked back upon as the golden age of Earth observations. It has emerged as a result of an explosion of passive and active remote sensing, both from ground and from space, as well as the development of entirely new technologies, for instance laser spectroscopy, which allows the analysis of the isotopic composition of rain and water in the atmosphere. Moreover, the record is beginning to become long enough to sufficiently sample many modes of natural variability, which offers qualitatively new opportunities for creative and critical analysis.

- ***Lessons from experience:*** research efforts developed over the last decade or two have helped articulate a winning strategy for addressing this grand challenge. This strategy is based on the recognized importance of developing physical understanding through a spectrum of models and theories as well as often highly idealized modelling frameworks. So doing involves decomposing the cloud problem into a series of more tractable questions. This framework is also crucial for breaking down other barriers to our understanding, for instance those related to the role of the atmospheric aerosol.

- ***Research community:*** A mature and interconnected research community now exists in ways that did not exist in the past, and allows us to more effectively combine methodologies. A wide variety of activities within the WCRP, centred for the most part around its working group on coupled modelling (WGCM), with strong links to the WCRP core project on the Global Energy and Water Cycle Experiment (GEWEX) and the WCRP/CAS Working Group on Numerical Experimentation (WGNE), will contribute to the grand challenge. Contributions from other core projects such as the WCRP Climate and Cryosphere Project (CLIC), the THORPEX project of the World Weather Research Programme, as well as a number of programmes focused on understanding the character and influence of various forcing agents within the International Geosphere-Biosphere Programme (IGBP) also help create a basis for progress on this grand challenge.

Initiatives

To meet the grand challenge, and break down the barriers identified above, we propose to develop targeted research efforts around five specific initiatives, each of which is defined to leverage the opportunities identified above.

As much as possible (and appropriate), the different initiatives described below will be developed through a hierarchy of models, theories and concepts of different complexities, and through the analysis of observations (space-borne, ground-based, and in-situ) including the reanalysis of meteorological observations. This Grand Challenge thus aims at integrating expertise from theory, modelling (process, cloud-resolving to large-scale modelling), observations and weather prediction.

I1: Climate and Hydrological Sensitivity

The aim of this initiative is to design critical tests for climate models, tests whose application will help assess the most likely estimates of climate and hydrological sensitivity, thereby helping to break down the first barrier (B1) identified above. Through these tests the reliability of different model estimates will be assessed. Progress in this direction is expected to result from intensifying on-going efforts to identify causes of inter-model differences in climate and hydrological sensitivity.

Model experiments designed and executed as part of the Coupled Model Intercomparison Project (CMIP) and the Cloud-Feedback Model intercomparison project (CFMIP), and efforts to diagnose and interpret outputs related to climate and hydrological sensitivity (some of which are taking place through joint CFMIP/GASS projects), are helping to point the way forward for this initiative. Additional efforts (for instance, through the CFMIP-GASS project on the intercomparison of large-eddy simulation models and single column models, CGILS, which is exploring how different forcing components influence subtropical boundary layer cloud feedbacks, new CFMIP initiatives targeting understanding cloud radiative effects and other cloud-climate feedback mechanisms, an emerging GASS project on aerosol-climate interactions, and the WGNE/WGCM Transpose AMIP project on the evaluation of climate models through short-term weather forecasts) are showing that it is possible to identify and isolate key climate processes and design analogue problems, which in turn makes it possible to develop insights and constraints from well established practices (e.g. the calculation of radiative effects of greenhouse gases by line-by-line models as done in the continuous intercomparison of radiation codes, or CIRC) or from qualitatively new modelling approaches, such as super-parameterization, global cloud-resolving, large-eddy resolving models over large domains, decadal prediction systems, and NWP models. These approaches provide natural links to initiatives three through five described below. Likewise, qualitatively new ways of processing climate model outputs (e.g., using satellite simulators such as are being developed within CFMIP, or incorporating isotopic information in models such as is done by GEWEX groups) allow the application of new observations to the evaluation of models and key processes, and will facilitate interaction with the second initiative of this grand challenge.

A novel, and crucial, element of this initiative will be to work with the observational community to identify signatures capable of providing early warning of potentially catastrophic cloud feedbacks or precipitation changes which might portend extraordinarily large values of the climate or hydrological sensitivity.

I2: Leveraging the Past Record

This initiative aims at targeting the exploitation of observations of the recent past, or proxies for changes over the more distant past, to improve understanding and assessment of climate sensitivity and precipitation projections.

Multi-decadal records of satellite and in-situ observations are becoming routine and provide new opportunities to test our understanding of how clouds and precipitation change as climate is warming, but also identify patterns of change (including secular trends, such as in ocean heat content or salinity) and forcing (long-term aerosol and greenhouse gas records) that can be used to constrain our understanding of key climate processes (for instance as identified in the first initiative). Understanding of climate change may well be limited by our vigilance in observing and documenting the climate change signal as it emerge from the noise of natural variability, but also the analysis of recent trends may provide clues as to the character of future changes. By continuing and augmenting recent efforts to bring observations and model intercomparison data into a common framework this initiative will work to improve communication between modelling and observations communities around cloud and circulation/precipitation issues so as to : facilitate the access of climate modellers to key observations (such as initiated by the Obs4MIPs project); identify observational gaps before they arise; and define the accuracy requirements of future observations systems. These activities naturally link to all the other initiatives.

On longer timescales (multi-decadal to millennium), vast improvements of the paleo-climatic data records, reconstructions and syntheses are expected (through the IGBP Past Global Changes, PAGES, project and the WGCM Paleoclimate model intercomparison, PMIP, efforts). For instance the development of novel laser spectroscopy techniques, high-resolution temporal sampling of proxy records, the increasing use of present day measurements and modelling to help interpret isotopic records (e.g., as part of GEWEX Stable Water Isotope Intercomparison Group, SWING), and new data records (for instance from ocean drilling programs or tropical ice cores, or through ion microprobe techniques such as NanoSIMS) greatly improve the chance of using the paleo-record to constrain modelling of the present and future. Additionally, coordinated paleoclimate modelling experiments performed with the same models as the projections of future climate change (i.e., the coordinated PMIP3/CMIP5 project) are, for the first time, making it possible to quantify the link between past and future climate changes, especially for crucial aspects of the projections such as feedbacks, climate sensitivity and precipitation changes. These links make close coordination with the first initiative (I1) essential.

I3: Coupling Clouds to Circulations

This initiative will focus on the parameterization problem, and targeting efforts in ways that help break down barriers to progress, particularly barrier B3. It will build on efforts like CGILS, a new GASS project that uses the weak-temperature gradient method to link fine-scale and single column models to large-scale dynamic responses, and the WGNE grey-zone project investigating the dependence of simulated cloud statistics on model resolution, as well as emerging initiatives within GASS (e.g., a proposed aerosol climate initiative) and CFMIP (e.g., projects exploring the effect of cloud processes in more idealized frameworks) to link advances in cloud resolving modelling to the wider spectrum of climate-variability and climate-change analysis. Examples of this type of analysis include the process-oriented analysis of climate and NWP models by the MJO task force (jointly sponsored by the WCRP-GEWEX and WWRP-THORPEX); or emergent and robust cloud-related changes in the climate as revealed through the analysis proposed in I1 (in the case of GCMs) or I2 (in the case of the observational record). In terms of the latter, new possibilities are emerging to better link clouds and precipitation to circulation systems, for instance through the high-temporal sampling of the Megha-Tropiques satellite, or the first measurements of vertical motion as part of EarthCARE.

In developing this initiative it will be important to identify and articulate compelling questions in a way that is cognizant of existing gaps in existing efforts; for instance insufficient emphasis of surface-atmosphere interactions over land. Care must also be taken to frame questions in a way that also advances model development initiatives through I5; as so doing completes the model development loop (from I1-I3-I5).

I4: Changing Patterns

The localization of dry and moist regions over the globe, as well as the occurrence of different weather regimes and climate zones, primarily depends on the large-scale atmospheric circulation. This initiative aims at better anticipating how the large-scale atmospheric circulation will respond to anthropogenic forcing on decadal and longer time scales. It targets the second barrier (B2) identified above, and to be successful will require strengthened connections between cloud experts and large-scale dynamicists, including expertise found within the WCRP core project on Stratospheric Processes and their Role in Climate (SPARC), the WCRP Working Group on Seasonal to Interannual Prediction (WGSIP), but also expertise within IGBP for better constraining the regional signal of forcing agents.

Again the CMIP5 and CFMIP projects help set the stage for this initiative. By developing the CMIP5 analysis and by complementing it with additional experiments targeting specific issues, for instance the effect of idealized aerosol forcing or the role of upper tropospheric temperature changes as isolated in radiative convective equilibrium experiments, the interpretation of circulation shifts, as they appear in the more complex simulations or in the observational record (thereby linking to I2), and the physical interpretation of sources of decadal climate predictability will be advanced. A key will be to better understand the relative role of local forcing versus large-scale or remotely forced changes in driving regional changes. Here links with the aerosol community and the CMIP5/CORDEX data will be particularly helpful, and provide an opportunity to improve the conceptual and methodological underpinnings of regional change studies (thereby also linking to I5 and the WCRP Grand Challenges on Water Availability and Regional Climate Predictions). The understanding of the impact of different anthropogenic forcings on circulation and climate will also contribute to the assessment of solar-radiation management strategies for climate mitigation.

An important and novel aspect of this initiative will be to focus on the role of model biases (for instance those associated with a poor representation of the surface state or of cloud processes) in masking, or skewing, regional signals, which provides a link to I5. In this context, model evaluation methods based on short-term weather forecasts (WGNE/WGCM Transpose-AMIP project) and intra-seasonal hindcasts (WCRP-THORPEX-GASS MJO-diab project), and other observational tests such as those related to natural variability (e.g. ENSO) or volcanic eruptions may also be very useful.

I5: Towards More Reliable Models

This initiative aims at improving the models used for projecting future climate changes, and links with I3 to target the third barrier (B3) identified above. Substantial progress will likely result from enhanced research efforts around two main issues: (i) the identification and reduction of long-standing biases in the representation of cloud and convective processes (and their associated effects on irradiances and circulations); and (ii) the assessment of the effect of model errors on the reliability of model projections and predictions.

To a large extent this initiative will synthesize and build on the fruits of the other four initiatives, and their associated activities, to identify and target key areas of model development. A key challenge will be to raise the profile of model development activities, particularly as relates to parameterized processes in climate models. Equally important is the need to demonstrate, using the methods developed in the other initiatives, that model developments can target and resolve long-standing model biases, like the double-ITCZ problem, thereby leading to more reliable models. Systematic and coordinated investigations of how physical or resolution shortcomings translate into climate errors will thus be essential in identifying these *key shortcomings*, and must be a focal point of this initiative.

Strategy of coordination and integration

- ***This Grand Challenge will be led by WGCM*** (the group that develops, promotes and oversees many of the leading MIPs, including CMIP, CFMIP (on cloud feedbacks) and PMIP (on paleoclimate). Close cooperation with the Global Atmospheric System Studies (GASS) project of GEWEX and Working Group on Numerical Experimentation (WGNE) of WCRP/CAS will be essential, and these groups may even take the lead on particular initiatives within this grand challenge. Further cooperation with the Working Group on Seasonal to Interannual Prediction (WGSIP) and CLIC within WCRP, plus the International Global Atmospheric Chemistry (IGAC) and the Past Global Changes (PAGES) projects within IGBP are also envisioned for specific specific questions, e.g., the aerosol, records of the distant past, sources of decadal predictability. Overall progress and achievements of the grand challenge will be reported and discussed annually at WGCM meetings.

- To strengthen the coordination and integration of the initiatives, ***we will organize a grand Challenge***

Joint Steering Committee (GC-JSC), including representatives of the key groups involved and incorporating key expertise (large-scale and paleoclimate modelling, satellite observation, cloud processes, model analysis, aerosol, and perhaps land-surface, processes). A first goal of the GC-JSC will be to associate each initiative with a clear goal and a person who will lead it.

- ***Many of the initiatives leverage on-going or planned WCRP projects***. As an example, many of the activities mentioned above are already included in projects being planned within CFMIP and GASS projects, as well as projects of the WCRP-WWRP-THORPEX MJO task force, the WGNE grey zone project, PMIP projects, etc. Hence organizational effort will not be required to start many new initiatives, rather it will be important to provide coordination and inspiration for existing efforts so as to help them better address the Grand Challenge's goals.

- We will work with the ***WMAC*** (WCRP Modelling Advisory Council) to discuss how the different modelling activities of WCRP can or could contribute to this Grand Challenge and how to get buy-in from the computing centres, and with the ***WDAC*** (WCRP Data Advisory Council) to develop a coordinated observing strategy. We will work with the WCRP leadership to foster agency support for specific initiatives within the Grand Challenge, for instance in the form of calls for European Projects, NASA/NSF/DOE programmes, ESA/JAXA projects, or G8 initiatives.

- To encourage and foster links with IGBP, the grand-challenge ***will organize a joint WCRP-IGBP workshop*** focused on exploring the relative role of uncertainty in anthropogenic forcing (for instance, in terms of changing regional aerosol burdens, temporal changes in greenhouse gases, or land-use patterns) versus response (cloud and circulation changes) in limiting predictive skill on regional scales.

- To give an impulse to the programme as a whole, ***a first step will be to organize workshops, to be held over the course of 2013 and 2014, involving small groups of key individuals on each of the initiatives identified above.*** The goal of the workshops will be to further sharpen the initiatives and more clearly articulate their relationship to the main barriers that this grand challenge seeks to surmount. The insights gained will be formulated in an engaging way for articles in high profile journals (e.g., Nature, Science or BAMS), so as to help motivate, guide and support contemporary and future generation of researchers on the topic of this Grand Challenge. We anticipate the Grand Challenge will run from 2014 through 2020.