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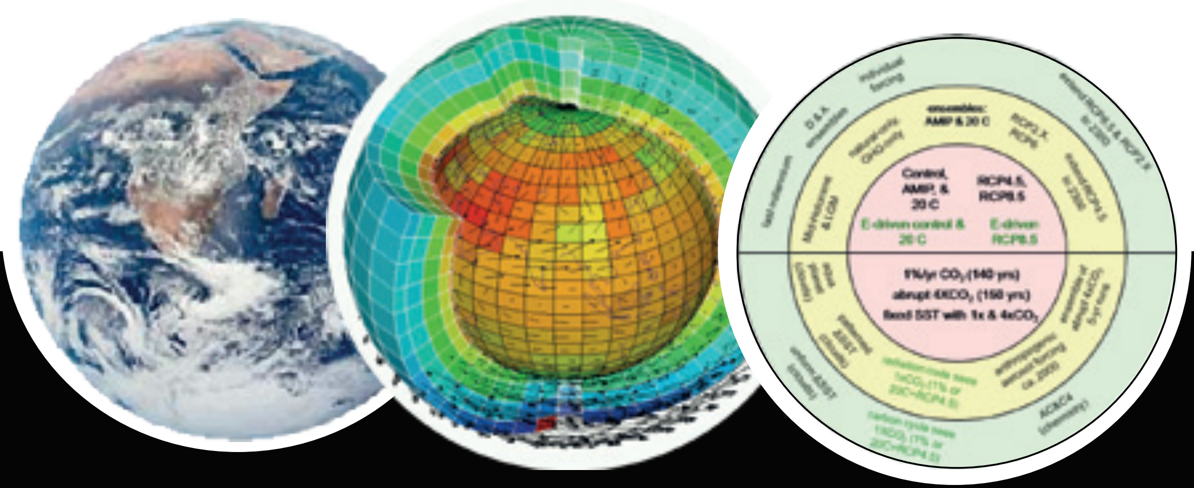
WCRP Coupled Model Intercomparison Project - Phase 5
- CMIP5 -



CLIVAR is an international research programme dealing with climate variability and predictability on time-sales from months to centuries. CLIVAR is a component of the World Climate Research Programme (WCRP). WCRP is sponsored by the World Meteorological Organization,the International Council for Science and the Intergovernmental Oceanographic Commission of UNESCO.

WCRP
World Climate Research Programme

Editorial

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Human activity has changed our climate over the past century, and further change is inevitable over the next several decades, even if strong mitigation actions are taken. It is thus imperative for CLIVAR to promote and facilitate predictive science that aims to inform adaptation decisions. This includes improving our ability to simulate future states of the climate system, including variations in the likelihood of extremes and precipitation, on time scales of seasons to decades and longer. It also requires advancing understanding of how human influences exacerbate (or damp) natural climate variations on global to regional scales.

Interest in the WCRP Coupled Model Intercomparison Project – Phase 3 (CMIP3) simulations coordinated by the Working Group on Coupled Modeling (WGCM) continues unabated, with several thousand registered users of the data and nearly 600 peer-reviewed publications in leading climate journals at last count. But with the publication of the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4), there has been a paradigm shift in climate modelling toward mitigation scenarios, with implied policy actions, relevant to longer term climate change out to 2100 and beyond. There is also an enhanced focus on shorter-term climate change out to about 2035, and a better quantification of key feedbacks including the carbon cycle. Moreover, this paradigm shift recognizes the need to better understand and interpret the observed record of climate in order to more accurately determine the role of human activity, other external forcings, and internal variability. A much broader set of model experiments is therefore required in order to respond to the growing need for climate science to inform both adaptation and mitigation decisions.

This special issue of CLIVAR Exchanges is thus devoted entirely to CMIP5, a multi-model experimental framework of unprecedented scale. The intent is to produce a useful "one-stop shop", through short overview articles, for information on key components of CMIP5. Through this extremely ambitious set of coordinated climate model experiments, the CLIVAR community has a unique opportunity to undertake high-impact multi-model research on the fundamental physics of climate and its expected changes to be assessed by the next IPCC report.

WCRP Modelling Strategy Developments

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WCRP is pleased to report on the newly formed WCRP Modelling Council in this special issue of CLIVAR Exchanges that is devoted to the exciting results from WCRP sponsored climate modelling activities. The WCRP Modelling Council is formed to coordinate research on development and use of climate and Earth system models across its four major projects (CliC, CLIVAR, GEWEX and SPARC), and its sister international global change research programs such as IGBP and WWRP. The Joint Scientific Committee (JSC) of WCRP initiated discussion on the formation of the Modelling Council in its 31st meeting in 2010 in Antalya, Turkey, and recently endorsed its formation at its 32nd meeting in Exeter, United Kingdom. The Council will replace the WCRP Modelling Panel which sunset in 2009. There has been considerable discussion within WCRP and with its sister research programmes on the functions and structure of the Council that are captured in the JSC report available on the WCRP website: (http://www.wcrp-climate.org/reports.shtml). These discussions all took place in the context of WCRP visioning for its future priorities and direction. The purpose of this Council is to promote:

- The greater use of observations and results of process studies in models;
- Model development and improvements.
- Collaboration amongst various climate science communities (including numerical weather prediction (NWP), seasonal to interannual prediction and climate projection as well as those dealing with biogeochemistry, air quality, terrestrial ecology, etc.);
- Application of models to problems of societal relevance, quantifying uncertainties and making sure they are well communicated and understood;

Five small teams of experts were identified and each team was asked to develop a short concept paper on the four scientific and technical themes identified above. The fifth team was asked to develop a governance concept for coordination of the functions associated with the first four themes, through a grass-root process and across the entire WCRP Projects and Program activities. The initial draft of the five concept papers were distributed for review and comment, and further refined as a result of a special modelling coordination meeting that was convened in November 2010, in Paris, France. A WCRP report (WCRP Series Report No.133 WMO/TD-N°.1569) from this workshop includes the five concept papers plus the overall summary of the deliberations that is provided below:

- A WCRP Modelling Council is essential and it should focus on coordination and integration of activities across WCRP Projects and Panels, and with the WCRP partners (e.g. IGBP, WWRP, etc.).

- The Council should promote model development, evaluation and applications in a way that makes the whole Programme activities greater than the sum of individual Working Groups and Panels through "grass roots" efforts and not a "top-down" approach.

- The Council should build on the strengths of the existing modelling activities rather than duplicate or re-create new ones, unless it is found absolutely essential, e.g. a new WCRP initiative in regional models and downscaling.

- The Council should develop an overall modelling strategy for the Programme with associated governing mechanism(s) to implement it, based on the principles stated above. Some examples of major topics that the strategy may encompass are:

- Model development
- Model evaluation
- Uncertainty analysis
- Greater use of observations in model development, evaluation and analysis
- Common software and standards in modelling
- WCRP Modelling Summit recommendations

The general view on the formation of this Council is to be cautious about how it will be governed. We were reminded to avoid the potential pitfalls of the past and to take full advantage of the difficult lessons learned by the "top-down and centralized" approach used because such approach is not consistent with the "grass roots and voluntary" approach that has been the hallmark of WCRP past successful efforts. There have also been considerable discussions on the membership and functions of the Council that are summarized in the meeting report (WCRP Series Report No.133 WMO/TD-N^{o}.1569). For example, in light of increased complexity in models and required spatial and temporal resolution in their projections, i.e. Earth system and seamless approaches, the participants recognized the need for greater collaboration with sister programmes such as the IGBP, WWRP, etc. Thus, there was considerable discussion about the relationship between these programmes and the Council. The general conclusion was to wait until the Council is fully functional and engages in some activities of common interest with these programmes to find out what is the most effective way to forge such partnership arrangements.

These discussions also identified an urgent need for access to more advanced and powerful computational capabilities, as was called for by the WCRP Modelling Summit (Shukla et al., 2009), in light of increased complexity and greater needs for enhanced spatial and temporal resolution in climate model development and simulations. These capabilities are also needed urgently for assimilation, analysis and re-analyses of very large volumes of Earth observations, especially from space-based systems, that are currently available and most likely to further increase in the future. This challenge present a great opportunity for closer collaboration between the WCRP Modelling and Data Councils to undertake the task of promoting greater coordination in the use of National computational capabilities in the spirit of making the whole greater than the sum of the individual capabilities. There is currently a proposal for establishing an International Center for Earth Simulations (ICES) through a private-public partnership in Switzerland which could also contribute toward this objective, especially in a research and development mode. The ICES proposal will be presented and further discussed at the WCRP Open Science Conference on 24-28 October 2011 in Denver, Colorado, USA.

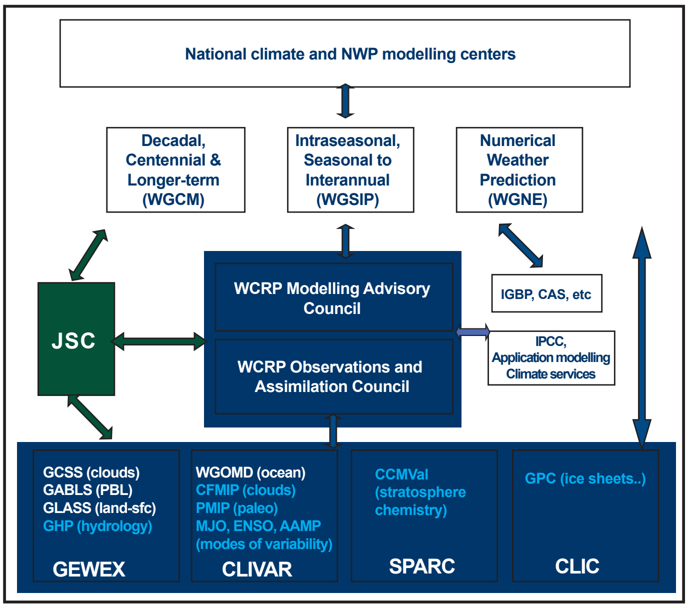


Figure 1. Conceptual framework for coordination of modeling activities within WCRP, and with participating organization and other international research coordination programmes.

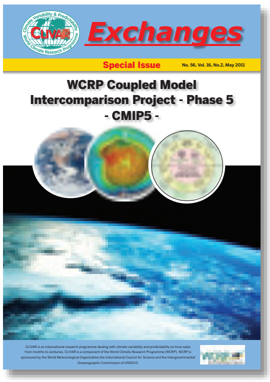
References

Shukla, J., R. Hagedorn, B. Hoskins, J. Kinter, J. Marotzke, M. Miller, T. N. Palmer, and J. Slingo, 2009: Strategies: Revolution in Climate Prediction is Both Necessary and Possible: A Declaration at the World Modelling Summit for Climate Prediction. Bull. Amer. Meteor. Soc., 90, 175–178.

World Climate Research Programme, 2011: Modelling Coordination Meeting Report, 15-16 November 2010, Paris, France. WCRP Series Report No.133, WMO/TD-N^{O}.1569, 31 pp.

Front Cover Figure

Caption for middle sphere: Visual representation of the meshes used in the LMDZ atmospheric general circulation model. Colours represent the air and surface temperatures simulated by the model inside each grid cell. Arrows represent the wind calculated by the model at the originating gridpoints (only a subsample of the wind field is shown for clarity). By Laurent Fairhead (LMD, France).



Introduction to CMIP5

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This special issue of CLIVAR Exchanges provides updates and details regarding the latest phase of the Coupled Model Intercomparison Project, CMIP5. About 20 modeling groups from around the world are currently running the CMIP5 experiments that represent the most ambitious multi-model intercomparison and analysis project ever attempted. The WCRP Working Group on Coupled Models (WGCM), in consultation with the IGBP Analysis Integration and Modeling of the Earth System (AIMES) and a number of other elements of WCRP and the climate research community, is coordinating the running and analysis of these model simulations. More details on CMIP5 can be found at Taylor et al. (2009; 2011). This article provides a brief background and introduction, as well as the latest updates on CMIP5 activities, including two workshops where CMIP5 results can be presented.

The motivation for CMIP5 emerged in the latter stages of the IPCC 4th Assessment report (AR4) process where a number of gaps became evident in the information CMIP3 could provide. At an Aspen Global Change Institute session in mid-2006, representatives from a number of interested communities (e.g. physical climate science, biogeochemistry, impacts/adaptation, integrated assessment modeling) formulated the basic concept for CMIP5, dividing the simulations into the near-term and long term time scales, with additional experiments to better address biogeochemical feedbacks in the climate system. The outlines of this process were published in Meehl and Hibbard (2007) and Hibbard et al. (2007). In parallel, the community interested in physical climate feedbacks, in particular those associated with clouds and moist processes, have elaborated a strategy to better assess these processes in models and better understand their role in climate change (Bony et al., 2008; Quaas et al., 2009). It led to the recommendation of using satellite simulators in some CMIP5 experiments to facilitate the evaluation of model-simulated clouds in comparison to observations, and to the proposition of adding very idealized model experiments (e.g. aquaplanet) to CMIP5 to better unravel the physical mechanisms that control robust climate responses. These new aspects of CMIP5 are designed to help in the interpretation of inter-model differences in climate change projections.

Thus, the scope of CMIP5 is much broader than CMIP3, with not only long term concentration-driven AOGCM experiments with the four new representative concentration pathway (RCP) mitigation scenarios (Moss et al., 2010), but also emission-driven Earth System Model (ESM) experiments, some of those with partial coupling to explore sensitivity of the carbon cycle feedback. The new field of climate research called decadal climate prediction (Meehl et al., 2009) will be represented by a number of hindcasts and near term prediction experiments. There will be many more experiments to explore the impact on climate of various natural and anthropogenic forcings, the reasons for model spread in terms of size and nature of feedbacks, and paleo-climatic experiments to assess the ability of CMIP5 models to reproduce past climate changes to better inform the credibility of the models' future climate change projections. Even more versions of models will involve aerosols-chemistry-climate models, higher resolution AOGCMs (about 50 km resolution) and higher resolution yet (about 25 km) atmosphere-only time slice experiments. CMIP5, together with model intercomparison projects run in parallel to CMIP5 (e.g. Transpose-AMIP, which will evaluate CMIP5 climate models in weather forecast mode), will make it possible to assess and to analyze models participating in CMIP5 over a wide range of time-scales (from the process to the paleo-climatic scale) and configurations. The articles in this CLIVAR Exchanges Special Issue provide further descriptions of the elements of CMIP5, including the long term experiments; carbon cycle feedbacks; the cloud feedback experiments recommended by the Cloud Forcing Model Intercomparison Project (CFMIP); the paleo-climate experiments put forward by the Paleo-climate Modelling Intercomparison Project (PMIP); global coupled climate models that extend the vertical domain to include more detail in the stratosphere, called high top models; the protocol to provide better descriptions of the models and experiments in CMIP5 called Metafor; the decadal climate prediction experiments; satellite observations for CMIP5 analyses; and aspects relevant to ocean modeling in CMIP5.

Some model data are already available for analysis through the PCMDI web page, with more steadily coming on line http://cmip-pcmdi.llnl.gov/cmip5/. The multi-model dataset will mature through the course of 2011 as more and more model data become available. We advise analysts to be flexible in their analyses, starting with a few models, but allowing the capability to include additional model data as more becomes available. Experience with CMIP3 indicates that general conclusions can be reached with a few models, and uncertainties can be better quantified with the addition of more models to reach final publishable results. We also suggest to analysts that they try to evaluate and analyze model simulations over a wide range of experiments, time-scales and configurations (coupled/atmosphere-only, with/without ocean initialization, etc), as it may provide hints about the origin of inter-model differences or model errors, and thus benefit the model development process.

With regards to opportunities to present results from CMIP5 model data analyses, the first is a CMIP5 poster session at the upcoming WCRP Open Science Conference (OSC) to be held in Denver, Colorado USA 24-28 October, 2011. For more information on the OSC, please check:
www.wcrp-climate.org/conference2011

The CMIP5 session at OSC is Session C34: **Global Model Evaluation and Projections: CMIP5 and Other Model Intercomparisons**, with conveners G. Meehl, D. Waugh, J. Fasullo, K. Williams. Though the emphasis is on new CMIP5 analyses, results from CMIP3 and other model intercomparisons such as CCMVal are also welcome. The session could also include results pertaining to, for example, reanalyses, transpose AMIP, and quantitative performance metrics. The deadline for submitting abstracts is 30 April 2011. Abstract submission is available now on the OSC web page noted above.

A few other key dates for the OSC:

- Early bird registration deadline for OSC: 30 June 2011
- General registration deadline for OSC: 24 October 2011

The second opportunity to present CMIP5 model analysis results will be a CMIP5 Workshop to be hosted by the International Pacific Research Center at the University of Hawaii, March 5-9, 2012. This will be comparable to the CMIP3 Workshop held there in 2005. The CMIP5 Workshop will be a similar "short presentation/poster" format. This workshop is currently being formulated, and further details will be made available on the WCRP, CLIVAR and PCMDI web pages.

To access the CMIP5 data, please register on the PCMDI CMIP5 web page: http://cmip-pcmdi.llnl.gov/cmip5

Due to the widespread interest in CMIP5, we encourage you to pass along the information in this Special Issue to your colleagues and associates.

References

Bony S, M Webb, B Stevens, C Bretherton, S Klein and G Tselioudis, 2008: CFMIP-GCSS plans for advancing assessments of cloud-climate feedbacks. GEWEX News, 18, No. 4, pp 10-12, Nov 2008.

Hibbard, K. A., G. A. Meehl, P. Cox, and P. Friedlingstein, 2007: A strategy for climate change stabilization experiments. EOS, 88, 217, 219, 221.

Meehl, G.A., and K.A. Hibbard, 2007: A strategy for climate change stabilization experiments with AOGCMs and ESMs. WCRP Informal Report No. 3/2007, ICPO Publication No. 112, IGBP Report No. 57, World Climate Research Programme: Geneva, 35 pp.

Meehl, G.A. L. Goddard, J. Murphy, R.J. Stouffer, G. Boer, G. Danabasoglu, K. Dixon, M.A. Giorgetta, A. Greene, E. Hawkins, G. Hegerl, D. Karoly, N. Keenlyside, M. Kimoto, B. Kirtman, A. Navarra, R. Pulwarty, D. Smith, D. Stammer, and T. Stockdale, 2009: Decadal prediction: Can it be skillful? Bull. Amer. Meteorol. Soc., 90, 1467—1485.

Moss, R., J. Edmonds, K. Hibbard, M. Manning, S. Rose, D. P. van Vuuren, T. Carter, S. Emori, M. Kainuma, T. Kram, G. A. Meehl, J.F.B. Mitchell, N. Nakicenovic, K. Riahi, S. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks, 2010: A new approach to scenario development for the IPCC Fifth Assessment Report. Nature, 463, doi:10.1038/nature08823.

Quaas J., S. Bony, W. D. Collins, L. Donner, A. J. Illingworth, A. Jones, U. Lohmann, M. Satoh, S. E. Schwartz, W.-K. Tao, and R. Wood, 2009: Current Understanding and Quantification of Clouds in the Changing Climate System and Strategies for Reducing Critical Uncertainties. Peer-reviewed book chapter for Clouds in the Perturbed Climate System: Their Relationship to Energy Balance, Atmospheric Dynamics, and Precipitation. pp 557-573, Heintzenberg, J., and R. J. Charslon, eds., www.fias.uni-frankfurt.de/esforum/"Ernst Strüngmann Forum Report, vol. 2, Cambridge, MA: http://mitpress.mit.edu/catalog/item/default.asp?ttype=2&tid=11796"The MIT Press.

Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2009: A summary of the CMIP5 Experimental Design. http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf

Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2011: The CMIP5 Experiment Design. Bull. Amer. Meteorol. Soc., submitted.

CMIP5 Long-term experimental Design

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1. Introduction

CMIP5 (Coupled Model Intercomparison Project phase 5) follows the highly successful phase 3 of CMIP (Meehl et al. 2007), which made available a coordinated set of global coupled climate model experiments, which were analyzed by the international climate science community and subsequently assessed in the 2007 IPCC Fourth Assessment Report. It is expected that CMIP5 will have an even greater impact on climate science research, which will be assessed in the IPCC Fifth Assessment Report due out in 2013.

The experiment design for CMIP5 was first described by Hibbard et al. (2007) and Meehl and Hibbard (2007), and the complete specifications are given in Taylor et al. (2009). CMIP5 includes two new parts when compared with CMIP3. The first is the formulation of experiments that are designed for assessing the skill of decadal climate predictions that have been initialized with observed information. These experiments are the so-called near term experiments and are discussed in more detail by Doblas-Reyes et al. in this issue of the Exchanges Newsletter.

The formulation of the long-term simulations is the second new part of the CMIP5 experiment design and is the focus here. The long-term experiment design now includes not only experiments for conventional climate models (i.e., Atmosphere Ocean General Circulation Models – AOGCMs -- and Earth-System Models of Intermediate Complexity – EMICS), but now also experiments for the newer earth system models (ESMs, see Friedlinstein et al., this issue).

ESMs close the carbon cycle by adding bio-geochemistry routines to the land and ocean components of the climate models. ESMs may also have components that can simulate changes in atmospheric chemistry and predict the formation and decay of atmospheric aerosols.

As noted above, for detailed specifications of all the experiments, the reader should study the experiment design document (Taylor et al. 2009, http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf), which can be obtained from the CMIP5 web site (http://cmip-pcmdi.llnl.gov/cmip5). Also a paper has been submitted describing the CMIP5 experimental design (Taylor et al., 2011).

2. Long term experiments

The core simulations within the suite of CMIP5 long-term experiments (Figure 1) include integrations for understanding differences in the response of models, and integrations to simulate the historical period and into the future. The overall design of the long-term experiments is similar to the design of earlier CMIP experiments.

Climate models of various types can participate in CMIP5. As in past phases of CMIP, atmosphere-ocean general circulation models will be an important part of CMIP5. These models consist of atmosphere, ocean, land and sea ice components. Simpler climate models or Earth system Models of Intermediate Complexity (EMICs, V. Petoukhov et al. 2005) are also encouraged to participate. EMICs typically use simplified atmospheric components relative to those found in AOGCMs. The oceanic component may or may not be simplified. An EMIC or AOGCM that closes the carbon cycle by adding terrestrial and oceanic bio-geo-chemical components is called an Earth System Model (ESM).

A novel approach is used in CMIP5 to allow the intercomparison of results from all the various types of climate models described above. The inclusion of integrations designed for ESMs is also new for CMIP.

As shown in Figure 1, the design of the long-term experiments includes a core set of integrations with two additional tiers of integrations. The core set includes long preindustrial control integrations where the radiative forcing is prescribed consistent with conditions found ca. 1850 and is unchanged throughout the integration. This type of integration can be used to document the natural variability resulting solely from interactions between the atmosphere, land, ocean, and sea ice components. Control integrations are also important for identifying any climate drifts present in the integration. For ESMs, a second long control integration is required where the atmospheric concentration of CO_2 is computed by the model rather than being prescribed at the pre-industrial value.

The core set of integrations also include simulations of the past 150 years or so. These start from the control integrations. The radiative forcing from changes in the solar input, volcanoes, and land use are prescribed as well as changes in greenhouse gases and aerosols. In ESMs, the CO_2 forcing is computed by the model from human carbon emissions of various types.

Two future scenarios (2005 to 2100) are part of the core set. RCP4.5 is a medium forcing integration. RCP stands for "Representative Concentration Pathway" (see Hibbard et al., this issue). The "4.5" is a rough estimate of the radiative forcing by 2100 relative to the pre-industrial period. RCP8.5 is a high radiative forcing case. See Moss et al. (2010) for more details on the RCPs.

In addition to the integrations highlighted above, the core set also includes several experiments to help understand the causes behind some of the differences in the models' response. Tier 1 and 2 contain important integrations to further help in the understanding of climate change and of the models' projections. Some of these integrations were originally designed as part of other MIPs (PMIP - Braconnot et al., this issue, CFMIP – Bony et al., this issue, etc.)

Several of the CMIP5 experiments require specification of concentrations or emissions of various atmospheric constituents (e.g., greenhouse gases and aerosols). The Integrated Assessment Model Consortium working with the Atmospheric Chemistry and Climate (AC&C) community has provided the concentrations, emissions and time-evolving land use changes to the modeling groups for use in the CMIP5 experiments (Lamarque et al. 2010).

3. CMIP3 / CMIP5 differences

As discussed above, relative to CMIP3, CMIP5 includes a broader variety of experiments and application of more comprehensive models to address a wider variety of scientific questions. CMIP5 also differs from earlier phases in that generally higher resolution models will be used and a richer set of output fields will be archived. There will be better documentation of the models and experiment conditions, and a new strategy for making model output available to researchers.

In CMIP5 coupled models, the resolution will likely range for the atmosphere component from 0.5 to 4 degrees and for the ocean component from 0.2 to 2 degrees. For some of the atmosphere-land-only models running the AMIP part of the core integrations, the resolution may approach 0.2 degrees. In general the highest resolution of CMIP5 models will exceed the highest resolution of CMIP3 models.

The variable list for CMIP5 is greatly expanded. This expansion was achieved through several years of work by various parts of the climate community. These new model output variables should greatly enhance evaluation of the climate models. That said, it is impossible to satisfy the needs of all possible users of model output, so the CMIP5 "requested output" list is far from exhaustive. Practical limits of disk space and volumes of data to be transferred were considered in developing the final lists. In addition for some variables, the models are not ready to provide the information. We estimate that about 3 PB (3000TB) of data will be made public in CMIP5. This represents at substantial increase over CMIP3.

4. Summary

CMIP5 is an enormously ambitious coordinated model intercomparison exercise involving most of the climate modeling groups worldwide. CMIP5 builds on the successful earlier phases of CMIP. We expect that much of the new climate science emerging over the next few years will be connected to this activity. Results from the CMIP5 multi-model dataset should provide input to national and international assessments of climate science (e.g., IPCC Fifth Assessment Report (AR5), now scheduled to be published in 2013).

The CMIP5 model output is freely available to researchers through gateways linked to modeling and data centers worldwide, where the data will be archived. Not only will a more comprehensive set of output be accessible, compared to previous phases of CMIP, but also it is expected that better documentation will be made available (e.g. see Guilyardi et al., this issue).

Scientists are encouraged in addition to provide feedback to individual modeling groups when they uncover aspects of a simulation that are in either unusually good or poor agreement with observations. In this way they might contribute to model improvements needed to further advance climate science.

References

Hibbard, K. A., G. A. Meehl, P. Cox, and P. Friedlingstein, 2007: A strategy for climate change stabilization experiments. EOS, 88, 217, 219, 221.

Lamarque, J.F., T. C. Bond, V. Eyring, C. Granier, A. Heil, Z. Klimont, D. Lee, C. Liousse, A. Mieville, B. Owen, M. G. Schultz, D. Shindell, S. J. Smith, E. Stehfest, J. Van Aardenne, O. R. Cooper, M. Kainuma, N. Mahowald, J. R. McConnell, V. Naik, K. Riahi and D. P. van Vuuren, 2009: Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. Atmos. Chem. Phys., 10, 7017-7039.

Meehl, G. A., C. Covey, T. L. Delworth, M. Latif, B. McAveney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor, 2007: The WCRP CMIP3 multimodel dataset: A new era in climate change research. Bulletin of the American Meteorological Society, 88, doi:10.1175/BAMS-88-9-1383.

Meehl, G.A., and K.A. Hibbard, 2007: A strategy for climate change stabilization experiments with AOGCMs and ESMs. WCRP Informal Report No. 3/2007, ICPO Publication No. 112, IGBP Report No. 57, World Climate Research Programme: Geneva, 35 pp.

Moss, R H., J A. Edmonds, K A. Hibbard, M R. Manning, S K. Rose, D P. van Vuuren, T R. Carter, S Emori, M Kainuma, T Kram, G A. Meehl, J F. B. Mitchell, N Nakicenovic, K Riahi, S J. Smith, R J. Stouffer, A M. Thomson, J P. Weyant and T J. Wilbanks, 2010: The next generation of scenarios for climate change research and assessment. Nature, 463, doi:10.1038/nature08823.

V. Petoukhov, M. Claussen, A. Berger, M. Crucifix, M. Eby, A. V. Eliseev, T. Fichefet, A. Ganopolski, H. Goosse, I. Kamenkovich, I. I. Mokhov, M. Montoya, L. A. Mysak, A. Sokolov, P. Stone, Z. Wang, A. J. Weaver, 2005: EMIC Intercomparison Project (EMIP–CO_2): comparative analysis of EMIC simulations of climate, and of equilibrium and transient responses to atmospheric CO_2 doubling. Climate Dynamics 25, 363–385, DOI 10.1007/s00382-005-0042-3.

Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2009: A summary of the CMIP5 Experimental Design. http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf.

Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2011: An overview of CMIP5 and the experiment design. Bull. Amer. Meteorol. Soc., submitted.

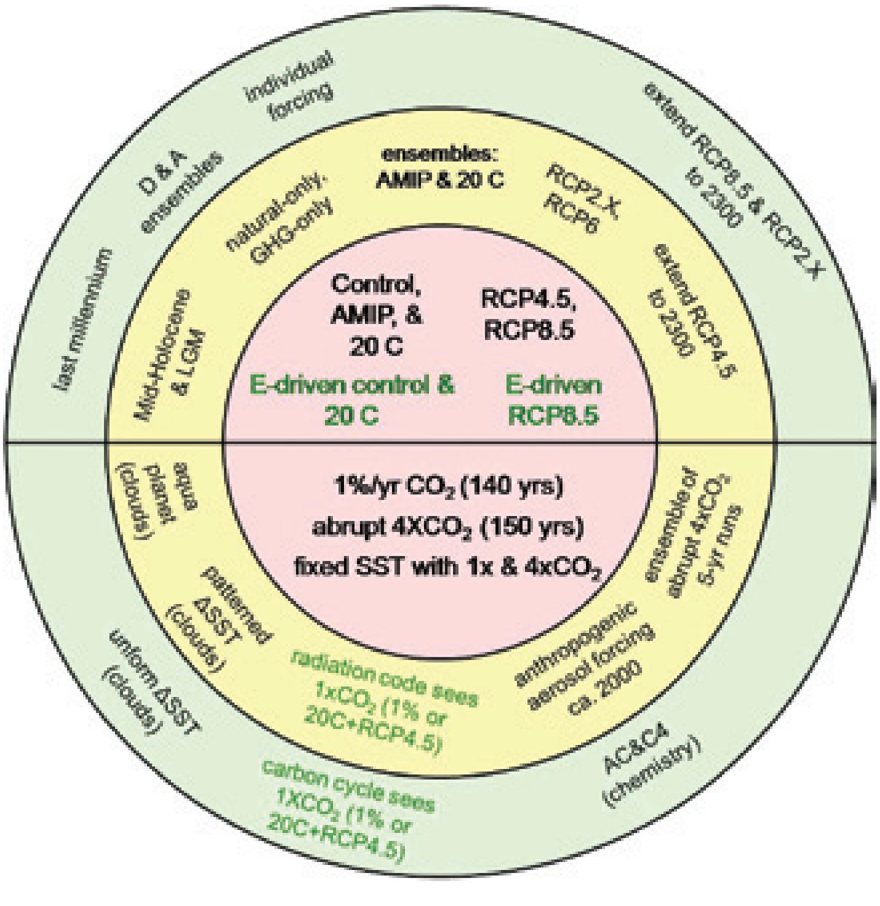

Figure 1 Schematic summary of CMIP5 long-term experiments. Green font indicates simulations to be performed only by models with carbon cycle representations. Experiments in the upper hemisphere are suitable either for comparison with observations or provide projections, whereas those in the lower hemisphere are either idealized or diagnostic in nature, and should provide better understanding of the climate system and model behavior.

CMIP5 near-term climate prediction

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Introduction

Near-term climate prediction (also known as decadal climate prediction) attempts to satisfy a growing demand for climate information for the next few years to a couple of decades (Meehl et al., 2009). It is well established that, based on knowledge of the initial conditions, important aspects of regional climate are predictable up to a year ahead. Predictability at this time scale is primarily, though not solely, associated with the El Niño Southern Oscillation (ENSO), and is currently addressed by seasonal forecasting. On multi-year timescales other factors are also important, including low frequency variations in ocean circulation and changes in external (or boundary) forcing from anthropogenic (e.g. greenhouse gases and aerosols) and natural sources (e.g. solar variability and volcanic eruptions).

Skilful interannual-to-decadal climate predictions have been achieved by using changes in boundary conditions such as atmospheric composition and solar irradiance. Both empirical methods (Lean and Rind, 2009) and dynamical climate model projections (Roukolainen and Räisänen, 2007) have been employed. The latter were performed as part of the Third Coupled Model Intercomparison Project (CMIP3), from which the part of the simulations corresponding to the first few years of the 21st Century were used to issue a climate prediction for the near term. However, these approaches do not attempt to predict natural internal variability. Improved skill could be expected using dynamical climate models that are initialized with the current state of the climate system.

For any prediction system, a critical question is to understand how far ahead the mean climate is predictable at regional spatial scales with some useful level of skill. The relative importance of the initial conditions in climate prediction is expected to decrease with forecast time, becoming negligible after several decades (e.g. Hawkins and Sutton, 2009). Initial conditions are more relevant than variations in atmospheric composition in seasonal forecasting, except perhaps after an explosive volcanic eruption, while atmospheric composition has primary importance after several decades. In the context of initialized climate prediction, the question of the extent to which a better knowledge of the initial conditions of the climate system contributes to the quality of these forecasts is less well understood. However, initial studies (Smith et al., 2007, 2010; Keenlyside et al., 2008; Pohlmann et al., 2009; Mochizuki et al., 2010) have shown some improved skill up to a decade ahead arising from initializing the ocean. Two approaches have been explored to initialize climate predictions. Smith et al. (2007, 2010), Pohlmann et al. (2009) and Mochizuki et al. (2010) used the so-called anomaly initialization method, where ocean observations are assimilated in the form of anomalies into the coupled model with the option of taking into account modelled error covariances. Following a similar strategy, Keenlyside et al. (2008) used only observed anomalies of sea surface temperature (SST) to initialize the coupled system. Following a strategy common in seasonal forecasting, van Oldenborgh et al. (2011) and Doblas-Reyes et al. (2011) describe the results of separately initializing the ocean and the atmosphere with observed states, in what is known as full initialization.

CMIP5 near-term climate prediction

To make further progress in the near-term climate predictions, the Fifth Coupled Model Intercomparison Experiment, known as CMIP5 (Taylor et al., 2009; 2011), has organized a set of experiments that include climate predictions up to 2035. The experiments are organized in a core set and an additional tier 1 set. The core experiments involve a set of ten year hindcasts initialized from climate states near the end of the years 1960, 1965, 1970, and every five years to 2005, with this last simulation representing an actual prediction beyond 2005 because forcings are no longer prescribed and a forecast is made beyond 2011. These simulations, will allow assessment of the forecast quality on time-scales when the initial climate state is most likely to exert some influence. Other core experiments will extend the ten-year simulations initialized in 1960, 1980, and 2005 by an additional 20 years. At least three ensemble members will be performed for each of the core experiments.

The tier 1 near-term experiments also include predictions with 1) additional initial states after the year 2000 when ocean data is of better quality, 2) volcanic eruptions removed from the hindcasts, 3) a hypothetical volcanic eruption imposed in one of the predictions of future climate, 4) different initialization methodologies, and 5) the option of performing high-resolution time-slice experiments with specified SST for certain decades in the future.

An example: Results from the EU ENSEMBLES project

The CMIP5 experiments are currently being run, and contributions from some centres have already been completed. To illustrate the type of information that can be

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[1] Near-term climate was considered as the 10-to-30 year period counting from a reference time, which in a forecast would correspond to the start of the prediction.

[2] An informal initiative led by the Hadley Centre has been launched to coordinate the exchange of quasi-operational decadal predictions once a year using the same forecast systems employed for the CMIP5 hindcasts.

[3] www.ensembles-eu.org

obtained from the decadal experiments, a previous exercise carried out in the framework of the EU-funded ENSEMBLES project and that opened the way to the CMIP5 core experiment will be used. Two climate forecast contributions, a multi-model and a perturbed-parameter ensemble, were made (Doblas-Reyes et al., 2010).

The ENSEMBLES multi-model consists of four forecast systems: CERFACS, ECMWF, IFM-GEOMAR and MOHC with the HadGEM2 model. Three-member ensemble re-forecasts were run for ten years starting on November 1 from 1960 to 2005 every five years. Volcanic aerosol concentrations from eruptions before the analysis date were relaxed to zero with a time scale of one year in the IFM-GEOMAR system (Keenlyside et al., 2008), while the other three models did not include any volcanic aerosol effect. In all cases, the effects of eruptions during the re-forecasts were not included to reproduce a realistic forecasting context. This is a major difference from the CMIP5 experiment. Three of the four models (the ECMWF, MOHC and CERFACS systems) used a full initialisation strategy. In contrast, IFM-GEOMAR used observed SST anomaly information to generate the initial conditions.

A second contribution (DePreSys; Smith et al., 2010) was run by the Met Office using a nine-member ensemble of HadCM3 model variants sampling modelling uncertainties through perturbations to poorly constrained atmospheric and surface parameters. Ten-year long re-forecasts were started on the first of November in each year from 1960 to 2005. In order to assess the impact of initialization an additional parallel set of re-forecasts (referred to as NoAssim) with the same nine model versions was run. The NoAssim re-forecasts are identical to those of DePreSys except that they are not explicitly initialized with the contemporaneous state of the climate system, the initial conditions being taken from the restarts of the corresponding long-term climate change integrations. NoAssim is used to assess the impact of the initial conditions in near-term climate prediction.

An illustration of the spatial distribution of the skill for the 2-5 year average near-surface temperature is shown in Figure 1. Anomalies have been computed following the WCRP recommendations. The systems have skill over large regions, especially over the tropical oceans and the North Atlantic, but also over large parts of the continents. Both the multi-model and DePreSys with start dates every five years have a similar distribution of the skill, with the largest differences appearing over the tropical oceans. Figure 1d shows the skill for DePreSys when one start date per year is used. A comparison with the skill of Figure 1b indicates that the spatial distribution does not change substantially, although the values are slightly reduced. A comparison between DePreSys and NoAssim reveals that most of the skill in temperature is due to the external forcing, skill improvements due to the initialization appearing mostly over the North Atlantic and the subtropical Pacific (see Smith et al., 2010).

The skill in the North Atlantic basin is consistent with previous studies (e.g. Knight et al., 2005) linking Atlantic multi-decadal variability (AMV) with variations of the Atlantic meridional overturning circulation (AMOC), and with a recent analysis showing skilful predictions of the AMOC a few years ahead (Pohlmann et al., 2011). Similarly, an AMV index, computed as the SST anomalies averaged over the region Equator-60ºN and 80º-0ºW minus the SST anomalies averaged over 60ºS-60ºN (Trenberth and Shea, 2006), shows decadal variability and has multi-year predictability (Murphy et al., 2010). Figure 2 shows that three out of four single-model forecast systems yield skilful predictions in the first few forecast years. The multi-model and DePreSys (using a five-year interval between start dates) ensemble mean have a similar behaviour as a function of the forecast time, showing in general larger correlation than the single-model forecast systems. The differences between the multi-model and DePreSys are subtle and the uncertainty in the forecast quality estimates is very large. In addition, a comparison of the AMV ensemble-mean correlation for DePreSys using one- and five-year interval between start dates shows that, although a five-year interval sampling allows to estimate the level of skill, local maxima along the forecast time might well be due to poor sampling of the start dates. This leads to one of the problems of the limited set of start dates chosen for the core CMIP5 experiment. It is difficult to extract significant conclusions about the differences between forecast systems with such small samples, high interval between start dates and small ensemble size. Unfortunately, the length of the forecasting period is limited to the period over which reasonably accurate estimates of the ocean initial state can be made, which starts around 1960. Besides, both the sample and ensemble sizes are limited by the substantial computing resources required to perform even the experiments described here.

The initialization significantly improves the AMV skill over the first few forecast years, although the uninitialized (NoAssim) re-forecasts are also significantly skilful at longer lead times highlighting the relevance of the external forcing (Figure 2). This is a useful result because several studies (e.g. Sutton and Hodson, 2005; Knight et al., 2006) suggest that important climate impacts, including rainfall over the African Sahel and the United States, Atlantic hurricanes and temperature over North America, North Africa and the Middle East, are associated with the AMV. This is also linked to the skilful multi-year predictions of Atlantic hurricane frequency achieved (Smith et al., 2010).

There is also skill in the Pacific Ocean, where the main decadal-scale feature is the slower component of ENSO (with a spatial scale larger than that of ENSO), often referred to as the Interdecadal Pacific Oscillation (IPO). The IPO shows predictability up to nine years ahead (Mochizuki et al., 2010). There are IPO teleconnections to precipitation in the western half of North America, eastern Australia and also the Sahel, although these teleconnections are weaker than the ENSO

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[4] In this contribution, experiments in which initial and boundary-condition information is restricted to what would have been known at the time of a real-time forecast are considered as re-forecasts, while those that also use information that could not have been available, such as the volcanic aerosol load, after the initial date are considered as hindcasts. Although the ENSEMBLES integrations do not fully comply with the re-forecast definition (because, for instance, re-analyses are used to initialize the system), they are referred to as re-forecasts to contrast them with the CMIP5 hindcasts.

[5] http://eprints.soton.ac.uk/171975/1/150_Bias_Correction.pdf

teleconnections. The climate variability in those regions is not always correctly represented in current climate models and the forecast skill in the teleconnection areas is quite modest. However, both the trends due to global warming and local patterns due to the changing aerosol forcing can add to the skill.

These early decadal prediction results provide some evidence that skilful predictions beyond the first year are viable, and motivate further analysis of the CMIP5 experiments.

The present and the near future

Based upon pioneering work on decadal climate prediction undertaken at the Met Office, in the framework of the ENSEMBLES project and on multiple discussions that took place in the past five years, CMIP5 has included an innovative set of experiments to assess the ability to predict the climate in the near future with the current forecast systems. Building upon these experiences, multiple projects and collaborative initiatives focus on or include a substantial near-term prediction component. This is the case of the EU-funded projects THOR, COMBINE, SUMO and QWeCI, which attempt to perform and analyze large sets of new near-term climate predictions, and the EU-funded project CLIMRUN, which intends to explore the possible applications of this climate information. US CLIVAR has sponsored a Decadal Prediction Working Group that may become responsible for coordinating many of the local analyses of the CMIP5 near-term predictions. As part of the WCRP decadal prediction coordination activities, a CMIP-WGCM-WGSIP subgroup has been formed to oversee the CMIP5 decadal prediction framework, while the different regional CLIVAR implementation panels (Atlantic, Pacific and Indian Ocean, as well as the Variability of the African System) have now specific activities focused on decadal prediction. The near-term prediction experiments will contribute to the IPCC fifth assessment report (AR5).

The CMIP5 near-term experiments are much richer than what has been briefly illustrated here. The large amount of experiments planned for the tier-1 set will address questions such as how best to initialize the forecasts and how to address the different uncertainties specific of these predictions. The tier-1 experiments should contribute to the assessment and development of the science of interannual to multi-decadal prediction by exploring different sensitivities of the forecast systems.

Many aspects remain unexplored in decadal prediction. This is a field that promises exciting developments in the coming years such as the assessment of the benefits of different initialization methods, the formulation of predictions with useful skill over regions and for variables still unexplored or the development of post-processing methods that allow the integration of forecast information from different forecast systems. Last, but not least, the development and use of appropriate benchmarks will necessarily take place as has already happened in seasonal forecasting. These include 1) the availability of an ensemble of long-term climate simulations, which should be used as a NoAssim benchmark, alongside each set of near-term climate predictions and 2) robust, simple statistical models based on persistence and/or relationships with the external forcing.

As already happened in the field of seasonal forecasting, the combination of model improvement, better observational datasets (for both initialization and verification) and a better understanding of the processes at the origin of the interannual to multi-decadal predictability should lead to more skilful multi-year predictions in the future, as well as to an increased benefit from a better informed society.

Acknowledgements

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References

Doblas-Reyes, F. J., M. Balmaseda, A. Weisheimer and T. N. Palmer, 2011: Decadal climate prediction with the ECMWF coupled forecast system: Impact of ocean observations. J. Geophys. Res. D, submitted.

Doblas-Reyes, F. J., A. Weisheimer, T. N. Palmer, J. M. Murphy and D. Smith, 2010: Forecast quality assessment of the ENSEMBLES seasonal-to-decadal Stream 2 hindcasts. ECMWF Technical Memorandum No. 621, 45 pp, ECMWF, Reading, UK.

Fan, Y. and H. van den Dool, 2007: A global monthly land surface air temperature analysis for 1948-present. J. Geophys. Res. D, 113, DOI 10.1029/2007JD008470.

Hansen, J., R. Ruedy, M. Sa and K. Lo, 2010: Global surface temperature change. Rev. Geophys., 48, RG4004, doi:10.1029/2010RG000345.

Hawkins, E. and R. Sutton, 2009: The potential to narrow uncertainty in regional climate predictions. Bull. Amer. Meteor. Soc., 90, 1095-1107.

Keenlyside N. S, M. Latif, J. Jungclaus, L. Kornblueh and E. Roeckner, 2008: Advancing decadal-scale climate prediction in the North Atlantic sector. Nature, 453, 84–88, HYPERLINK "http://dx.doi.org/doi:10.1038/nature06921" doi:10.1038/nature06921.

Knight, J. R., R. J. Allan, C. K. Folland, M. Vellinga and M. E. Mann, 2005: A signature of persistent natural thermohaline circulation cycles in observed climate. Geophys. Res. Letts., 32, L20708, doi:10.1029/2005GL024233.

Knight, J.R., C.K. Folland and A.A. Scaife, 2006: Climatic impacts of the Atlantic Multidecadal Oscillation. Geophys. Res. Lett., 33, L17706, doi:10.1029/2006GL026242. ;

Lean, J. L. and D. H. Rind, 2009 How will Earth's surface temperature change in future decades. Geophys. Res. Lett., 36, L15708, doi:10.1029/2009GL038932.

Meehl, G. A., L. Goddard, J. Murphy, R. J. Stouffer, G. Boer, G. Danabasoglu, K. Dixon, M. A. Giorgetta, A.M. Greene, E. Hawkins, G. Hegerl, D. Karoly, N. Keenlyside, M. Kimoto, B. Kirtman, A. Navarra, R. Pulwarty, D. Smith, D. Stammer and T. Stockdale, 2009: Decadal prediction, can it be skillful? Bull. Amer. Meteor. Soc., 90, 1467-1485, doi: 10.1175/2009BAMS2778.1.

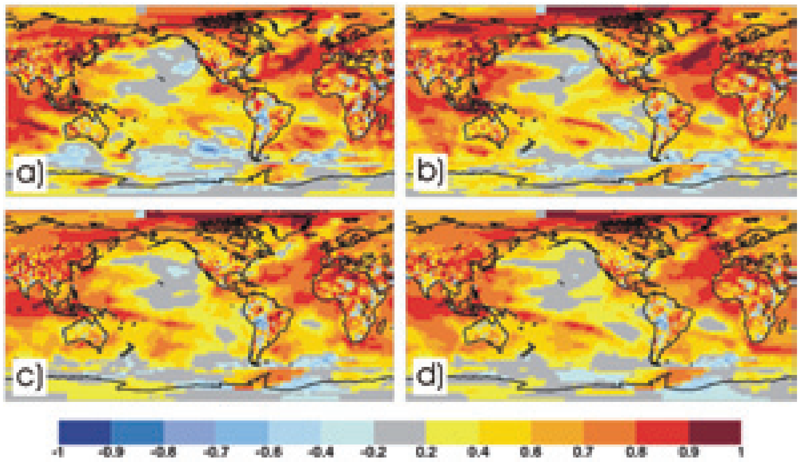

Figure 1: Near surface air temperature ensemble-mean centred correlation for a) the ENSEMBLES multi-model, b) DePreSys, both with five-year intervals between start dates, and c) NoAssim, d) DePreSys with one-year intervals between start dates, for the forecast period 2-5 years. A combination of GHCN (Fan and van den Dool, 2007), ERSST (Smith and Reynolds, 2003) and GISS (Hansen et al., 2010) temperatures is used as a reference. The correlation has been computed with re-forecasts started over the period 1960-2005.

Mochizuki, T., M. Ishii, M. Kimoto, Y. Chikamoto, M. Watanabe, T. Nozawa, T. T. Sakamoto, H. Shiogama, T. Awaji, N. Sugiura, T. Toyoda, S. Yasunaka, H. Tatebe and M. Mori, 2010: Pacific decadal oscillation hindcasts relevant to near-term climate prediction. PNAS, 107, 1833-1837, doi: 10.1073/pnas.0906531107.

Murphy, J., V. Kattson, N. Keenlyside, M. Kimoto, G. Meehl, V. Mehta, H. Pohlmann, A. Scaife and D. Smith, 2010: Towards prediction of decadal climate variability and change. Proc. Environment. Sci., 1, 287-304.

van Oldenborgh, G. J., F. J. Doblas-Reyes, B. Wouters and W. Hazeleger, 2011: Decadal prediction skill in a multi-model ensemble. Climate Dyn, submitted.

Pohlmann, H., J. H. Jungclaus, A. Köhl, D. Stammer and J. Marotzke, 2009: Initializing decadal climate predictions with the GECCO oceanic synthesis: Effects on the North Atlantic. J. Climate, 22, 3926-3938.

Pohlmann, H., D. M. Smith, M. A. Balmaseda, E. D. da Costa, N. S. Keenlyside, S. Masina, D. Matei, W. A. Muller and P. Rogel, 2011: Skillful predictions of the mid-latitude Atlantic meridional overturning circulation in a multi-model system. Geophys. Res. Letts., submitted

Ruokolainen, L. and J. Räisäinen, 2007: Probabilistic forecasts of near-term climate change: sensitivity to adjustment of simulated variability and choice of baseline period. Tellus A, 59A, 309-320, doi: 10.1111/j.1600-0870.2007.00233.x.

Smith, T. M. and R. W. Reynolds, 2003: Extended reconstruction of global sea surface temperature based on COADS data (1854-1997). J. Climate, 16, 1495-1510.

Smith D. M, S. Cusack, A. W. Colman, C. K. Folland, G. R. Harris and J. M. Murphy, 2007: Improved surface temperature prediction for the coming decade from a global climate model. Science, 317, 796–799, http://dx.doi.org/doi:10.1126/science.1139540" doi:10.1126/science.1139540.

Smith, D. M., R. Eade, N. J. Dunstone, D. Fereday, J. M. Murphy, H. Pohlmann, and A. A. Scaife, 2010: Skilful multi-year predictions of Atlantic hurricane frequency. Nature Geoscience, DOI: 10.1038/NGEO1004.

Sutton, R.T. and D.L.R. Hodson, 2005: Atlantic Ocean forcing of North American and European summer climate. Science, 309, 115-118.

Taylor, K. E., R. J. Stouffer and G. A. Meehl, 2009: A summary of the CMIP5 Experimental Design. http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2011: The CMIP5 Experiment Design. Bull. Amer. Meteorol. Soc., submitted.

Trenberth, K. E. and D. J. Shea, 2006: Atlantic hurricanes and natural variability in 2005. Geophys. Res. Lett., 33, L12704, doi 10.1029/2006GL026894.

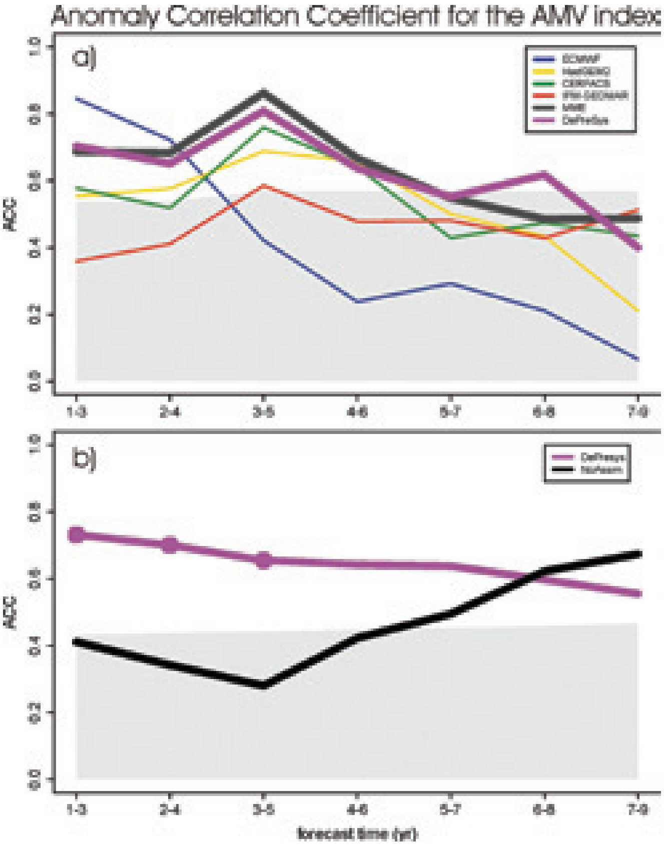

Figure 2: a) Ensemble-mean centre correlation between the single forecast systems contributing to the ENSEMBLES multi-model (thin lines), the multi-model (MME, thick black) and DePreSys with the observed (based on ERSST data; Smith and Reynolds, 2003) AMV index over the period 1960-2010, where all systems have five-year intervals between start dates. b) Ensemble-mean correlation of the AMV index for the initialized (DePreSys, purple) and uninitialized (NoAssim, black) re-forecasts with one-year interval between start dates; solid dots are drawn over the DePreSys line for the forecast periods where the correlation difference with NoAssim is statistically significant ($\alpha<0.05$). Confidence intervals ($\alpha<0.05$) for correlations different from zero are shown in grey.

A primer on the Representative Concentration Pathways (RCPs) and the coordination between the climate and integrated assessment modeling communities

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Socio-economic scenarios are used in climate research to provide plausible descriptions of how the future may evolve with respect to a range of variables including socio-economic change, technological change, energy and land use and emissions of greenhouse gases and air pollutants. Pathways for radiative forcing, as main output variables from socio-economic scenarios are used as input for climate model runs to calculate possible changes in climate. Both socio-economic scenarios and climate calculations can be used as a basis for assessment of possible climate impacts and as a basis for assessment of mitigation costs for avoiding specific climate impacts. As such, scenarios may play an important role in linking different types of climate research. In the past, several sets of scenarios have performed such a role including the IS92 scenarios (Leggett et al., 1992) and more recently, the scenarios from the Special Report on Emission Scenarios (SRES) (Nakicenovic et al., 2000).

After the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), it was clear that new scenarios were needed for use by the research community (Moss et al. 2010). First, more detailed information was required for state-of-the-art climate model runs than provided by the previous scenarios. Second, there was increasing interest in scenarios that explicitly explore the impact of different climate policies, in addition to the no climate policy scenarios explored so far (e.g., SRES). This would allow the community to better evaluate the "costs" and "benefits" of long-term climate goals. Finally, there was also an increasing interest in exploring the role of adaptation in more detail. This requires further integration of information for scenario development across the different disciplines involved in climate research. The need for new scenarios prompted a request from IPCC for development of a new set of scenarios to facilitate future assessment of climate change (IPCC, 2007). The IPCC also decided that the development of such scenarios would not be directly coordinated by the IPCC, but rather, by the research community. The Integrated Assessment Modelling Community (IAMC) offered to play a leading role in the formulation of these new scenarios.

Both Integrated Assessment and climate models have grown increasingly sophisticated in the period since the AR4. New components in climate models include dynamic vegetation, the terrestrial and marine carbon cycle, and complex, interactive atmospheric chemistry, sea ice dynamics, as well as direct and indirect effect of aerosols in next-generation Earth System Models (ESMs). Concurrently, Integrated Assessment Models have been implementing increasingly more comprehensive climate system and land use components in their models. At the conclusion of AR4, in 2006, these new developments were highlighted in a multi-disciplinary workshop co-sponsored by the WCRP's Working Group on Coupled Models (WGCM) and the IGBP's Analysis, Integration and Modelling of the Earth System (AIMES) projects under the auspices of the Aspen Global Change Institute (AGCI) (Hibbard et al., 2007, Meehl and Hibbard, 2007).

Representatives from climate, integrated assessment modelling and the impacts, adaptation and vulnerability communities met to begin discussions for near and long-term experimental design for the climate modelling community, as well as how to begin development of a new set of scenarios for Fifth IPCC Assessment Report (AR5). From this workshop, it was clear that a collaborative approach would be needed to generate new socio-economic scenarios that: (1) represented appropriate differences in radiative forcing to detect significant differences in long-term climate signals, (2) provided a rich resource for the socio-economic and impacts communities to develop scenarios based on future policy; and (3) represented peer-reviewed publications (Moss et al., 2010, van Vuuren et al., 2011). Following the AGCI meeting, a broader representation of users and developers of socio-economic scenarios met under the auspices of the IPCC for an expert meeting in Noordwijkerhout, the Netherlands. Socio-economic user communities were represented by officials from national governments (e.g., many from the United Nations Framework Convention on Climate Change (UNFCCC), international organizations, multilateral lending institutions, and non governmental organizations (NGOs), with the research communities represented by the integrated assessment model (IAM), impact, adaptation and vulnerability (IAV) and climate model (CM) communities. At that meeting a new, parallel process for scenario development was outlined (Moss et al., 2008).

The community subsequently designed a process with three elements (Moss et al., 2010):

- Development of a set of four emission, concentration and land-use trajectories - referred to as "representative concentration pathways" (RCPs),

- A parallel development phase with climate model runs and development of new socio-economic scenarios, and
- A final integration and dissemination phase.

The main purpose for the first step (development of the RCPs) was to provide information on possible development trajectories for the main forcing agents of climate change consistent with current scenario literature allowing subsequent analysis by both climate models (CMs) and Integrated Assessment Models (IAMs). The intent was for climate modellers to utilize the time series of radiative forcing, concentration and emissions of greenhouse gases and air pollutants and land-use change from the RCPs (Table 1, Figure 1) to conduct new climate model experiments and produce new climate scenarios. At the same time, IAMs will explore the range of different technological, socioeconomic and policy futures that could lead to a particular concentration pathway and magnitude of climate change. The choice to develop the RCPs as a first step thus allowed climate modellers to proceed with experiments in parallel with emission and socio-economic scenario development, expediting the overall scenario development process (Moss et al., 2010).

A careful selection process was used to identify the RCPs, using criteria that reflected the needs of both climate scenario developers and the CM community. Two important characteristics of RCPs are reflected in the naming convention. The word "representative" signifies that each of the RCPs represents a larger set of scenarios in the literature. In fact, as a set the RCPs were required to be compatible with the full range of emissions scenarios available in the current scientific literature, with and without climate adaptation/ mitigation policies. The words "concentration pathway" emphasize that these RCPs are not simply emissions scenarios, but contain information about the concentration of greenhouse gases and aerosols. The radiative forcings derived from the RCPs are the primary inputs for the climate models,facilitating the calculation of the associated emission levels (which can be compared to the original emissions of the IAMs) (see Hibbard et al., 2007). In total, a set of four pathways were designed that lead to radiative forcing levels of 8.5, 6, 4.5 and 2.6 W/m^2 around the end of the century (Table 1; Figure 1). Each of the RCPs covers the period 1850-2100, and extensions have been formulated for the period thereafter (up to 2300) (see van Vuuren et al., 2011 for details).

Two limitations of the RCPs should be noted. First, RCPs include detailed information about emissions and concentrations of greenhouse gases and aerosols, but do not include a full set of data on economic, demographic, energy and land-use activities. Such data are available from the groups that developed the individual scenarios from which the RCPs were selected, but they have not been archived in the RCP database, in order to allow a more substantial process in developing scenarios for these parameters in the parallel process phase of the scenario development. Second, the emissions pathways, which are inputs to multiple CMs, are based on a specific set of assumptions regarding the impact of an evolving climate. Since each CM produces its own climate trajectory, the assumptions of the RCPs will not be fully consistent with an individual CM. An important activity after CM runs is therefore to explore the assumptions used by the RCPs in the context of climate model simulation results, assessing the implications of any inconsistencies. In the future, alternative ways to develop scenarios may also be explored. For example, IAMs and individual CMs may be combined to form an integrated earth system model that can be used to produce a scenario.

Several criteria were outlined for the development and implementation of the RCPs including the requirement for pre-existing peer-reviewed documentation, land use and emissions data harmonizations (i.e., consistent with base-year data and downscaled); and the requirement that all relevant information be available for download through a central repository (van Vuuren et al., 2011). As the RCPs evolved, the climate and integrated assessment communities jointly agreed to a suite of desirable RCP characteristics (Moss et al., 2010, van Vuuren et al., 2011) (Table 1) including:

Range: Set of RCPs 'should be compatible with the full range of stabilization, mitigation, and baseline emissions scenarios available in the current scientific literature.'

Number: Four RCPs were identified to span the range of published literature. This decision was based to avoid an inclination to select a middle, or intermediate scenario as an average or, 'best estimate'. The naming convention, e.g., RCP 8.5, reflects the socio-economic pathway that reaches a radiative forcing of 8.5 W/m^2 by the year, 2100.

Separation and Shape: To be statistically distinguishable by the climate modeling communities, radiative forcing pathways required at least 3 W/m^2 separation by the end of the 21st century and/or the shape of the scenarios should be distinctly different.

Robustness: Given the substantial computational and human resource requirements associated with running global climate models, the RCPs and the scenarios on which they are based should be robust and consistent. The criterium for a robust scenario is whether several models can produce similar radiative forcing outcomes with plausible and technically sound scenarios (e.g., plausible assumptions in energy technology efficiencies, etc).

Comprehensiveness: For internally consistent data, the IAMs must simulate all radiative forcing factors (full suite of greenhouse gasses (GHGs), aerosols, chemically active gases, and land use/land cover). For the decadal prediction, or near-term experiments, the IAM radiative forcings at higher resolution (e.g., 0.5^o lat x lon) to 2035 were required for experimental climate change and atmospheric chemistry decadal predictions.

In earlier IPCC assessments, the emissions scenarios that provide radiative forcing and atmospheric chemistry information were passed from the IPCC Working Group 3 (mitigation) to Working Group 1 (physical climate science) communities with little communication. A major step made in the RCP development is the close communication between the CM and IAM research communities, such as the joint design of data transfer protocols that were integral to the development of the RCPs. As part of the process, CM and IAM researchers also cooperated on other topics, as for instance designing a joint agenda for future land research (Hibbard et al., 2010). This recognition led to an on-going collaboration between the two communities to develop a consistent and harmonized land use/land cover and emissions database from historic through the present to future simulations (see van Vuuren et al., 2011; Meinshausen et al., 2010, Lamarque, et al., 2010a,b). For the first time ever, Hurtt et al. (2010) developed a harmonized, or consistent land-use history data together with future scenario data from multiple IAMs into a single consistent, spatially gridded set of land-use change scenarios for studies of human impacts on the past, present, and future Earth system. The goals of the land use reconstruction were to (1) develop a consensus land-use history reconstruction for all IAM and climate modelling communities; (2) minimize the differences between the end of the historical reconstructions and beginning of future projections; and (3) preserve as much future information from IAMs as possible.

The relationship between emissions, concentrations and radiative forcing for the long-lived greenhouse gases is reported in the RCPs described by Meinshausen et al. (2010). Each RCP has associated emissions and concentration paths for each greenhouse gas. For CO_2, RCP8.5 follows the upper range of available literature (rapidly increasing concentrations). RCP6 and RCP4.5 show a stabilizing CO_2 concentration (close to the median range of the existing literature). Finally, RCP2.6 has a peak in CO_2 concentrations around 2050 followed by a modest decline to around 400 ppm CO_2 by the end of the century For more details on greenhouse gas (e.g., N_2O, CH_4) emissions and CO_2 and non-CO_2 concentration see van Vuuren et al., and Meinshausen et al. (2011)^2. j

The generation of the RCPs was only intended to be the start of the scenario development process and they have been tailored to serve the needs of the climate modelling communities. They were never intended to serve the needs of the impacts, adaptation and vulnerability (IAV) community. A major goal for the ongoing parallel process is to develop scenarios that can provide a full suite of scenarios to serve all major climate and climate-impacts research communities. This phase of the process is ongoing and will focus on the development of internally consistent logic to support the development of additional socio-economic pathways. Alternative pathways will be useful as background for IAV researchers to explore the implications of climate change and societal response through emissions mitigation and adaptation strategies. Hence, there is a need for an IAV/IAM community effort similar to the CM/IAM collaboration to define a new set of scenarios to complement the RCPs.

In conclusion, the RCPs represent an important step in the development of new scenarios for climate research as well as coordination and collaboration across the climate and integrated assessment modelling communities. The RCPs provide a detailed and internally consistent set of scenarios that can be used for climate simulation and study. They cover a range of radiative forcing pathways consistent with the current literature. The same holds for the concentration pathways for individual greenhouse gases (CO_2, CH_4, N_2O). The process by which the RCPs were developed, and the content of the RCP data base are documented more thoroughly than was the case with previous scenario exercises designed to be useful to the climate modelling community (e.g., see van Vuuren et al., 2011, Moss et al., 2010). Data on land use and air pollution has been made available with sectoral detail for different source categories and in a geographically explicit manner at 0.5° latitude x 0.5° longitude degree spatial resolution. The data on greenhouse gas emissions have been run through one consistent carbon cycle and climate model. The RCPs have also been harmonized with the latest data on historical periods and the harmonization algorithms have allowed for a smooth transition from the historical periods into the scenario period. The scaling factors used for this harmonization do not distort the original underlying IAM scenarios. This elaborate development process was necessary so that the RCPs can provide a consistent analytical thread across communities involved in climate research.

References

Hibbard, K. A., G. Meehl, P. Cox, P. Friedlingstein, 2007: A strategy for climate change stabilization experiments. EOS, 88, 217-221.

Hibbard, K.A., A. Janetos, D. P. van Vuuren, J. Pongratz, S. Rose, R. Betts, M. Herold, and J. Feddema, 2010: Research priorities in land use and land cover change for the Earth system and integrated assessment modeling. International Journal of Climatology, 30(13), 2118-2128, doi:10.1002/joc.2150.

Hurtt, G., L. Chini, S. Frolking, R. Betts, J. Edmonds, J. Feddema, G. Fisher, K. K. Goldewijk, K. A. Hibbard, R. Houghton, A. Janetos, C. Jones C, G. Kinderman, T. Konoshita, K. Riahi, E. Shevliakova, S. Smith, E. Stehfest, A. Thomson, P. Thornton, D. P. van Vuuren, Y. Wang, 2010: Land use Change and earth system dynamics. Climatic Change.

Lamarque, J. F., T. C. Bond, V. Eyring, C. Granier, A. Heil, Z. Klimont, D. Lee, C. Liousse, A. Mieville, B. Owen, M. G. Schultz, D. Shindell, S. J. Smith, E. Stehfest, J. Van Aardenne, O. R. Cooper, M. Kainuma, N. Mahowald, J. R. McConnell, V. Naik, K. Riahi, D. P. van Vuuren, 2010a: Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. Atmos. Chem. Phys. Discuss, 10.

Lamarque, J. F. , G. Page Kyle, M. Meinshausen, K. Riahi, S. Smith, D. P. van Vuuren, A. J. Conley, F. Vitt, 2010b: Global and regional evolution of short-lived radiatively-active gases and aerosols in the Representative Concentration Pathways. Climatic change.

Leggett, J., W. Pepper, R. J. Swart, 1992: Emissions Scenarios for the

IPCC: an Update. In Houghton J. T. , B. A. Callander, and S. K. Varney (eds.) Climate Change 1992. The Supplementary Report to the IPCC.

Meehl, G.A., and K.A. Hibbard, 2007: A strategy for climate change stabilization experiments with AOGCMs and ESMs. WCRP Informal Report No. 3/2007, ICPO Publication No. 112, IGBP Report No. 57, World Climate Research Programme: Geneva,35 pp.

Meinshausen, M., S. J. Smith, K. Calvin, J. S. Daniel, M. L. T. Kainuma, J. F. Lamarque, K. Matsumoto, S. A. Montzka, S. Raper, K. Riahi, A. Thomson, G. J. M. Velders, D. P. van Vuuren, 2010: The RCP Greenhouse Gas Concentrations and their Extensions from 1765 to 2300. Climatic Change.

Moss R, Babiker M, Brinkman S, Calvo E, Carter T, Edmonds J, Elgizouli I, Emori S, Erda L, Hibbard KA, Jones R, Kainuma M, Kelleher J, Lamarque JF, Manning M, Matthews B, Meehl J, Meyer L, Mitchell J, Nakicenovic N, O'Neill B, Pichs R, Riahi K, Rose S, Runci P, Stouffer RJ, van Vuuren D, Weyant J, Wilbanks T, van Ypersele JP, Zurek M (2008) Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies. IPCC Expert Meeting Report on New Scenarios. Intergovernmental Panel on Climate Change, Noordwijkerhout.

Moss, R. H., J. A. Edmonds, K. A. Hibbard, M. R. Manning, S. K. Rose, D. P. van Vuuren, T. R. Carter, S. Emori, M. Kainuma, T. Kram, G. Meehl, J. F. B. Mitchell, N. Nakicenovic, K. Riahi, S. J. Smith, R. J. Stouffer, A. M. Thomson, J. P. Weyant, T. J. Wilbanks, 2010: The next generation of scenarios for climate change research and assessment. Nature, 463, 747-756.

Nakicenovic et al., 2000: Special Report on Emissions Scenarios (SRES). Cambridge University Press, Cambridge, UK.

van Vuuren, D. P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. A. Hibbard, G. C. Hurtt, T. Kram, V. Krey, J. F. Lamarque, T. Matsui, M. Meinhausen, N. Nakicenovic, S. J. Smith, S. K. Rose, 2011: The Representative Concentration Pathways: An Overview. Accepted to Special Issue Climate Change

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The Paleoclimate Modeling Intercomparison Project contribution to CMIP5

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PMIP goals and rapid history

The Paleoclimate Modeling Intercomparison Project (PMIP:Joussaume and Taylor, 1995) launched in 1991, was one of the first MIPs following on from AMIP (Gates, 1992). PMIP's objectives were to understand the mechanisms of past climate changes and to test the capability of the models used for future climate projections to represent a climate different from the modern one. These initial goals are still valid, although PMIP is now in its third phase and has greatly enlarged its foci (see: Otto-Bliesner et al., 2009; http://pmip3.lsce.ipsl.fr/share/overview/PMIP_flier_print.pdf). It is not possible to test large climatic fluctuations based only on the instrumental period, or to assess fully the role of the climate feedbacks arising from the coupling between the atmosphere and longer time-scale reservoirs such as the ocean, the land surface or the ice-sheet, or from interactions between the climate and biochemical cycles, because the instrumental period is too short. Models that have similar skill in representing the modern climate do not necessarily vary in the same direction when forced with anthropogenic greenhouse gases. There is thus a need to put the ongoing climate change into a larger perspective, and to analyse how the climate has responded to past changes in forcing arising from changes in the Earth's orbital parameters, trace gases, or to volcanic eruptions and variations in the total solar irradiance. Even though past climates do not provide direct analogues for the future, they offer a wide range of cases from which it is possible to understand climate feedbacks and to evaluate model results.

Since its initiation, PMIP has focused on the analysis of general circulation models, specifically to test the models used for future climate projections. Time slice simulations were used because of the computing cost of running these models. Simplified, fast models (so called intermediate complexity models or EMICs) were also used for these time slice simulations in order to provide a reference for their use for long-term transient experiments and in palaeoclimate studies. The main focus for time slice experiments were the Last Glacial Maximum (LGM), 21 000 years before present (BP), and the mid-Holocene (MH), 6 000 years BP: intervals which correspond to times when differences in boundary conditions led to extreme climates that are relatively well documented by palaeoenvironmental data. Several important results have emerged from these data-model comparisons, particularly in regard to the land/sea and tropical cooling at the LGM, the changes in monsoon during the mid-Holocene, and the role of vegetation feedback. Results of the first phase of PMIP are gathered in PMIP 2000 (PMIP, 2000), and Braconnot et al. (2007) provides an overview of PMIP2 simulations. A more complete list of publication is available on the PMIP website (http://pmip2.lsce.ipsl.fr/). The PMIP simulations have also been used by the wider scientific community, for example as climate forcing for a range of ecological models in order to investigate the impact of climate changes on species and biodiversity (see website).

Now in its third phase (Otto-Bliesner et al., 2009), PMIP continues to focus on simulations that are relevant to evaluating the models used for investigating the likely trajectory of future climate but is opening new avenues of investigation including additional time periods and transient simulations. Progress in each of these areas was discussed at the PMIP meeting in Kyoto in December 2010, sponsored by the Japan Society of Promoting Science, the University of Tokyo and the Japan Agency for Marine-Earth Science and Technology.

The third phase of PMIP and its role in CMIP5

An important aspect of PMIP3 is the inclusion of three key time periods as part of the Phase 5 Coupled Modelling Intercomparison Project (CMIP5, Taylor et al., 2009; 2011) within Tier 1 (the Last Glacial Maximum 21,000 years ago, and mid-Holocene 6,000 years ago) and Tier 2 (Last Millennium). This is a new and exciting development because previously palaeoclimate simulations were done with different model versions– typically coarser resolution – from those used for future simulations, interrupting the direct link between past and future. The LGM and MH have long been a PMIP focus, and the project has extensive experience both in terms of model runs and in terms of benchmarking with palaeodata. Several groups have also expressed a strong interest for developing model-model and model-data comparison for the last millennium. PMIP will also be assessing carbon-cycle modeling, through its daughter project PCMIP (PalaeoCarbon Modelling Intercomparison Project, Abe-Ouchi and Harrison, 2009), focusing on simulations of the LGM and the Last Millennium.

Simulating the Last Glacial Maximum provides an opportunity to assess the models´ ability to simulate extreme cold conditions, as well as for studying the feedbacks associated with both a decrease in atmospheric CO_2 concentration and an increase in ice sheet elevation by 2 to 3 km over North America and northern Europe. This period is well suited to provide constraints on climate sensitivity and to compare the feedbacks operating in different climate models. The ocean thermohaline circulation is also different from the present one and PMIP2 results suggest a high sensitivity of climate models to LGM boundary conditions and show that models do not capture the changes in the density gradients between the northern and the southern hemispheres very well (Otto-Bliesner et al., 2007). The simulation of the mid-Holocene conditions is a sensitivity experiment in which the seasonal contrast of incoming solar radiation at the top of the atmosphere is changed; 6000 years BP, the seasonal contrast was larger in the northern summer, leading to an increase of the northern hemisphere summer monsoons. The increased monsoons and the northward shift of forest in the Northern Hemisphere are key features to be captured in these simulations. The last millennium is a period during which climate variability is mainly driven by slow variations in solar irradiance and volcanic eruptions. It is well suited to study the natural variability in a climate state close to the modern one and to analyse the climate response to natural forcings. These simulations are also extremely useful for detection attribution studies (e.g. Hegerl et al., 2011).

However, several of the new PMIP simulations also have relevance to CMIP5. Simulations of other warm periods such as the Pliocene, the Eocene, the Last Interglacial and transient simulations of the Holocene and the Last Interglacial, have obvious relevance to understanding the mechanisms of regional climate changes in a warmer future world. Another new focus within PMIP is transient simulations of the last deglaciation and freshwater hosing experiments, such as the 8.2 ka event and Heinrich event H1. These experiments and model data comparisons will provide new estimates of forcing thresholds that influence polar amplification, the low-latitude hydrologic cycle, and the relationship between climate-ice-sheet and sea-level under different climate states. The transient experiments represent an important step towards a better understanding of the dynamics and temporal response of the different components of the climate system.

Boundary conditions for PMIP3/CMIP5 simulations

Table 3 summarizes the different purposes of the CMIP5 paleoclimate experiments. The experimental design for the different simulations can be found on the PMIP website and model groups interested to run these experiments are invited to follow the recommendations closely.

There are several changes in the experimental design compared to PMIP 2. Previously, there were recommendations for the pre-industrial control experiments to make sure that all the models used the same changes in forcing between the pre-industrial and the past. This will not be the case for CMIP5, since the reference here is the CMIP5 PI simulations for which different modelling groups could use different definitions of trace gases, solar constant, land surface or orbital parameters. Also the model complexity will vary between models depending on whether the carbon cycle, vegetation dynamics or aerosols are considered. The only constraint is that the model version and complexity is the same as in the CMIP5 PI experiment so as to be able to test exactly the same model in a different climate context. However, the PMIP protocols have to be respected for palaeo-experiments.

The mid-Holocene simulation is the easiest one to run. The experimental protocol is the same as in PMIP2. The major changes compared to present day are the orbital parameters and the values of the trace gases. Groups are invited to perform sensitivity experiments to the remnant ice-sheet in the North America or to vegetation.

Setting the boundary conditions for the LGM is more complex because it requires a change in the land-sea mask in the ocean model, and it is important that oceanic throughflows are properly represented. Interpolation of the coupling fields between the ocean and the atmosphere need then be revisited. A new ice-sheet reconstruction has been created for CMIP5. It is a blended product made from three new ice-sheet reconstructions (Abe-Ouchi et al. in prep) that correct some of the known biases of previous reconstructions. The individual ice-sheets are also provided for optional simulations to test the sensitivity of the model results to the uncertainties in the ice-sheet reconstructions. The other mandatory changes for these simulations concern the lower concentration of atmospheric trace gases. Previous results show that the LGM ocean circulation can be very sensitive to the change in river pathways in the vicinity of the ice-sheet. It is in general difficult to modify the model routing scheme to take into account the change in river pathways, but groups are encouraged to do it when possible following the guidelines given in Tarasov' s reconstruction on PMIP website.

The emphasis with the last millennium simulation is on model-data comparisons rather than model-model comparisons, because the forcings are small compared to the internal variability and there are large uncertainties in these forcings. Analyses of pre-PMIP3 simulations of the transition from the Medieval Climate Anomaly to the Little Ice Age (González-Rouco et al., 2011) reveal model-to-model differences and pronounced model-to-reconstruction discrepancies. This points to differences in the models' sensitivity to external forcings and to deficiencies in the representation of internal feedbacks, but may also indicate that such centennial-scale anomalies are largely influenced by internal variability.

Each model group will only perform a limited number of simulations and it is important that the ensemble PMIP simulation reflect as much as possible model structural uncertainties, climate noise, and uncertainties in boundary conditions. This is critical for detection and attribution studies for which it is important to have a large sampling of noise. For these simulations seven reconstructions of the solar irradiance and two reconstructions of the volcanic forcing are available (Schmidt et al., 2010). In addition, the experimental protocol considers changes in trace gases and in land use. Particular attention is required when preparing these experiments to ensuring the correct representation of the transition from the last millennium to the PI and historical simulations. Modelling groups will be encouraged to run additional sensitivity experiment for short periods so as to test, for example, the climatic response to volcanic eruptions.

New data syntheses simulations

Since its initiation, PMIP has fostered large-scale palaeodata syntheses specifically for use in model evaluation (Harrison 2000). The need for well-documented syntheses is even greater now, because of the increasing use of Earth System Models which require reconstructions of a wider range of parameters for specific time slices, because of the additional time periods under consideration, and because of the challenges of evaluating transient simulations both of the last millennium and of earlier rapid climate-change events. There are already a number of data sets documenting the LGM and MH that will be used to evaluate the CMIP5 experiments. These include global compilations of sea-surface temperature (MARGO: Waelbroeck et al., 2009), fire regimes (Power et al., 2008), dust deposition (Kohfeld and Harrison, 2001), and regional compilations of climate (e.g. Jackson et al., 2000; Wu et al., 2007). PMIP has worked with the Palaeoclimate Commission (PALCOMM, Project 0801) of the International Quaternary Association (INQUA) to produce new global data sets of quantitative climate reconstructions for the LGM and MH (Bartlein et al., 2010). These new data sets are based on an evaluation of multiple existing regional reconstructions and provide gridded estimates of the change (and uncertainties) in six bioclimatic variables: growing degree days (a measure of the accumulated temperature sum during the growing season), mean temperature of the warmest month, mean temperature of the coldest month, mean annual temperature, mean annual precipitation and plant available moisture. As shown in Figure 1, these reconstructions can be used to document how well the PMIP models document regional climate changes. Efforts are already underway to expand the spatial coverage of these data sets specifically in order to improve the coverage in the tropics and the Southern Hemisphere. Several methods have been developed to compare model results to this type of reconstructions, even though most of them have only been applied to specific regions. The combination of this new dataset with the surface ocean data set produced by MARGO now provides a near global coverage of quantitative information and new model-data comparison are under development that will take into account both the uncertainties in the model results and in the data reconstructions. In these comparisons, PMIP simulations are either considered as an ensemble (as it is the case in Figure 1) or as individual simulations.

Understanding the relationship between mean climate change and short-term climate variability (e.g. changes in ENSO) is a comparatively new focus for PMIP. Although there are many types of data that document changes in annual to decal climate variability (e.g. tree rings, corals, speleothems, annually-laminated sediments), there has been to date no comprehensive synthesis of these data -- a synthesis that is urgently required because the spatial fingerprint of these modes of variability is likely to have changed in response to changes in mean climate (see e.g. Zhao et al., 2007). The IGBP core project Past Global Changes (PAGES) has initiated efforts to identify high-resolution records of the past 2000 years and to use these records to reconstruct the changing patterns of short-term climate variability (http://www.pages-igbp.org/). A similar effort is required to document short-term variability at the LGM and during the MH.

PMIP is also working with PALCOMM (Projects 0801, 0804, 0905) to improve the data available to evaluate carbon-cycle simulations of the LGM and Last Millennium. Syntheses of data on key aspects of the terrestrial carbon cycle, including changes in vegetation composition, peat accumulation, biomass burning and emissions are already underway.

PMIP is also encouraging the creation of data syntheses for other time periods, and for the proposed transient experiments. PlioMIP, for example, is making use of the PRISM3D data set (http://geology.er.usgs.gov/eespteam/prism/prism_pliomip_data.html). The ACER (Abrupt Climate Change and Environmental Responses) project has created global reconstructions of vegetation and inferred climate for iconic Dansgaard-Oeschger events during the last glacial period (Harrison and Goni, 2010). The aim is to have these data sets, and other large-scale data sets suitable for model evaluation, available via the PMIP website.

Priorities for next year

One outcome of the PMIP 2010 meeting was to identify major analytical goals for the next two years, including providing constraints on climate sensitivity, understanding changes in the hydrological cycle, the role of vegetation and oceanic feedbacks. The PMIP workshop also identified a need for a better understanding of the climatic controls on various palaeoenvironmental sensors, particularly marine organisms, and increased efforts will be made to develop models to translate changes in climate into palaeoenviromental responses for direct comparison with the palaeoenvironmental records. This approach has been used previously in PMIP, for example, in translating simulated climates into vegetation changes for comparison with pollen-based vegetation reconstructions.

The paleoclimate simulations in CMIP5 also offer unique opportunity to use the same models in different configurations and thereby to increase our understanding of the relationship between climate feedbacks, or climate variability and teleconnections, with the background climate state. The impact of model biases in the simulation of different past climates will also be analysed in order to document model uncertainties and problems better. Projects considering a climate phenomenon (e.g. the monsoon) at several different times will be encouraged, as well as the development of evaluation criteria from a combination of past climates that would be relevant to assess the realism of changes in mean climate and climate variability in future climate projections.

In the next two years, PMIP will be sponsoring a series of small workshops, including ones focusing on data-model comparisons for the Pliocene (PlioMIP: August 2011), the compilation of new data sets on climate variability (September 2011), on the last-millennium carbon cycle (PCMIP: November 2011), and on benchmarking the CMIP5 simulations (February 2012). In addition, PMIP will continue to hold annual meetings bringing the palaeoclimate modeling community together to discuss progress on all of the PMIP foci. The next PMIP meeting is planned for May 2012 in Scotland.

References

Abe-Ouchi, A. and Harrison, S.P., 2009: Constraining the carbon-cycle feedback using palaeodata: the PalaeoCarbon Modelling Intercomparison Project. EOS, 90(16): 140.

Bartlein, P.J. et al., 2010: Pollen-based continental climate reconstructions at 6 and 21 ka: a global synthesis. Climate Dynamics.

Braconnot, P. et al., 2007: Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum - Part 1: experiments and large-scale features. Climate of the Past, 3(2): 261-277.

Gates, W.L., 1992: AMIP: the Atmospheric Model Intercomparison Project. Bull. Amer. Meteor. Soc., 73, 1962-1970.

González-Rouco, F.J. et al., 2011: Medieval Climate Anomaly to Little Ice Age transition as simulated by current climate models. PAGES news, 19(1), 7-11.

Harrison , S., 2000: Palaeoenvironmental data set and model evaluation in PMIP. Paleoclimate Modeling Intercomparison Project (PMIP), proceedings of the Third PMIP workshop, WCRP-111, WMO/TD-No. 1007, Canada.

Harrison, S.P. and Goni, M.F.S., 2010: Global patterns of vegetation response to millennial-scale variability and rapid climate change during the last glacial period. Quaternary Science Reviews, 29(21-22), 2957-2980.

Hegerl, G.J. et al., 2011: Influence of human and natural forcing on European seasonal temperatures. Nature Geoscience, 4, 99-103.

Jackson, S.T. et al., 2000: Vegetation and environment in Eastern North America during the Last Glacial Maximum. Quaternary Science Reviews, 19(6), 489-508.
Joussaume, S. and Taylor, K.E., 1995: Status of the Paleoclimate Modeling Intercomparison Project. in Proceedings of the first international AMIP scientific conference, WCRP-92, Monterey, USA, 425-430.

Kohfeld, K.E. and Harrison, S.P., 2001: DIRTMAP: the geological record of dust. Earth-Science Reviews, 54(1-3), 81-114.

Otto-Bliesner, B., Joussaume, S., Braconnot, P., Harrison, S.P. and Table 1. Paleoclimate experiments selected as part of Tier 1 and Tier 2 simulations in CMIP5

Abe-Ouchi, A., 2009: Modeling and data synthesis of past climates. EOS, 11, 93.
Otto-Bliesner, B.L. et al., 2007: Last Glacial Maximum ocean thermohaline circulation: PMIP2 model intercomparisons and data constraints. Geophysical Research Letters, 34(12).

PMIP, 2000: Paleoclimate Modeling Intercomparison Project (PMIP), proceedings of the third PMIP Workshop. WCRP-111,WMO/TD-No. 1007, 271 pp.

Schmidt, G.A. et al., 2010: Climate forcing reconstructions for use in PMIP simulations of the last millennium (v1.0). Geoscientific Model Development, 3(3), 1549-1586.

Taylor, K. E., R. J. Stouffer and G. A. Meehl, 2009: A summary of the CMIP5 Experimental Design. http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2011: The CMIP5 Experiment Design. Bull. Amer. Meteorol. Soc., submitted.

Waelbroeck, C. et al., 2009: Constraints on the magnitude and patterns of ocean cooling at the Last Glacial Maximum. Nature Geoscience, 2(2), 127-132.

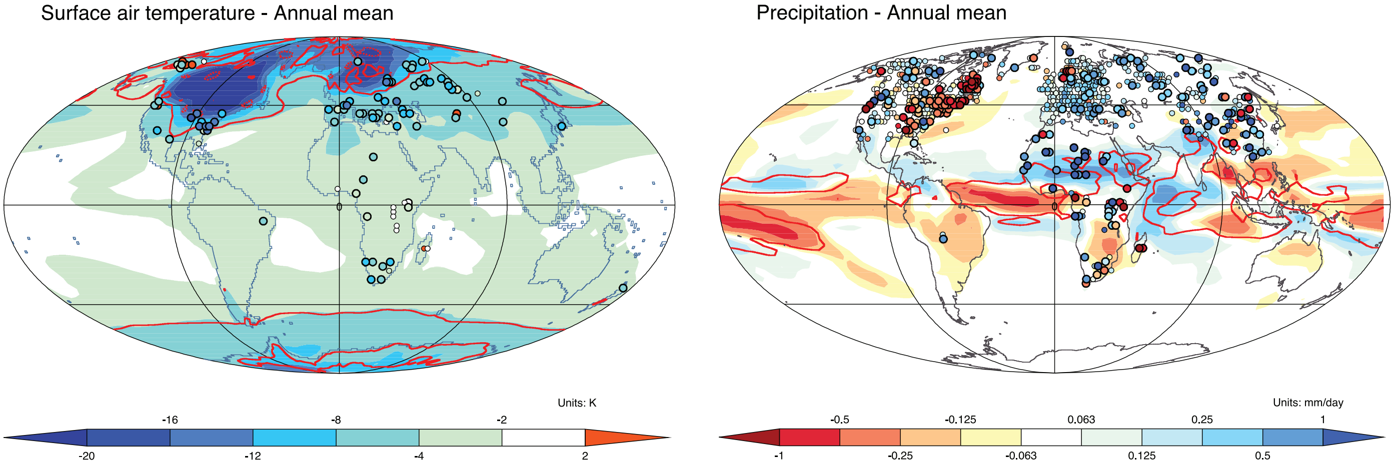
Wu, H.B., Guiot, J.L., Brewer, S. and Guo, Z.T., 2007: Climatic changes in Eurasia and Africa at the last glacial maximum and mid-Holocene: reconstruction from pollen data using inverse vegetation modelling. Climate Dynamics, 29(2-3), 211-229.

Zhao, Y., Braconnot, P., Harrison, S.P., Yiou, P. and Marti, O., 2007: Simulated changes in the relationship between tropical ocean temperatures and the western African monsoon during the mid-Holocene. Climate Dynamics, 28(5), 533-551.

Table 1. Paleoclimate experiments selected as part of Tier 1 and Tier 2 simulations in CMIP5

	Period	**Purpose**	**Imposed boundary conditions**	**# of years**
TIER1	Last Glacial maximum (21 kyr ago)	a) Compare with paleodata the model response to ice-age boundary conditions. b) Attempt to provide empirical constraints on global climate sensitivity.	• Ice-sheet and land-sea mask • Greenhouse concentration of well-mixed greenhouse gases • Orbital parameters	⋕100 (after spin-up period)
	Mid-Holocene (6kyr ago)	a) Compare with paleodata the model response to known orbital forcing changes and changes in greenhouse gas concentrations.	• Orbital parameters • Atmospheric concentration of well-mixed greenhouse gases	⋕100 (after spin-up period)
TIER2	Last millennium (850-1850)	a) Evaluate the ability of models to capture observed variability on multi-decadal and longer time-scales. b) Determine what fraction of the variability is attributable to "external" forcing and what fraction reflects purely internal variability. c) Provides a longer-term perspective for detection and attribution studies	• Solar variations • Volcanic aerosols • Well mixed greenhouse gases • Land use • Orbital parameters	1000 (after spin-up period)

Figure 1. Change in annual mean air temperature (K) for the LGM (top) and of annual mean precipitation (mm/day) for the mid Holocene (bottom). The colour map represents the ensemble average of all available PMIP2 simulations. The red isolines highlight the mean root mean square difference between two PMIP simulations providing an idea of model spread. The dots represent the data points discussed in Bartlein et al. (2010). The dot colour reflects the magnitude of the anomaly and the symbol size reflects the significance of the grid-cell average of that anomaly: a large symbol is plotted when the absolute value of a t-statistic calculated using the anomaly values and the pooled standard error exceeds 2.0.Table 1. Paleoclimate experiments selected as part of Tier 1 and Tier 2 simulations in CMIP5.



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

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

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

1. CMIP5 idealized experiments

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

Gregory and Webb (2008) found that changes in atmospheric structure induced by the direct CO_2 radiative effect can lead to a “rapid cloud response” (not mediated by the global mean surface temperature response) that can explain a significant fraction of the inter-model spread in cloud feedbacks. Experiment 6.5 of CMIP5 (Taylor et al., 2009) consists of an atmospheric simulation using observed sea-surface temperatures (SSTs) while quadrupling the CO_2 concentration in the atmosphere. By analyzing the results of this experiment, it will be possible to examine the fast response of clouds to CO_2 increases and thus to assess the role of this response in the spread of cloud feedbacks across models. It will also be possible to assess the validity of the traditional forcing/feedback diagnostics used so far to interpret inter-model differences in climate sensitivity.

Two complementary experiments (6.6 and 6.8) will allow us to examine the cloud response to a +4K SST (in the absence of CO_2 changes), either spatially uniform or associated with a scaled spatial pattern typical of coupled model SST responses in CMIP3 model projections at time of CO_2 quadrupling. It will then be possible to examine the effects of local and remote changes in SST on cloud feedbacks, and to better assess the influence of large-scale atmospheric dynamical changes on cloud feedbacks.

Finally, a series of short, idealized aqua-planet experiments (6.7) will make it possible to compare models and their predicted climate response to different types of perturbations (a globally uniform surface warming or a quadrupling of CO_2), in a simpler and more idealized context. These experiments use the protocol proposed by Neale and Hoskins (2001) and Medeiros et al. (2008). They will be useful to better interpret the origin of inter-model differences in cloud feedbacks (as shown for instance by Medeiros et al. 2008), but also in many other aspects of climate change (e.g. large-scale atmospheric circulations). These idealized simulations will also facilitate the comparison between general circulation models (GCMs) and the new generation of computationally-demanding climate models such as global Cloud Resolving Models (Miura et al. 2005) or Super-Parameterizations (Khairoutdinov et al. 2005), as well as between GCMs and theoretical or conceptual models.

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

2. CMIP5 model outputs from the CFMIP Observations Simulator

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

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

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

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

3. Process-oriented diagnostics

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

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

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

The CMIP5 experiments also include a set of tendency terms which diagnose the increments to clouds, temperature and water vapour from different physical schemes such as convection, boundary layer, radiation, dynamics, etc

(Williamson et al. 2005; Ogura et al. 2008). These, along with upwelling and downwelling radiative fluxes throughout the atmoshere will provide a wealth of information with which to understand cloud feedback mechanisms.

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

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

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

In CMIP3, the response of marine planetary boundary-layer (PBL) clouds to climate warming had been identified as a leading source of inter-model discrepancies in climate change cloud feebacks (Bony and Dufresne 2005; Webb et al. 2006). To better understand the physical processes responsible for this response, and assess their dependence on model formulation, CFMIP and GCSS have jointly organized a project examining the response of several PBL cloud types to an idealized climate change simulated by single-column versions of CMIP5 models on the one hand, and by Large-Eddy Simulation (LES) and Cloud Resolving Models (CRMs) on the other hand. This project, referred to as CFMIP-GCSS Intercomparison of Large Eddy Models and Single Column Models (CGILS, Zhang and Bretherton 2008; Zhang et al. 2010), will allow us to examine and to interpret the part of the PBL cloud feedbacks spread across CMIP5 models that results from differences in model formulation (the large-scale forcing will be identical in all models), and to compare the physical processes at work in single-column models with those at work in LES models forced in identical conditions.

Three case studies will be examined, that correspond to three different PBL cloud types (stratus, stratocumulus and shallow cumulus). The large-scale forcing associated with current climate conditions is an idealization of the forcing actually found at three locations over the GCSS Pacific Cross-Section Intercomparison (GPCI) cross-section that extends from California to the central Pacific Inter-Tropical Convergence Zone (ITCZ). The change of large-scale conditions (sea surface temperature, large-scale vertical velocity, etc) associated with an idealized climate change is derived from Zhang and Bretherton (2008) and described at http://atmgcm.msrc.sunysb.edu/cfmip_figs/Case_specification.html. Currently, 16 single-column models and 5 LES models are participating in this inter-comparison.

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

5. Conclusion

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

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References

Bodas-Salcedo, A., M. J. Webb, S. Bony, H. Chepfer, J.-L. Dufresne, S. A. Klein, Y. Zhang, R. Marchand, J. M. Haynes, R. Pincus, and V. O. John, 2011: COSP: satellite simulation software for model assessment. Bull. Amer. Meteor. Soc., in press.

Bony S and J-L Dufresne, 2005: Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models, Geophys. Res. Lett., 32, No. 20, L20806, doi:10.1029/2005GL023851.

Charney, J. G., 1979: Carbon dioxide and climate : a scientific assessment. National Academy Press, 33pp.

Chepfer H, S Bony, D Winker, M Chiriaco, J-L Dufresne and G. Sèze, 2008: Use of CALIPSO lidar observations to evaluate the cloudiness simulated by a climate model. Geophys. Res. Lett., 35, L15704, doi:10.1029/2008GL034207.

Chepfer, H., S. Bony, D. Winker, G. Cesana, J. L. Dufresne, P. Minnis, C. J. Stubenrauch, and S. Zeng, 2010: The GCM-Oriented CALIPSO Cloud Product (CALIPSO-GOCCP). J. Geophys. Res., 115, D00H16, doi:10.1029/2009JD012251.

Dufresne J-L and S Bony, 2008: An assessment of the primary sources of spread of global warming estimates from coupled ocean-atmosphere models. J. Climate, 21(19), 5135-5144.

Gregory, J. M., and M. J. Webb, 2008: Tropospheric adjustment induces a cloud component in CO_2 forcing. J. Climate, 21, 58-71.

Hannay, C., et al. 2009: Evaluation of forecasted Southeast Pacific Stratocumulus in the NCAR, GFDL and ECMWF Models. J. Climate, 22, 2871-2889.

Haynes J. M., R. T. Marchand, Z. Luo, A. Bodas-Salcedo, G. L. Stephens, 2007: A multipurpose radar simulation package: Quickbeam. Bull. Am. Meteorol. Soc., Nov, 1723-1727, DOI:10.1175/BAMS-88-11-1723.

Khairoutdinov, M. F., C. DeMott, and D. A. Randall, 2005: Simulation of the atmospheric general circulation using a cloud-resolving model as a super-parameterization of physical processes. J. Atmos. Sci., 62, 2136-2154.

Klein, S. A., and C. Jakob, 1999: Validation and sensitivities of frontal clouds simulated by the ECMWF model. Mon.Wea.Rev., 127, 2514–2531.

Lohmann U., Feichter J., 2005: Global indirect aerosol effects: A Review. Atmospheric Chemistry and Physics, 5 (2005), 715-737 - SRef-ID: 1680-7324/acp/2005-5-715.

Medeiros, B., B. Stevens, I. M. Held, M. Zhao, D. L. Williamson, J. G. Olson, and C. S. Bretherton, 2008: Aquaplanets, climate sensitivity, and low clouds. J. Climate, 21, 4974–4991.

Miura, H., H. Tomita, T. Nasuno, S.-I. Iga, M. Satoh,T. Matsuno, 2005: A climate sensitivity test using a global cloud resolving model under an aqua-planet condition. Geophys. Res. Lett., 32, L19717, doi:10.1029/2005GL023672.

Neale R. B., and B. J. Hoskins, 2001: A standard test for AGCMs including their physical parameterizations. I. The proposal. Atmos. Sci. Lett., 1, doi:10.1006/asle.2000.0019.

Ogura, T., M. J. Webb, A. Bodas-Salcedo, K. D. Williams, T. Yokohata and D. R. Wilson, 2008. Comparison of Cloud Response to CO_2 Doubling in Two GCMs. SOLA, Vol. 4, pp.29-32.

Phillips, T.J., et al., 2004: Evaluating parameterizations in general circulation models: Climate simulation meets weather prediction. Bull. Am. Meteorol. Soc., 85(12), 1903-1915 .

Randall, D. A., R. A. Wood, S. Bony, R. Colman, et al., 2007. Climate models and their evaluation. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Schiffer, R.A., and W.B. Rossow, 1983: The International Satellite Cloud Climatology Project (ISCCP): The first project of the World Climate Research Programme. Bull. Amer. Meteorol. Soc., 64, 779-784.

Soden, B.J., and I.M. Held, 2006: An assessment of climate feedbacks in coupled ocean-atmosphere models. Journal of Climate, 19(14), 3354-3360.

Stephens, G. L., et al., 2002: The CloudSat mission and the A-Train. Bull. Am. Meteorol. Soc., 83, 1771-1790.

Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2009: A summary of the CMIP5 Experimental Design. http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf.

Webb, M., C. Senior, S. Bony, and J.-J. Morcrette, 2001: Combining ERBE and ISCCP data to assess clouds in the Hadley Centre, ECMWF and LMD atmospheric climate models. Climate Dyn, 17, 905–922.

Webb M J, C A Senior, D M H Sexton, W. J. Ingram, K D Williams, M A Ringer, B J McAvaney, R Colman, B J Soden, R Gudgel, T Knutson, S Emori, T Ogura, Y Tsushima, N Andronova, B Li, I Musat, S Bony and K Taylor, 2006: On the contribution of local feedback mechanisms to the range of climate sensitivity in two GCM ensembles, Climate Dynamics, 27(1), 17-38, DOI: 10.1007/s00382-006-0111-2.

Williams, K.D. and M.E. Brooks, 2008: Initial tendencies of cloud regimes in the Met Office Unified Model. J. Climate, 21(4) 833-840 doi:10.1175/2007JCLI1900.1.

Williamson, D.L., et al., 2005: Moisture and temperature balances at the Atmospheric Radiation Measurement Southern Great Plains Site in forecasts with the Community Atmosphere Model (CAM2). J. Geophys. Res. 110, D15S16, doi:10.1029/2004JD005109.

Winker, D. M., M. A. Vaughan, A. Omar, Y. Hu, K. A. Powell, Z. Liu, W. H. Hunt, and S. A. Young, 2009: Overview of the CALIPSO mission and CALIOP data processing algorithms. J. Atmos. Oceanic Technol., 26(11), 2310{2323, doi:10.1175/2009JTECHA1281.1.

Xie, S., et al., 2008: Simulations of Arctic mixed-phase clouds in hindcasts with CAM3 and AM2 for M-PACE. J. Geophys. Res., 113(D04211) doi:10.1029/2007JD009225.

Zhang, M., and C. Bretherton, 2008. Mechanisms of low cloud-climate feedback in idealized single-column simulations with the community atmospheric model, Version 3 (CAM3). J. Climate, 21, 4859–4878.

Zhang, M, Bretherton, C, Webb, M and Siebesma, P, 2010: CFMIP-GCSS Intercomparison of Large Eddy Models and Single Column Models (CGILS). GEWEX News, May 2010, available at www.gewex.org.

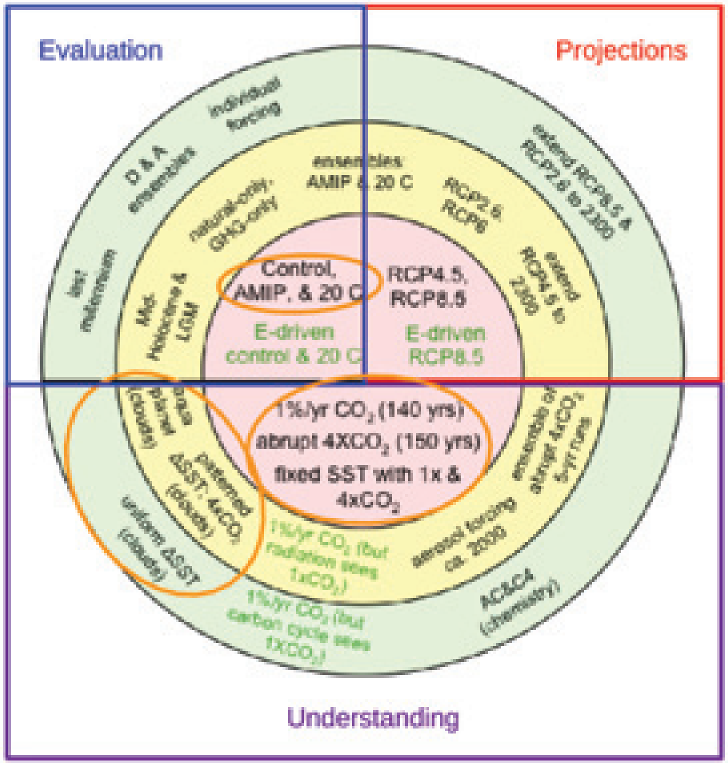

Figure 1: CMIP5 long-term experiments (described in Taylor et al. 2011) will aim at evaluating the realism of climate models on the recent and longer-term past, at providing climate projections for the 21st century and beyond, and at understanding inter-model differences in their simulation of the current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

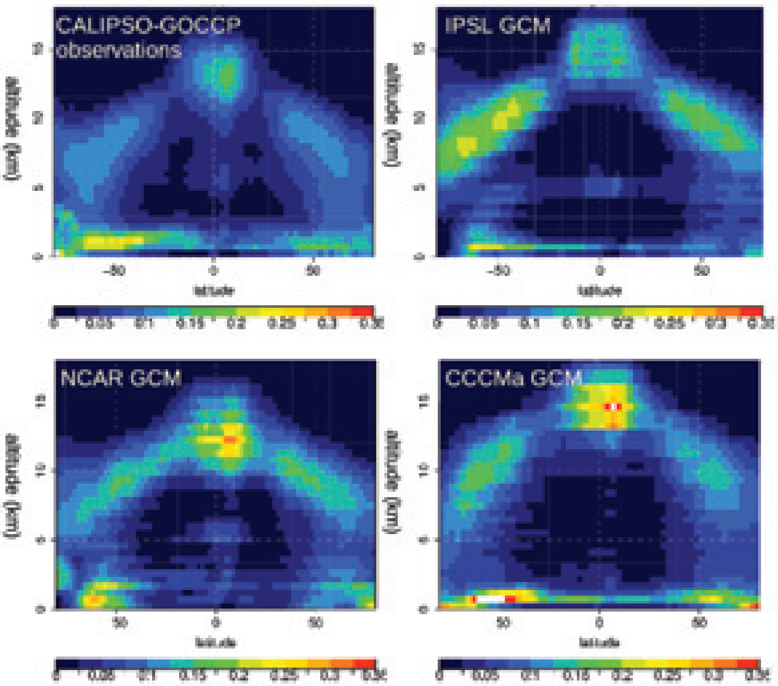

Figure 2: Comparison of the annually, zonally-averaged vertical distribution of the cloud fraction derived from the CALIPSO-GOCCP satellite observational dataset (Chepfer et al. 2010) and from several general circulation models using the CFMIP Observations Simulator Package (COSP) during the model development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

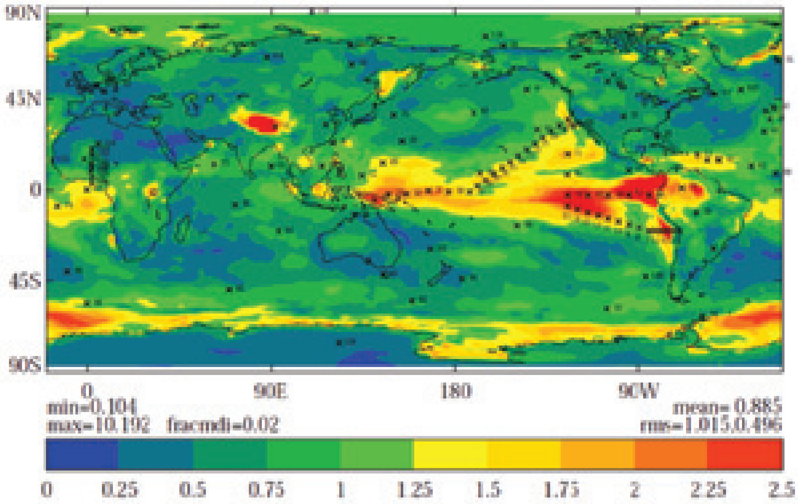

Figure 3: To facilitate the detailed evaluation and analysis of cloud processes simulated by CMIP5 models over a large range of climatic conditions, high-frequency (half-hourly) process-oriented model outputs (CMIP5 output table referred to as cfSites) will be provided by modelling groups over an ensemble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

Climate response to aerosol forcings in CMIP5

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Aerosols and clouds both remain major sources of uncertainty in our ability to understand past and future climate change. Anthropogenic aerosols are responsible for a radiative forcing of climate through their direct effect (interaction with radiation) and their indirect effects (interaction with clouds). Quantification of the direct and indirect effects of anthropogenic aerosols has proven difficult and is fraught with uncertainties (Haywood and Boucher, 2000; Lohmann et al., 2010). As a result, the net anthropogenic radiative forcing since pre-industrial time is also uncertain (Kiehl, 2007), and best attempts to quantify the probability distribution function for the net anthropogenic forcing (i.e. the forcing due to increases in greenhouse gases and aerosols) at the time of the AR4 could not rule out negative values (Haywood and Schulz, 2007; Forster et al., 2007). This uncertainty in the aerosol forcing confounds observational estimates of the climate sensitivity from the past temperature record. Clouds also respond to climate forcing mechanisms in multiple ways, which feeds back onto climate. The sign of the net cloud feedback is likely to be positive, but its magnitude is proving difficult to ascertain (Bony et al., 2006).

For the first time in an IPCC assessment report, our knowledge of aerosols and clouds and their role in climate change will be assessed in a single chapter (WGI AR5 Chapter 7), offering a unique opportunity to take stock of aerosols and clouds and their interactions in an international collaborative context. This newsletter article aims to foster interest in the aerosol simulations called for by CMIP5 and to facilitate coordinated research efforts to make best use of them in quantifying and understanding aerosol-related uncertainties in climate projections. International activities focusing on cloud feedbacks (CFMIP) are discussed in Bony et al. in this issue.

The Aerosol Comparisons between Observations and Climate (AEROCOM) Project and Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) initiatives are providing a very useful international framework to evaluate global aerosol models and quantify aerosol radiative forcings. While there is an overlap between the models contributing to AEROCOM and those participating in CMIP5, it remains important to quantify the effects of aerosols in CMIP5 simulations. This is because not every CMIP5 model is taking part in AEROCOM/ACCMIP and because some modeling groups contribute to AEROCOM/ACCMIP with their most complex aerosol scheme but chose to run the CMIP5 simulations with a less complex scheme owing to computational constraints. The CMIP5 protocol (Taylor et al., 2009; 2011) already specifies a number of simulations that are highly relevant to understanding aerosol forcing and the climate response to this forcing. We would like to encourage the various CMIP5 modeling groups to conduct these important experiments which promise to be of high interest in the IPCC process. It will be critical to evaluate aerosol trends in the CMIP5 simulations against long-term measurements of atmospheric aerosols concentrations, aerosol deposition in snow (e.g., McConnell et al., 2007) and global dimming / brightening trends (Wild et al., 2009).

Experiments 6.4a ("fixed SST with all aerosols") and 6.4b ("fixed SST with sulfate aerosols only") are in the suite of Tier 1 "long-term" experiments (Taylor et al., 2009:2011). They can be used in combination with Experiment 6.2a ("control fixed SST experiment") to quantify the present-day aerosol adjusted radiative forcing (a quantity also referred to as quasi-forcing or radiative flux perturbation, as in Lohmann et al. (2010)). Quantifying aerosol forcing is paramount in understanding future climate projections in scenarios because the concentration of anthropogenic aerosols gets decoupled from that of greenhouse gases. Kiehl (2007) also found that the total anthropogenic forcing is inversely correlated to climate sensitivity when considering a wide range of CMIP3 climate models. It will be interesting to establish whether this is still the case for CMIP5 models.

It is also now appreciated that rapid adjustments (i.e. those feedbacks happening on timescales shorter than a few months and which are usually not mediated by a surface temperature change) depend on the nature of the forcing mechanism (e.g. Andrews et al., 2010). It will be critical to understand how rapid adjustments differ in response to the aerosol and CO_2 forcings, and to what extent they are a robust feature of CMIP5 climate models. In that respect an additional experiment ("fixed SST with black carbon aerosols only"), not included in Taylor et al. (2009), would be very useful (see Table 1).

Taylor et al. (2009) also call for historical simulations with natural forcings only and greenhouse gas forcing only (Experiments 7.1 and 7.2 as part of the "long-term" Tier 1 suite). Similar historical simulations with individual forcing mechanisms such as anthropogenic aerosols are planned under 7.3 (Tier 2). These experiments will form the basis for detection and attribution studies aiming to evaluate the impact of anthropogenic forcings over the last 150 years. We would like to encourage modeling groups to conduct an aerosol simulation as part of 7.3. Ideally the simulation should be an "all forcing except aerosol" experiment to isolate the impact of aerosols on the historical period, but there could be some benefit of including an "aerosol forcing only" experiment as well (see Table 1). Such simulations may also be helpful to reduce the uncertainty in the aerosol forcing by constraining the model with appropriate observable quantities. A number of models have already conducted such an experiment (see Figure 1), and other modeling groups are in the process of doing so.

The concentration of anthropogenic aerosols gets decoupled from that of greenhouse gases in the RCP scenarios, with the total amount of anthropogenic aerosols decreasing while GHG concentrations keep increasing or get stabilized. Analysis of future simulations with and without aerosols should provide useful information to interpret the CMIP5 climate projections. We would like to encourage modeling groups to extend the historical simulation with "all forcing except aerosol" proposed above with an RCP4.5 scenario that also has "all forcing except aerosol" (see Table 1).

A coordinated effort to analyze the simulations listed in Table 1 will be required. We propose to hold an aerosol session at the CMIP5 workshop that is currently scheduled for 5-9 March 2012 at the University of Hawaii in order to finalize a coordinated input to the IPCC process.

References

AEROCOM, http://dataipsl.ipsl.jussieu.fr/AEROCOM/

Andrews, T., P. M. Forster, O. Boucher, N. Bellouin, and A. Jones, 2010: Precipitation, radiative forcing and global temperature change. Geophys. Res. Lett., 37, L14701, doi:10.1029/2010GL043991.

Bony, S., et al., 2006: How well do we understand and evaluate climate change feedback processes? J. Climate, 19, 3445–3482.

Bony, S. et al., 2011: CFMIP experiments and outputs for a better evaluation and understanding of clouds and cloud feedbacks in CMIP5 models. CLIVAR Exchanges Newsletter, this issue.

Forster, P. M. de F., V. Ramaswamy, P. Artaxo, T. Berntsen, R. A. Betts, D. W. Fahey, J. A. Haywood, J. Lean, D. C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland, 2007: Changes in atmospheric constituents and in radiative forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, pp. 129-234.

Haywood, J., and O. Boucher, 2000: Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: A review. Rev. Geophys., 38(4), 513-543.

Haywood, J. and M. Schulz, 2007: Causes of the reduction in uncertainty in the anthropogenic radiative forcing of climate between IPCC (2001) and IPCC (2007). Geophys. Res. Lett., 34, L20701, doi:10.1029/2007GL030749.

Kiehl, J. T., 2007: Twentieth century climate model response and climate sensitivity. Geophys. Res. Lett., 34, L22710, doi:10.1029/2007GL031383.

Lohmann, U., L. Rotstayn, T. Storelvmo, A. Jones, S. Menon, J. Quaas, A. M. L. Ekman, D. Koch, and R. Ruedy, 2010: Total aerosol effect: radiative forcing or radiative flux perturbation? Atmos. Chem. Phys., 10, 3235-3246, doi:10.5194/acp-10-3235-2010.

McConnell, J. R., R. Edwards, G. L. Kok, M. G. Flanner, C. S. Zender, E. S. Saltzman, J. R. Banta, D. R. Pasteris, M. M. Carter, and J. D. W. Kahl, 2007: 20th-century industrial black carbon emissions altered Arctic climate forcing. Science, 317, 1381-1384.

Taylor, K. E., R. J. Stouffer and G. A. Meehl, 2009: A summary of the CMIP5 Experimental Design. http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf.

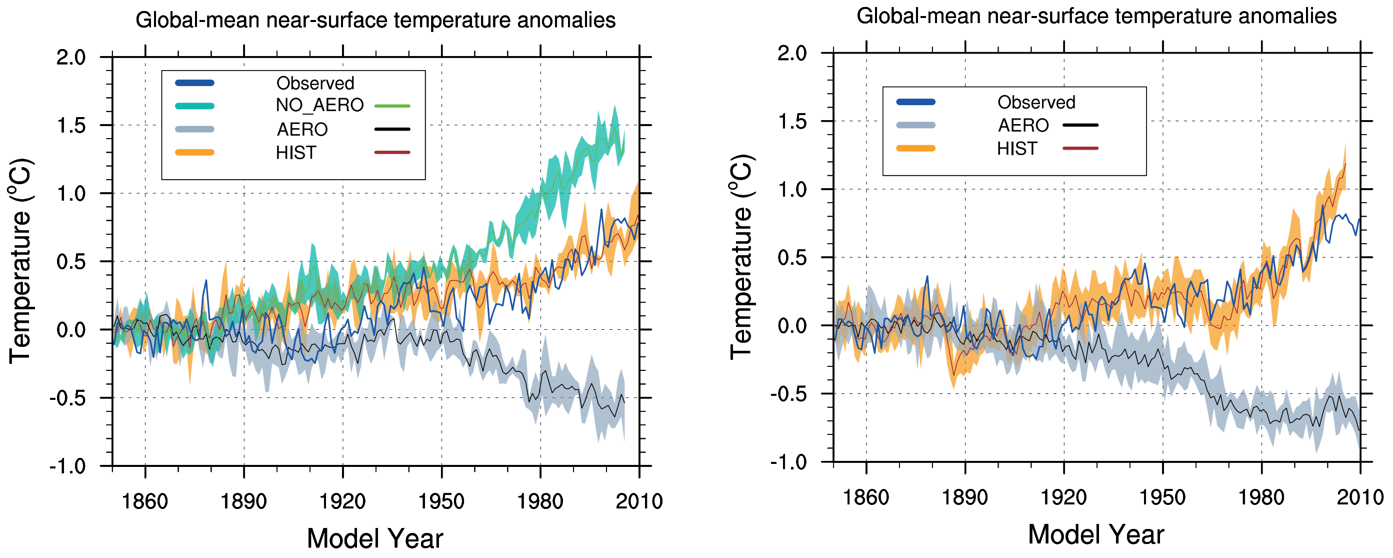
Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2011: The CMIP5 Experiment Design. Bull. Amer. Meteorol. Soc., submitted.

Wild, M., 2009: Global dimming and brightening: A review. J. Geophys. Res., 114, D00D16, doi:10.1029/2008JD011470.

Table 1: List of existing and proposed new CMIP5 experiments

Experiment	Description	Comment
6.2a	Fixed SST control experiment	Core in Taylor et al. (2011)
6.4a	Fixed SST with all anthropogenic aerosols	Tier 1 in Taylor et al. (2011)
6.4b	Fixed SST with anthropogenic sulfate aerosols	Tier 1 in Taylor et al. (2011)
	Fixed SST with black carbon aerosols	New experiment
7.3–aerosols–1	Historical simulation with all forcings except anthropogenic aerosols. Mini-ensemble if possible	Tier 2 in Taylor et al. (2011) but not specifically identified as such
7.3–aerosols–2 (2nd priority)	Historical simulation with anthropogenic aerosol forcings only. Mini-ensemble if possible	Tier 2 in Taylor et al. (2011) but not specifically identified as such
	RCP 4.5 scenario until 2100 with all forcings except anthropogenic aerosols starting from experiment 7.3–aerosols–1 above . Mini-ensemble if possible	New experiment

Figure 1: Global-mean near-surface temperature anomalies in simulations with all natural and anthropogenic forcings (HIST), with the anthropogenic aerosol forcing alone (AERO), and with all natural and anthropogenic forcings except the aerosol forcing (NO_AERO) in the CSIRO climate model (left panel) and the CanESM2 (right panel). The shading represents variations among the ensemble members. The observed global-mean near-surface temperature anomaly is shown with a blue line.



Climate-carbon interactions in the CMIP5 Earth System models

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Over the last 10 years, a growing number of models have investigated the coupling between the climate system and the global carbon cycle and found a potentially large positive feedback between climate and CO_2 with significant uncertainty across a range of 11 coupled climate-carbon cycle models (Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP): Friedlingstein et al., 2006) Such models, called Earth System Models (ESMs) in the following, account for the representation of the climate system (as in standard Atmosphere Ocean General Circulation Models) coupled to a representation of both the land and the ocean carbon cycle. With such ESMs, atmospheric CO_2 concentration can be simulated, in contrast to AOGCMs where it has to be imposed as an external forcing. Changes in atmospheric CO_2 (CA) result from the imbalance between anthropogenic emissions (EMI) and the net fluxes exchanged between the atmosphere and the land and ocean reservoirs (FAL and FAO respectively):

Having atmospheric CO_2 as a prognostic variable potentially leads to a larger uncertainty in climate projections as the atmospheric CO_2 concentration and hence radiative forcing from CO_2 might vary widely from one model to another. Indeed at the time of the IPCC AR4, the 11 C4MIP models simulated the evolution of climate and carbon cycle following the SRES A2 emissions scenario for the 21st century and found atmospheric CO_2 ranging anywhere between 700 and 1000 ppmv (Friedlingstein et al., 2006). As a result climate projections showed a larger range of response than the SRES A2 simulations of the AOGCMs driven by a given CO_2 concentration scenario (Meehl et al., 2007). The uncertainty in the simulated atmospheric composition comes from models' differences in their representation of the land and ocean carbon cycle, in particular the carbon cycle response to change in atmospheric CO_2 and change in climate. Climate uncertainty due to carbon cycle feedbacks is of comparable magnitude to uncertainty in physical feedbacks such as clouds (Gregory et al., 2009).

Although more realistic, climate simulations driven by CO_2 emissions make analysis of simulated climate scenario more challenging as it is hard, if not impossible, to separate the climate response of the model (which depends on climate feedbacks) from the carbon cycle response (which depends on carbon cycle feedbacks). It also complicates model intercomparison, as different models experience different rates and magnitudes of forcing.

In order to circumvent this issue, the CMIP5 protocol (Taylor et al., 2009; 2011) proposes all but one of the experiments are driven by atmospheric CO_2 concentration, not emissions. The one exception being the Historical/RCP 8.5, the higher end scenario, where models should be run twice, once with a CO_2

concentration forcing and once with a CO_2 emission forcing. In the concentration-driven experiments the models still constitute a bridge between emissions and concentration, but now concentration is the boundary condition and the permissible emissions required to follow the CO_2 pathway are diagnosed from the model output.

The CMIP5 simulations that are of direct interest for the climate-carbon cycle community fall into two distinct categories: (i) realistic scenarios (designed to make projections) and (ii) idealized scenarios (designed to aid process understanding and comparison of model sensitivity). Specifically, they are:
The historical (#3.2*) followed by the RCP 3PD, 4.5, 6 and 8.5 scenarios (#4.1, 4.2, 4.3, 4.4) driven by CO_2 concentration;
The historical (#5.2) followed by the RCP 8.5 scenario (#5.3), driven by CO_2 emissions
The CMIP 1% CO_2 per year scenarios (#6.1, 5.4.1, 5.5.1)
* # numbers refer to the simulation label in Taylor et al. (2009).

1) When driven by CO_2 concentrations, ESMs with an interactive carbon cycle will still compute the land and ocean fluxes, inverting equation (1) now allows the models to diagnose the anthropogenic emissions, EMI, compatible with the prescribed atmospheric CO_2 concentration pathway: It is worth remembering that the RCP scenarios (Moss et al., 2010) have been developed by Integrated Assessment Models (IAMs) that do have a simplified representation of the climate system and the carbon cycle calibrated against more complex models. However ESMs have a more comprehensive and up-to-date representation of these components and feedbacks; hence the compatible emissions simulated by ESM should be seen as our best estimate (Figure 1). IAMs could be used then to infer the socio-economic route required to meet these emission trajectories. They might differ from the ones originally simulated by the IAMs. In these simulations, ESMs propagate independent uncertainty from CO_2 to climate and from CO_2 concentration to anthropogenic emissions.

2) When driven by CO_2 emissions, the ESM will simulate for the RCP8.5, the atmospheric CO_2. Again this might differ from the CO_2 concentrations used in the RCP8.5 concentration driven scenario as the ESM carbon cycle might differ from the one of the IAMs. Hence the simulated climate change for the RCP8.5 will account for the uncertainty in both the climate and the carbon cycle.

3) The RCP scenarios include all anthropogenic forcings (greenhouse gases, aerosols and land use change). The use of such scenarios for analysis of the carbon cycle feedbacks (as in Friedlingstein et al., 2006) is then complicated by these non-CO_2 forcing. It was then decided to use the idealized CMIP1% CO_2 per year to investigate the climate-carbon feedback strength across the different ESMs following the methodology proposed by Gregory et al., (2009). In addition to the standard CMIP1%, two runs are recommended, a "biogeochemistry" run (BGC) where the carbon cycle models "see" the increase in CO_2, while the climate system does not; and a "radiative" run (RAD) where the climate system "sees" the increase in CO_2, while the carbon cycle models do not.

The use of these 3 runs will allow us to isolate the climate response of the models from the carbon cycle response to CO_2 and to climate, and hence calculate the climate-carbon cycle feedback parameters. The BGC-coupled simulation (termed "uncoupled" in Friedlingstein et al., 2006) is higher priority, but Gregory et al. (2009) showed that non-linearity in BGD and RAD simulations may be important and so all three simulations are recommended. Additionally, BGC and RAD counterparts for the HIST/RCP4.5 simulation are proposed in CMIP5 (expt. #s 5.4.2, 5.5.2), which will enable quantification of the impacts of carbon cycle feedbacks on permissible emissions. However, if only one set of uncoupled experiments are performed by a modelling centre, we recommend choosing the idealized 1% simulations.

In addition to the RCPs and CMIP scenarios, there will be palaeoclimate simulations with the same ESMs where the carbon cycle will allow diagnosing changes in land and ocean carbon reservoirs across the Last Glacial Maximum/ Holocene transition and over the Last Millennium.
New to CMIP5 is the ability of some ESMs to simulate both the biophysical and biogeochemical effects of land use, and a harmonised set of gridded land-use scenarios has been developed from the RCPs for use in ESMs (Hurtt et al. 2011). The impact of land-use change on the carbon cycle is large. More than half of the world's land surface has been affected by land-use activities, and cumulatively to present day, land-use emissions of CO_2 are comparable to fossil fuel emissions (Houghton, 1999). Land-use changes also alter the surface albedo, roughness and hydrological cycle. However, IAMs and ESMs use a large diversity of approaches for representing land-use changes with very different assumptions made within the RCPs and very different response of the carbon cycle to these forcings simulated by the ESMs. A detailed and critical assessment of ESM treatment of land use is required.

It is anticipated that multi-model analysis be performed on carbon response to climate change, compatible emissions, feedback analysis, process oriented model evaluation or more specific analysis on the role of nitrogen, impact of land use change, etc. Several groups have already performed some of these simulations (e.g. Arora et al., 2011) and models outputs are being made available on the CMIP5 web site via the Earth System Grid. Contacts have already been made with Journal of Climate to ensure a special issue on "Analysis of the climate-carbon interaction in the CMIP5 Earth System Models", where all papers relevant to the C4MIP activities, making use of the CMIP5 archive could be submitted.
This special issue will be coordinated by P. Friedlingstein (University of Exeter), Chris Jones (Met Office Hadley Centre) and Vivek Arora (Canadian Centre for Climate Modelling and Analysis).

CMIP5 presents a unique opportunity to update the first C4MIP analysis of carbon cycle feedbacks in coupled climate-carbon cycle models using a greater number of state-of-the-art ESMs from a wider modelling community, and encompassing improved experimental design and model processes.

References

Arora, V. K., J. F. Scinocca, G. J. Boer, J. R. Christian, K. L. Denman, G. M. Flato, V. V. Kharin, W. G. Lee, and W. J. Merryfield , 2011: Carbon emission limits required to satisfy future representative concentration pathways of greenhouse gases. Geophys. Res. Lett. , 38, L05805, doi:10.1029/2010GL046270.

Friedlingstein P, Cox P, Betts R, Bopp L, Von BW, Brovkin V, Cadule P, Doney S, Eby M, Fung I, Bala G, John J, Jones C, Joos F, Kato T, Kawamiya M, Knorr W, Lindsay K, Matthews HD, Raddatz T, Rayner P, Reick C, Roeckner E, Schnitzler KG, Schnur R, Strassmann K, Weaver AJ, Yoshikawa C, Zeng N, 2006: Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison. J. Climate, 19, 3337-3353.

Gregory, JM, Jones, CD, Cadule, P., Friedlingstein, P., 2009: Quantifying carbon-cycle feedbacks. Journal Of Climate, 22, 5232-5250.

Houghton RA, 1999: The annual net flux of carbon to the atmosphere from changes in land use 1850-1990. Tellus, 51B, 298-313.

Hurtt GC, Chini LP, Frolking S, Betts R, Feddema J, Fischer G, Klein Goldewijk K, Hibbard K, Janetos A, Jones C, Kindermann G, Kinoshita T, Riahi K, Shevliakova E, Smith S, Stehfest E, Thomson A, Thornton P, van Vuuren D and Wang YP. 2009: iLEAPS Newsletter. Issue No. 7, 6-8.

Meehl, G.A. et al., 2007: Global climate projections Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Eds: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller. Cambridge University Press.

Moss, R.,H., Edmonds, J.,A., Hibbard, K.,A., Manning, M.,R., Rose, S.,K., van Vuuren, D.,P.,, Carter, T.,R., Emori, S., Kainuma, M., Kram, T., Meehl, G.,A., Mitchell, J.,F., Nakicenovic, N., Riahi, K., Smith, S.,J., Stouffer, R.,J., Thomson, A.,M., Weyant, J.,P., Wilbanks, T.,J., 2010: The next generation of scenarios for climate change research and assessment. Nature. 463(7282), 747-56.

Taylor, K. E., R. J. Stouffer and G. A. Meehl, 2009: A summary of the CMIP5 Experimental Design. http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2011: The CMIP5 Experiment Design. Bull. Amer. Meteorol. Soc., submitted.

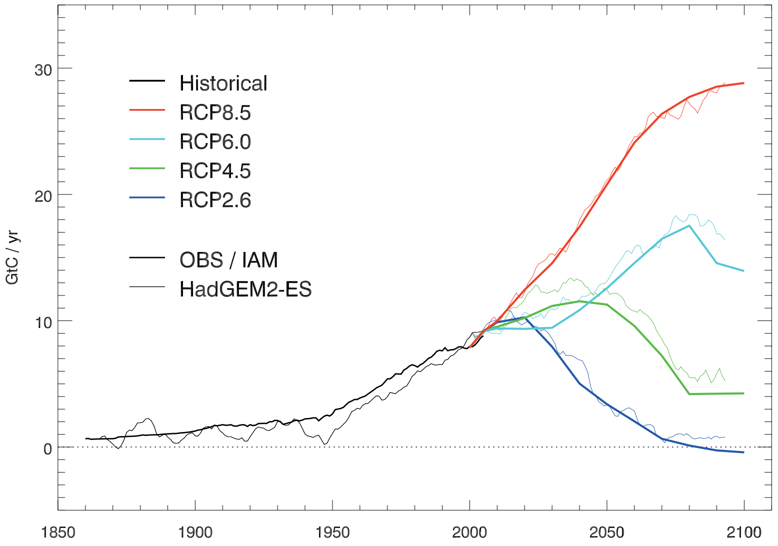

Figure 1. Permissible emissions as simulated by HadGEM2-ES (thin lines) compared with observed CO_2 emissions for the historical period and those projected for the RCP scenarios by the integrated assessment models (IAMs) which created the RCPs (thick lines)

Stratosphere-resolving Models in CMIP5

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There is growing evidence that variability in the stratosphere has a significant impact on surface climate (Baldwin and Dunkerton, 2001, Thompson et al., 2002, Charlton et al., 2004, Scaife et al., 2005, Manzini et al., 2006, Ineson and Scaife, 2009, Cagnazzo and Manzini, 2009, among others). During boreal winter, there is the potential that models with a well resolved stratosphere will lead to an improved representation of blocking and cold air outbreaks over Europe, due to the simulation of realistic stratospheric sudden warming events in the stratosphere resolving models. In addition, stratospheric changes induced by anthropogenic climate change may contribute substantially to changes in storm tracks, sea level pressure and precipitation.

Stratospheric dynamics may also be implicated in linking remote changes in the Earth system, such as ozone depletion/recovery and ocean carbon fluxes (Lenton et al., 2009). A suggested mechanism for this is that ozone depletion leads to a stronger southern hemisphere polar night jet in October which in turn leads to increased zonal wind over the southern ocean decreasing the uptake of CO_2 by the southern ocean (Le Quéré et al., 2007). Figure 1 shows this trend in zonal wind in ERA40, a coupled stratosphere-resolving model, known as a high top model, run at the UK Met Office (Martin et al., 2011) for CMIP5, and and equivalent standard, low top climate model (differing only in vertical resolution). In this particular case, the high/low top model comparison indicates sensitivity of the zonal wind trend to the representation of stratospheric dynamics.

Recently, the Stratospheric Processes and their Role in Climate (SPARC) Chemistry-Climate Model Validation phase 2 (CCMVal-2) multi-model intercomparison has demonstrated that the CCMval-2 models, generally with a better-resolved stratosphere, perform better than AMIP CMIP-3 models in the stratosphere and perform equally well if not better in the troposphere (Chapter 10, Baldwin et al., 2010).
These advancements in the knowledge of how stratospheric representation operates in climate models have lead a number of climate modeling groups to undertake the Coupled Model Intercomparison Project Phase 5 (CMIP5) experiments with models that include a well-resolved stratosphere, the so-called "high-top models".

"High-top models" currently refer to coupled atmospheric-ocean-sea ice general circulation models (AOGCMs), or their extension to Earth System Models (ESMs), whose atmospheric model extends above the stratopause. More specifically, to properly simulate stratospheric processes, the development of high-top models needs to include also revised implementations of radiation, gravity wave effects, and how radiative active trace fields are represented. Paying particular attention to the evolution of ozone has already been demonstrated as important (Son et al., 2008).

The high-top models therefore distinguish themselves from the large majority of climate/Earth system models, such as those that participated to CMIP3 and used for the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) (Chapter 8, Randall et al., 2007). Consequently, the label "low-top" is now applied to any AOGCMs/ESMs, which atmospheric model component does not reach the stratopause. Most of the low-top models do extend to the middle stratosphere; however, high-top models typically extend to the middle/upper mesosphere. A few models extend to the lower thermosphere.

From the point of view of stratospheric dynamics, the major limitation of the low top models is that in this class of models, the explicit simulation of stratospheric variability is hampered in the upper layers of the model domain and in the lower stratosphere. This technique may provide reasonable results for the modelled mean climate, but it reduces the modelled stratospheric variability and therefore its downward influence. Its quantitative implications for tropospheric and surface variability for seasonal to decadal and longer time scale are just starting to become apparent.

The status of development of high-top models and their potential participation in CMIP5 have been recently reviewed in a workshop lead by the SPARC DynVar Activity on Modelling the Dynamics and Variability of the Stratosphere-Troposphere System (Manzini et al., 2011). Topics addressed in the workshop included: Influence of the stratosphere on the tropospheric circulation, on the ocean circulation via air-sea interactions, and on snow and sea ice fields; role of the stratosphere in the tropospheric circulation response to climate change; and mechanisms for two-way stratosphere-troposphere coupling. Presentation sections were complemented by discussions on how to best analyze, make full use, and exchange knowledge from the ensembles of CMIP5 runs, with the role of the stratosphere in focus.

A major outcome of the DynVar workshop is that about 10 modeling groups are carrying out analysis of the CMIP5 simulations with high top models and comparing this with the low top model simulations. The modeling groups represented at the DynVar workshop are listed in Table 1, together with information of the model names, atmospheric resolution, scenario, and contacts. Of the 10 high top models represented at the DynVar workshop, three models include interactive atmospheric chemistry and at least three modeling systems will additionally be run with CO_2 emissions, requiring modules for the land and ocean carbon cycle.

Following the workshop, Research Groups have been established within the SPARC DynVar Activity, to foster analysis of the CMIP5 archive, with the role of the stratosphere in focus.

A SPARC/DynVar workshop will be held jointly with CLIVAR's Stratosphere Historical Forecast Project (SHFP), which is carrying out a similar activity for high top and low top seasonal forecasts. The workshop will take place in spring/summer 2012. For more and updated information see the SPARC DynVar web site (http://www.sparcdynvar.org/).

References

Baldwin et al., 2010: Effects of the stratosphere on the troposphere, in the SPARC Report on the Evaluation of Chemistry-Climate Models, V. Eyring, T. G. Shepherd, D. W. Waugh (Eds.), SPARC Report No. 5, WCRP-132, WMO/TD-No. 1526, http://www.atmosp.physics.utoronto.ca/SPARC

Baldwin, M.P., and T.J. Dunkerton, 2001: Stratospheric Harbingers of Anomalous Weather Regimes. Science, 294, 581-584.

Cagnazzo, C. and E. Manzini, 2009: Impact of the startosphere on the winter tropospheric teleconnections between ENSO and the North Atlantic and European Region. J. Climate, 22, 1223-1238. DOI: 10.1175/2008JCLI2549.1.

Charlton, A.J., A. O'Neill, W.A. Lahoz and A.C. Massacand, 2004: Sensitivity of tropospheric forecasts to stratospheric initial conditions. Q. J. R. Meteorol. Soc., 130, 1771–1792.

Ineson, S. and A.A. Scaife, 2009: The role of the stratosphere in the European climate response to El Niño. Nature Geosceince, DOI:10.1038/NGEO381.

Lenton, A., F. Codron, L. Bopp, N. Metzl, P. Cadule, A. Tagliabue, and J. Le Sommer, 2009: Stratospheric ozone depletion reduces ocean carbon uptake and enhances ocean acidification. Geophys. Res. Lett., 36, L12606, doi:10.1029/2009 GL038227.

Le Quéré, C., C. Rödenbeck, E.T. Buitenhuis, T.J. Conway, R. Langenfelds, A. Gomez, C. Labuschagne, M. Ramonet, T. Nakazawa, N. Metzl, N. Gillett and M. Heimann, 2007: Saturation of the Southern Ocean CO_2 Sink Due to Recent Climate Change. Science, 316 (5832), 1735-1738, doi: 10.1126/science.1136188.

Manzini, E., M.A. Giorgetta, M. Esch, L. Kornblueh, and E. Roeckner, 2006: The influence of sea surface temperatures on the Northern winter stratosphere: Ensemble simulations with the MAECHAM5 model. J. Climate, 19, 3863-3881.

Manzini, E., N. Calvo, E. Gerber, M. Giorgetta, J. Perlwitz, L. Polvani, F. Sassi, A. Scaife, T. Shaw, 2011: Report on the SPARC DynVar Workshop 2 on Modelling the Dynamics and Variability of the Stratosphere-Troposphere System. SPARC Newsletter, 36, 19-22.

Martin, G.M. et al., 2011: The HadGEM2 family of Met Office Unified Model Climate Configurations. Submitted to Geoscientific Model Development.

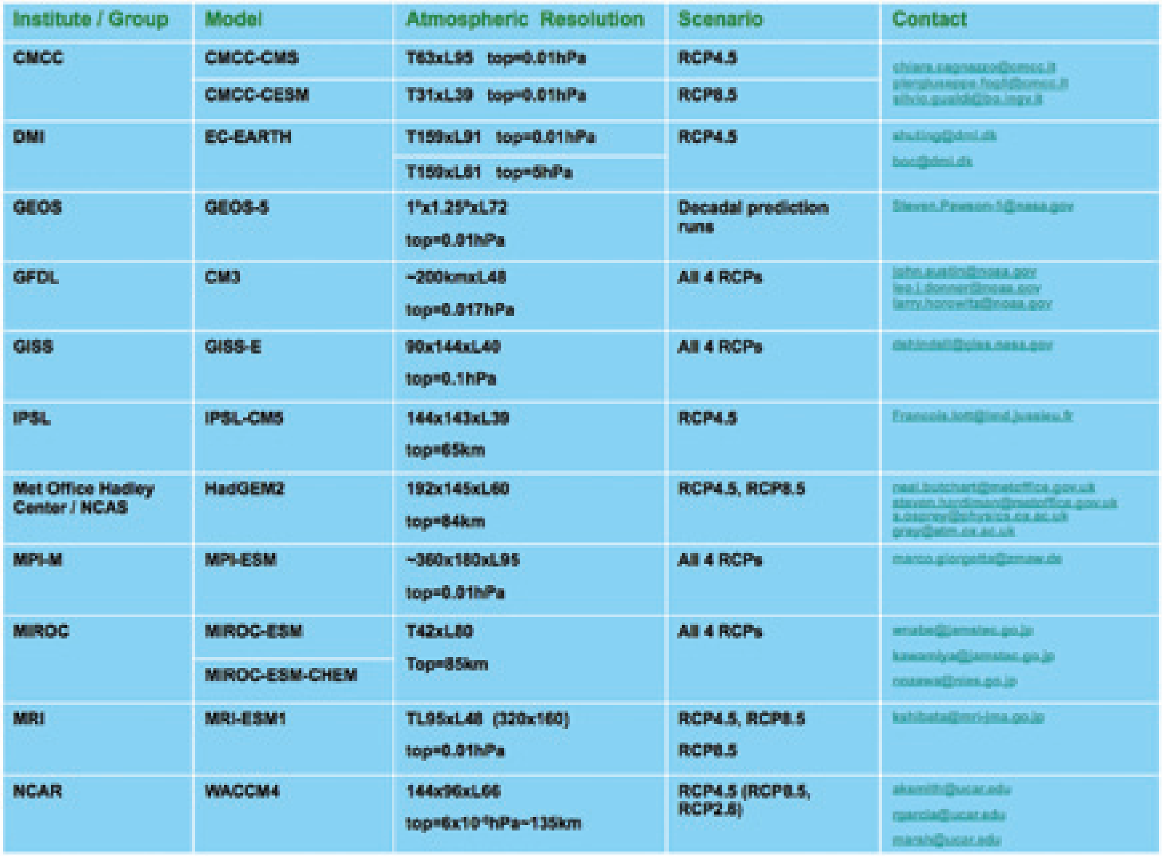
Randall, D.A., et al., Climate Models and Their Evaluation, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Scaife, A.A, J.R. Knight, G.K. Vallis, C.K. Folland, 2005: A stratospheric influence on the winter NAO and North Atlantic Surface Climate. Geophys. Res. Lett., 32, L18715.

Son, S.-W., L. M. Polvani, D. W. Waugh, H. Akiyoshi, R. Garcia, D. Kinnison, S. Pawson, E. Rozanov, T.G. Shepherd, K. Shibata, 2008: The Impact of Stratospheric
Ozone Recovery on the Southern Hemisphere Westerly Jet. Science, 320, 1486-1489.

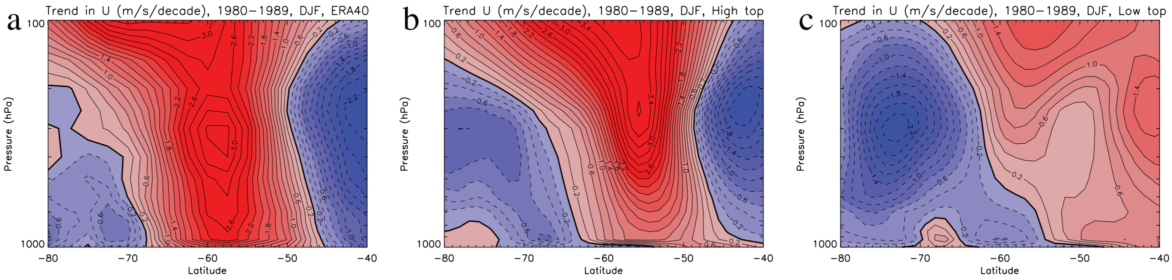
Thompson, D.W.J., M.P. Baldwin and J.M. Wallace, 2002: Stratospheric Connection to Northern Hemisphere Wintertime Weather: Implications for Prediction. J. Climate, 15, 1421-1428.

Table 1: High top models participating to CMIP5 so far.



Institute / Group	Model	Atmospheric Resolution	Scenario	Contact
CMCC	CMCC-CMS	T63xL95 top=0.01hPa	RCP4.5	chiara.cagnazzo@cmcc.it pierghuseppe.fogli@cmcc.it silvio.gualdi@bo.ingv.it
	CMCC-CESM	T31xL39 top=0.01hPa	RCP8.5	
DMI	EC-EARTH	T159xL91 top=0.01hPa	RCP4.5	shuting@dmi.dk boc@dmi.dk
		T159xL61 top=5hPa		
GEOS	GEOS-5	1°x1.25°xL72 top=0.01hPa	Decadal prediction runs	Steven.Pawson-1@nasa.gov
GFDL	CM3	~200kmxL48 top=0.017hPa	All 4 RCPs	john.austin@noaa.gov leo.j.donner@noaa.gov larry.horowitz@noaa.gov
GISS	GISS-E	90x144xL40 top=0.1hPa	All 4 RCPs	dshindell@giss.nasa.gov
IPSL	IPSL-CM5	144x143xL39 top=65km	RCP4.5	Francois.lott@lmd.jussieu.fr
Met Office Hadley Center / NCAS	HadGEM2	192x145xL60 top=84km	RCP4.5, RCP8.5	neal.butchart@metoffice.gov.uk steven.hardiman@metoffice.gov.uk a.osprey@physics.ox.ac.uk gray@atm.ox.ac.uk
MPI-M	MPI-ESM	~360x180xL95 top=0.01hPa	All 4 RCPs	marco.giorgetta@zmaw.de
MIROC	MIROC-ESM	T42xL80 Top=85km	All 4 RCPs	emate@jamstec.go.jp kawamiya@jamstec.go.jp nozawa@nies.go.jp
	MIROC-ESM-CHEM			
MRI	MRI-ESM1	TL95xL48 (320x160) top=0.01hPa	RCP4.5, RCP8.5 RCP8.5	kshibata@mri-jma.go.jp
NCAR	WACCM4	144x96xL66 top=6x10⁻⁶hPa~135km	RCP4.5 (RCP8.5, RCP2.6)	aksmith@ucar.edu rgarcia@ucar.edu marsh@ucar.edu

Figure 1: December-January-February (DJF) trend ($ms^{-1}decade^{-1}$) in zonal wind in ERA40 (left), a coupled high top model, run at the UK Met Office for CMIP5 (middle), and equivalent low top model (right). The trends are computed over the 1980-1989 period.



Physical Ocean Fields in CMIP5

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Background and motivation

The Coupled Model Intercomparison Project (CMIP) presents a hugely valuable resource to the climate science community. In particular, the CMIP archive offers the best scientific tool available for projecting future climate states. Nonetheless, from a physical process perspective, model comparisons such as CMIP typically archive few ocean fields required to help characterise physical mechanisms. CMIP3, for example, suffered from the following shortcomings.

- There was insufficient output to construct global budgets of ocean mass, heat, and salt, with incomplete information regarding the surface boundary fluxes. Furthermore, those boundary fluxes archived were generally not on the ocean model native grid.

- There were few if any fields of use for studying the impact of subgrid scale (SGS) parameterizations, with such information of leading order importance for understanding ocean climate model behaviour.

- Vector fields (e.g., velocity, mass transport, fluxes) were remapped to a spherical grid from the non-spherical native grids of most contributing models. Remapping occurred despite the absence of a generally applied algorithm to handle complex land-sea boundaries, thus resulting in incomplete and/or untrustworthy vector fields.

It was with this background that the CLIVAR Working Group for Ocean Model Development (WGOMD) prepared the report "Sampling the Physical Ocean Fields in the WCRP CMIP5 Simulations'' (Griffies et al., 2009). This report was written from the perspective of physical ocean scientists aiming to enhance the scientific potential available from CMIP5 simulations. Included are discussions of space and time sampling and detailed rationale for archiving the requested fields. The purpose of the present article is to summarize salient points from the WGOMD CMIP5 report, and to highlight some of the potential scientific uses of this model dataset.

Even with many more ocean fields requested for CMIP5, and with a more robust sampling strategy, the CMIP5 request for physical ocean fields represents only a fraction of what a process scientist may actually require to perform a full analysis of, say, the mechanisms contributing to simulated ocean heat transport. Nonetheless, the CMIP5 archive is a nontrivial step forward in that it will allow for a significantly more precise mechanistic and quantitatively accurate characterization of the simulations than previously available.

Summary of the requested fields

The WGOMD CMIP5 report (Griffies et al., 2009) contains ten tables (numbered 2.1 through 2.10) of requested physical ocean fields. The scientific rationale for including each field in CMIP5 is included in the report's body, as are sampling specifications (e.g., daily, monthly, climatology, native model grid, remapping in the vertical, physical units, etc.). We here briefly summarize the ten tables and present a bit of the rationale for some of the fields.

Static fields and functions (Table 2.1)

These fields provide basic information about the model configuration, such as the ocean bottom topography, model grid information, and details about the equation of state. The bottom topography is particularly important for understanding certain features of the simulated transport through straits and throughflows, as well as overflow regions such as the Denmark Straits.

Scalar fields (Table 2.2)

This table contains scalar fields such as temperature, salinity, density, surface height, mixed layer depth, and vertically integrated streamfunction. Additionally, there are requests for ideal age and CFC-11 (just for the 20th century historical simulations), each of which provides the analyst with useful information regarding ventilation. There are requests for daily fields (sea surface temperature and its square, daily maximum of mixed layer depth), with such requests acknowledging that certain questions about variability and impacts can be best addressed with such high frequency sampling.

Vector fields (Table 2.3)

This table requests a number of vector fields, such as the velocity and transport. Particular requests are made for native grid transport of heat and mass by both the resolved currents and subgrid scale processes such as parameterized eddy advection or quasi-Stokes transport.

CMIP5 acknowledges that the most quantitatively accurate representation of transport vectors is on the model's native grid, and it is on this grid that fields are requested. Should modelers choose to also provide conservatively remapped vector fields, and then certain of those fields will be accepted as well. However, it is anticipated that many centres will not archive the remapped vector fields, largely due to resource limitations and the absence of a community standard algorithm for remapping in the presence of complex land-sea boundaries.

Mass transport through selected regions (Table 2.4)

CMIP5 requests 15 vertically integrated mass transports through a selection of straits, such as the Drake Passage, Indonesian Throughflow, and Denmark Strait, and certain regions, such as the Equatorial Undercurrent at 155 ° W from the surface to 350m.

This request acknowledges that modelling centres are more adept at computing the various mass transports through a selection of such "choke points" than analysts working often with just the velocity vectors and grid information. It is even more convenient to have 15 time series archived for the purpose of evaluating the simulation of certain key transport regions.

Boundary mass fluxes (Table 2.5)

This is the first of four tables that request boundary flux information on the ocean native grid, with such information critical for understanding how the ocean model is being forced through buoyancy and momentum fluxes. Additionally, global budgets of ocean properties, such as mass, heat, and salt, require such flux information in order to asses, for example, model drift and conservation properties (e.g., does the ocean model conserve heat, mass, and salt?). Table 2.5 requests details of the mass fluxes exchanged with the atmosphere, sea ice, and rivers. Note that for that minority of ocean models that employ the obsolete virtual salt flux, rather than a water flux, all fields requested in Table 2.5 will be identically zero.

Boundary salt fluxes (Table 2.6)

The most climatologically important exchange of salt across the liquid ocean interface occurs with sea ice, with this table requesting such salt flux. Additionally, all virtual salt flux fields are requested from models that do not employ a real water flux.

Boundary heat fluxes (Table 2.7)

There are numerous fluxes of heat that cross the ocean interfaces, such as radiative, latent, and turbulent heat through the surface, and geothermal heating at the ocean bottom. The penetration of shortwave radiation into the ocean interior represents an important source of heating in the upper ocean layers in parts of the World Ocean.

Additionally, the exchange of mass with the atmosphere, river, and sea ice has an associated sensible heat flux of the exchanged water parcel. Each of these heat fluxes is requested in Table 2.7.

Surface momentum fluxes (Table 2.8)

This table requests the momentum flux associated with the net surface stress applied at the liquid ocean surface by air-sea plus ice-sea interactions.

Vertical SGS characterization (Table 2.9)

Ocean climate models used for CMIP5 are generally quite reliant on a suite of subgrid scale (SGS) parameterizations for the many critical unresolved processes occurring in the ocean. Vertical downgradient diffusion of salt, heat, and momentum is the most common means for parameterizing unresolved vertical transfer, with a growing number of physical processes, such as tide mixing, now having associated methods for computing a vertical diffusivity or viscosity. This table requests a suite of such mixing coefficients, as well as their impact on mechanical energy.

Lateral SGS characterization (Table 2.10)

This table requests information about the lateral SGS parameterizations, such as the diffusivity used for neutral diffusion and parameterized quasi-Stokes streamfunction in the tracer equation,as well as lateral viscosity used in the momentum equation.

Potential scientific uses

It remains for the scientific research community to discover new uses for the ocean fields requested for CMIP5. Nonetheless, we present here two examples of scientific questions where the CMIP5 archive will prove to be far more valuable than the CMIP3 archive.

Southern Ocean climate change

Mesoscale eddy processes play a central role in establishing stratification and tracer transport in the Southern Ocean. Eddies are also critical for determining the response of circulation and ventilation patterns to surface forcing changes. Recent evidence from observations suggests that the Southern Ocean stratification has not changed, in contrast to increases in wind stress (Boening et al., 2008). CMIP3 models, however, generally respond to increasing winds by increasing the ocean baroclinicity (e.g., Fyfe and Saenko, 2006). A number of recent papers have aimed at understanding the various responses of parameterized eddies to changes in Southern Ocean winds (e.g., Farneti et al., 2010, Hofmann and Maqueda, 2011, Farneti and Gent, 2011), with these studies identifying elements of the eddy parameterization as key to determining the ocean response to wind changes. Unfortunately, CMIP3 archived no fields associated with the eddy parameterization; i.e., no diffusivities nor impacts on kinetic energy, whereas CMIP5 does request such fields. Consequently, we conjecture that a more mechanistic understanding will arise from an analysis of how the CMIP5 models respond to climate change as a function of their eddy parameterizations.

Heat budget for the ocean

The global ocean is not in a steady state. Additionally, CMIP control simulations are unlikely to be fully equilibrated due to the millennial time scales associated with the deep ocean. Nonetheless, in a recent paper, (Lucarini and Ragone, 2011) performed a heat (more precisely, an enthalpy) budget for the CMIP3 climate models with the assumption that the models were sufficiently equilibrated to determine the conservation properties of the global heat budgets. Their analysis identified what appear to be nontrivial sources of non-conservation in the simulated climate system. In general, these results highlight the need for careful analyses of heat in the full climate system as well as in each of the component models.

The conclusions from such global analyses as performed by (Lucarini and Ragone, 2011) rely on accurate flux data in the CMIP archive. Namely, the globally integrated flux of properties such as mass, heat, and salt result from small differences between large terms. CMIP3 did not archive sufficient fluxes to perform an accurate heat budget for the ocean, nor did it save ocean surface fluxes on the ocean native grid. In contrast, CMIP5 will archive all fields needed to perform an accurate mass, heat, and salt budget for the ocean. This dataset will thus allow for further examination of certain questions raised by (Lucarini and Ragone, 2011) related to global heat budgets in climate models.

Future issues

We close by identifying the following three considerations for future CMIPs, though note that these are only three issues amongst many. First, there is a need to specify requirements for fluxes of heat (advective and SGS fluxes) enabling CMIP analysts to perform a thorough study of three dimensional ocean heat transport. This is not an easy problem, given the growing suite of model architectures, with general vertical and horizontal grids now becoming the norm rather than the exception. Second, there is a need to compare eddy tracer fluxes in mesoscale eddy permitting models. Again, we are faced with specifying how to compare three dimensional fluxes from different models, and how to temporally sample the eddy flux fields. Third, the present methods used to describe ocean data for CMIP are not sufficient for the needs of general vertical coordinate models and unstructured horizontal grids, even though the model development community is moving forward with such models for climate research (see Griffies et al., 2010 for an assessment of various model development paths). Furthermore, the use of general vertical and horizontal grids makes it more difficult to directly compare model output. Relatedly, the absence of an agreed upon remapping algorithm for vector fields contributes particularly to this difficulty.

Acknowledgements

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References

Boening, C. W., Dispert, A., Visbeck, M., Rintoul, S., and Schwarzkopf, F., 2008: The response of the Antarctic Circumpolar Current to recent climate change, Nature Geoscience, 1, 864–869.

Farneti, R. and Gent, P., 2011: The effects of the eddy-induced advection coeffcient in a coarse-resolution coupled climate model. Ocean Modelling, doi:10.1016/j.ocemod.2011.02.005.

Farneti, R., Delworth, T., Rosati, A., Griffies, S. M., and Zeng, F., 2010: The role of mesoscale eddies in the rectification of the Southern Ocean response to climate change. Journal of Physical Oceanography, 40, 1539–1557.

Fyfe, J. and Saenko, O., 2006: Simulated changes in extratropical Southern Hemisphere winds and currents. Geophysical Research Letters, 33 (L06701), doi:10.1029/2005GL025 332.

Griffes, S., Adcroft, A., Banks, H., Boening, C., Chassignet, E., Danabasoglu, G., Danilov, S., Deleersnijder, E., Drange, H., England, M., Fox-Kemper, B., Gerdes, R., Gnanadesikan, A., Greatbatch, R., Hallberg, R., Hanert, E., Harrison, M., Legg, S., Little, C., Madec, G., Marsland, S., Nikurashin, M., Pirani, A., Simmons, H., Schroeter, J., Samuels, B., Treguier, A.-M., Toggweiler, J., Tsujino, H., Vallis, G., and White, L., 2010: Problems and Prospects in Large-Scale Ocean Circulation Models. in Proceedings of the OceanObs09 Conference: Sustained Ocean Observations and Information for Society, Venice, Italy, 21-25 September 2009, edited by J. Hall, D. Harrison, and D. Stammer, vol. 2, ESA Publication WPP-306.

Griffies, S. M., Adcroft, A. J., Aiki, H., Balaji, V., Bentson, M., Bryan, F., Danabasoglu, G., Denvil, S., Drange, H., England, M., Gregory, J., Hallberg, R., Legg, S., Martin, T., McDougall, T. J., Pirani, A., Schmidt, G., Stevens, D., Taylor, K., and Tsujino, H., 2009: Sampling Physical Ocean Fields in WCRP CMIP5 Simulations.

Hofmann, M. and Morales-Maqueda, M., 2011: The response of Southern Ocean eddies to increased midlatitude westerlies: A non-eddy resolving model study. Geophysical Research Letters, 38 (L03605), doi:10.1029/2010GL045 972.

Lucarini, V. and Ragone, F., 2011: Energetics of climate models: Net energy balance and meridional enthalpy transport. Reviews of Geophysics, 49, RG1001, doi:10.1029/2009RG000 323.

The Coordinated Regional Downscaling Experiment: CORDEX

An international downscaling link to CMIP5

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1. Introduction

The provision of climate information at regional to local scales is an important requirement to support informed decision making in response to potential climate change. Such information is needed to assess the impacts of climate change on human and natural systems, enabling the development of suitable adaptation and risk management strategies at the regional to local level.

To date most regional climate change information has been based on Coupled Global Climate models (CGCMs), with particular use being made of coordinated multi-CGCM experiments, such as the 3rd Coupled Model Intercomparison Project (CMIP3, Meehl et al. 2007). CMIP3 brought together ~20 CGCM groups around a common set of future greenhouse gas (GHG) emission scenarios, enabling the production of a comprehensive set of coordinated future climate projections. Over the ~5 years since CMIP3, significant improvements have occurred in CGCMs, arising from a more accurate and more complete representation of the climate system, along with increased CGCM resolution.

The 5th Coupled Model Intercomparison Project (CMIP5) (Meehl and Bony, this issue) is now underway, with a new set of so-called Reference Concentration Pathways (RCPs, Moss et al. 2010) that provide future estimates of GHG concentrations, aerosol and land-use, being used to force the latest generation CGCMs. CMIP5 will produce both long-term (centennial timescale) global climate projections (Stouffer et al., this issue) and short-term (inter-annual to decadal) initialized climate predictions (Doblas-Reyes et al., this issue). Despite recent advances, the horizontal resolution of most CGCMs making CMIP5 centennial projections will be of order 1-2°, primarily due to computational limitations. This limits their ability to represent important local forcing features, such as complex topography, land surface heterogeneity, coastlines and regional water bodies, all of which can modulate the large-scale climate on regional to local scales. Coarse resolution also precludes CGCMs from providing an accurate description of extreme weather events, which are of fundamental importance in assessing the societal impact of changes in climate variability. In other words, there still exists a fundamental spatial scale gap between the regional climate information directly available from CMIP5 and that required for impact assessment and decision making.

Various downscaling techniques have been developed to bridge this scale gap. Two widely used methods are; (i) Dynamical downscaling (DD), where a Regional Climate Model (RCM) is run over a limited geographical area at increased resolution, driven at the lateral and surface boundaries by CGCM simulation data (Giorgi, 1999) and (ii) Empirical-Statistical Downscaling (ESD), where statistical relationships are first developed between large scale climate predictors and regional to local scale predictands. These relationships are then applied to CGCM output in order to downscale the simulated large scale climate of the CGCM to the local scale (Hewitson and Crane 1996). While many different ESD methods exist (Giorgi et al. 2001; Wigley and Wilby 2000), they all share this basic conceptual framework. A number of papers that review downscaling methods, discussing their relative merits and limitations, are available in the literature (Laprise et al., 2008; Schmidli et al., 2007; Giorgi, 2006; Wang et al., 2004; Leung et al., 2003; Mearns et al., 2003; Giorgi and Mearns, 1999) and the interested reader is referred to these for more details.

2. A coordinated framework for regional climate change projection: Downscaling CMIP5 simulations to regional scales

2.1 Background and previous coordinated RCD projects

Both dynamical and statistical downscaling, here referred to jointly as Regional Climate Downscaling (RCD), are beginning to be widely used in climate change research, providing a link between climate model projections and the impact, adaptation and vulnerability (IAV) communities (Huntingford and Gash, 2005). This growth has occurred, to some degree, through numerous independent local efforts where scientists develop methodologies targeted at very specific regional to local needs. As a result there is a large heterogeneity of RCD approaches, with little formalized guidance on best practices, or perhaps more importantly, common pitfalls to be avoided. This creates a risk that newcomers to the field, who require local to regional climate information, utilize data from RCD methods of questionable quality, over-interpreted levels of certainty or exaggerated apparent spatial detail, with potential negative consequences for subsequent IAV assessment and planning.

Recognizing these risks, the World Climate Research Program (WCRP) established in 2008 a Task Force on Regional Climate Downscaling (TFRCD) whose mandate was to:

1) Develop a framework to evaluate and where possible improve RCD techniques for use in downscaling global climate projections
2) Foster an international coordinated effort to produce improved multi-model RCD-based high resolution climate change information and related uncertainties, over regions worldwide, for input to IAV work.
3) Promote greater interaction and communication between the climate modeling and end-user communities, in order to better support IAV activities and national to regional decision making.

The TFRCD, in consultation with the wider community, developed the Coordinated regional Downscaling Experiment, or CORDEX, framework to directly address points 1 and 2 of the mandate and to initiate efforts to address point 3. In this article we outline the aims and experimental framework of CORDEX and discuss how CORDEX relates to CMIP5 in potentially providing added-value and bridging the scale gap between CMIP5 projections and the needs of the IAV and decision-making communities. We present preliminary results from the first set of CORDEX simulations and discuss activities planned for the coming few years.

We use the term "regional" in a broad sense to indicate the entire range of spatial scales less than ~5000 km^2, or the continental scale and below. Climate change signals on these scales are primarily determined by a combination of large-scale (continental or larger) phenomena that are significantly modulated by a multitude of small scale regional forcings (e.g. topography, land-use and coastlines). While current CGCMs can capture, at least in principle, the large scale climate signals and changes therein, due to limited spatial resolution they are not able to represent the modulation of such signals by small scale forcing. Furthermore, small scale atmospheric processes play an important role in determining both the frequency and intensity of weather extremes such as extra-tropical and tropical cyclones or intense convective precipitation. It is well documented that such extreme events are more accurately simulated in numerical models as resolution is increased (Jung et al., 2006; Oouchi et al., 2006). Suitable RCD techniques can, therefore, add regional to local value to CGCM simulations, particularly in the very areas of highest interest to the IAV communities, namely local detail and at the extremes of the climate distribution. It is, nevertheless, important to underline that any potential added-value from downscaling is contingent on the quality of the large scale climate simulated by the CGCM. Furthermore, local-regional climate changes generated through downscaling should be consistent with the climate change signals seen on the larger-scales in the driving CGCM.

At the continental to sub-hemispheric scale, different CGCMs can simulate climate variability and its response to anomalous GHG forcing somewhat differently. As a result the same downscaling method driven by two different CGCMs will, and probably should, give different regional-local scale climate change signals. This fact, referred to as "model configuration" uncertainty, is one of the greatest sources of uncertainty in regional climate projections and propagates directly from the CGCM simulation to all RCD techniques. It compounds with other sources of uncertainty, such as GHG emission uncertainties, internal variability and non-linearities in the climate system and, for the downscaling problem, choice of RCD method (Giorgi, 2005) in determining the total uncertainty envelope in making regional to local scale climate projections. To provide useful and robust climate information, such uncertainties need to be fully characterized, and where possible reduced. This requires the generation of ensembles of simulations, sampling all relevant sources of uncertainty, with the goal of delivering probabilistic climate change information in the form of Probability Density Functions (PDFs). The larger the ensemble, the better the uncertainty space can be sampled and robust regional climate change projections developed. The main sources of uncertainty in regional climate change projections can be summarized as: (i) GHG emission uncertainty, (ii) CGCM differences, (iii) CGCM internal variability, (iv) RCD method/model/resolution differences and (v) RCD internal variability. Furthermore, it is also possible that systematic errors in either or both CGCMs and RCMs can affect the realism of simulated climate projections. The relative contribution of all these sources to the total uncertainty will be dependent on the region of interest.

A number of earlier projects have developed matrices of regional climate change projections that sample parts of the uncertainty space discussed above. Such efforts have occurred somewhat independent of each other, by necessity organized by geographic location and funding opportunities. Examples include the PRUDENCE (Christensen and Christensen 2007) and ENSEMBLES (van der Linden and Mitchell 2009) projects in Europe, NARCCAP (Mearns et al. 2009) in North America, RMIP over East Asia and CLARIS (Solman et al. 2009) in South America. CORDEX brings together these activities into a coordinated and shared global effort to (i) advance the science of regional climate downscaling, (ii) utilize internationally accepted RCD methods to generate regional climate change information for all terrestrial regions of the globe, plus key climate-sensitive regions such as the Arctic (iii) make these projections accessible to the IAV and decision-making communities, (iv) characterize and communicate in the most comprehensive and clear way the uncertainties in these projections; and (v) support the use of such projections in IAV research and decision-making through a sustained interaction with these communities. The core of this effort, the development of high-resolution regional climate change projections, builds directly on CMIP5 by using the set of CMIP5 multi-model, multi-RCP centennial projections as the basis for all downscaling activities. As a result, CMIP5 in combination with CORDEX will deliver coordinated sets of high-resolution regional climate change projections for all land-regions of the globe, using the most advanced CGCMs and downscaling methods for the most recent estimates of future GHG emissions and land-use change. For many areas of the world this will constitute the first ever opportunity to develop a rigorous assessment of possible future climate change at spatial scales of utility to local policy and decision makers.

Therefore, within this context CORDEX essentially has a twofold purpose to 1) provide a framework to evaluate and benchmark model performance (Model Evaluation Framework); and 2) design a set of experiments to produce coordinated climate projections and estimated uncertainties (Climate Projection Framework). Here we provide a short overview of the CORDEX framework. For a more detailed discussion the reader is referred to Giorgi et al. (2009).

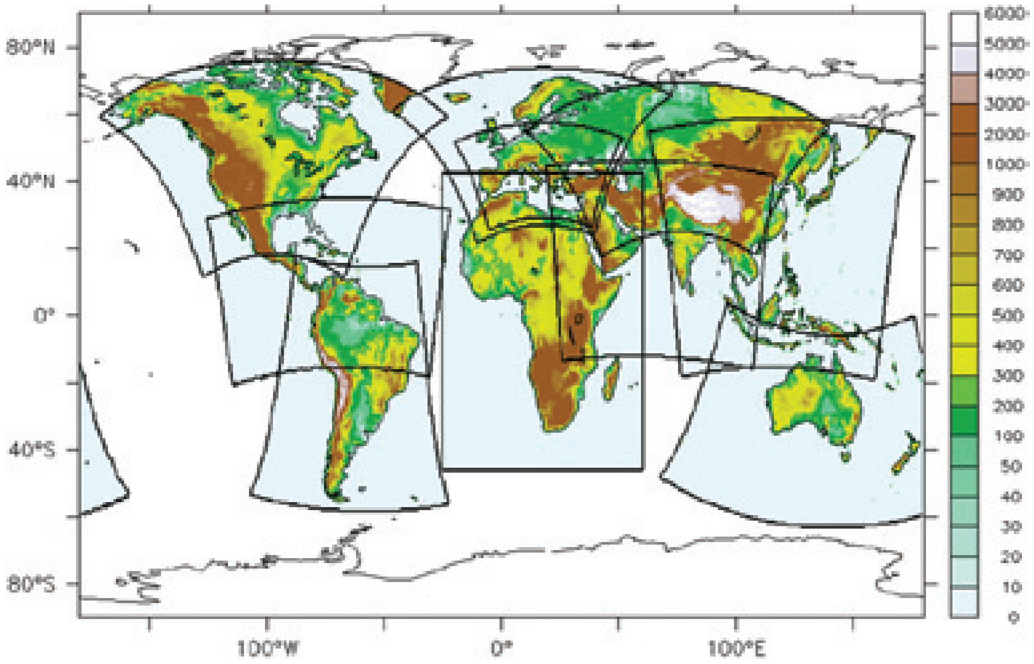

Figure 1 shows a schematic of the CORDEX RCM domains where these should be interpreted as interior analysis domains (i.e. not including the RCM boundary relaxation zone).

2.2 Model domains and resolution

The domain selection is based on a combination of physical considerations, consideration of the resources required to carry out the simulations and on the availability of existing programs. In the first phase of CORDEX the standard RCM horizontal resolution will be ~50 km. While many groups today run RCMs at significantly higher resolution, it was considered important to encourage as wide an international participation within CORDEX as possible, thereby supporting the development of a large multi-CGCM/RCD projection set for all domains. For some regions, e.g. Europe, activities are already underway to explore the benefits of increased RCM resolution (a ~10km resolution euro-CORDEX matrix will be developed) both for simulating observed regional climate processes and for the generation of a multi-CGCM/RCM matrix of future projections. For other regions such capabilities do not presently exist, it was therefore felt that a 50km resolution offered the best chance of developing a large matrix of regional projections.

2.3 Model Evaluation framework

An important first step in CORDEX is to evaluate the performance of various RCD methods for the recent past, both to help define the reliability of future projections and to identify areas requiring improvement. To facilitate this, a set of so called "perfect boundary conditions" experiments will be performed for all domains. For RCMs, lateral and surface boundary conditions from the ECMWF ERA-interim reanalysis (Uppala et al., 2008) will be used to force models over the 20-year period 1989-2008. For each region a set of evaluation and diagnostic teams are being formed whose tasks include the design of a set of benchmark regional metrics for RCM evaluation and the collection of suitable, quality-controlled observations to support this task. The evaluation metrics will consider both climate-performance metrics and metrics targeted more towards the interests of regional user groups. They will include both metrics common to all domains (e.g biases and pattern correlations) and regionally specific metrics for evaluating regionally-specific processes relevant. The evaluation/diagnostic teams will be composed of interdisciplinary groups of scientists mostly local to the region and it is envisaged that they will maintain a strong dialogue with the IAV and end-user communities for the region. The formation of such regional analysis teams is intended to serve three main purposes; 1) to evaluate the strengths and weaknesses of the down-scaled products; 2) to facilitate active participation of scientists and experts from the region in CORDEX; and 3) to contribute to the long-term and sustained training of regional climate experts who will lead analysis and interpretation of CORDEX results for use in applications specific to their own regions. This capacity building aspect of CORDEX is gaining significant endorsement and support by the regional institutions and government and non-government sponsoring organizations.

2.4 Climate projection framework

The climate projection framework is based on the CMIP5 centennial projections (Taylor et al., 2009; 2011). In particular, the latter period of the historical simulations (1950-2005) and then, in terms of priority, the 2006-2100 period of the RCP 4.5 and 8.5 projection runs, with RCP 2.6 runs being considered where available. To meet this aim, CMIP5 CGCMs are requested to save 6-hourly, global model level data suitable for forcing RCMs over the period 1950-2100 from at least 1 historical simulation, 1 RCP 4.5 and 1 RCP 8.5 projection run, with RCP 2.6 being optional. CORDEX will utilize this data to generate multi-CGCM/RCP/RCD regional climates for each of the CORDEX domains. Ideally, all RCM simulations will span the 1950-2100 period, allowing an evaluation of the simulated control climate from each CGCM-RCM couplet, as well as a continuous estimate of climate change through the 21st century. For many groups this may prove computationally too demanding, therefore a second option recommends prioritizing the period 1979-2050. In both cases a crucial step is to employ the same evaluation process, outlined in section 2.3, for each CGCM-RCM simulation and domain to fully characterize systematic errors in the downscaled climate products as a basis for quantifying the reliability of future climate simulations.

2.5 Data management

A critical aspect of CORDEX will be the management and transfer of large amounts of data. This includes the CMIP5 CGCM boundary conditions, the RCD regional climate data and the observations needed for evaluating the model performance over each region. An initial CORDEX data site has been established at cordex.dmi.dk, with other sites soon to come online. A final list of CORDEX variables to be saved, along with a designated file structure is close to being released to the RCD community. This CORDEX product list is separated into core and tier 1 variables, known to be high priority in the IAV community and necessary to evaluate the quality of RCD simulated climates. This data will be stored online at the CORDEX archives. A more detailed list of tier 2 variables, required for in-depth, process-level regional studies will initially be saved at the individual RCD-producing centres. CORDEX file structures and formats follow as closely as possible CMIP5 specifications, with the establishment of the Earth System Grid (ESG) federated node concept for the CORDEX archiving centres. The ultimate goal is to have CORDEX archiving and access as similar to CMIP5 data as possible, thereby increasing the ease of use for both data sets.

3. CORDEX-Africa: The first region targeted for coordinated downscaling.

As a framework, CORDEX will support development and coordination of downscaling activities for the coming ~5-10 years. Nevertheless, there already exists a high demand for regional to local climate information. Many of the CORDEX regions will self organize over the coming years and develop matrices of regional climate change projections that sample all or part of the uncertainty envelope described above. However, in a number of regions of the world access to reliable regional climate change information is extremely limited. One example is Africa. It is in these regions we envisage the collaboration developed through CORDEX will bring the largest benefits. With this in mind the international community decided to target Africa for an intensive

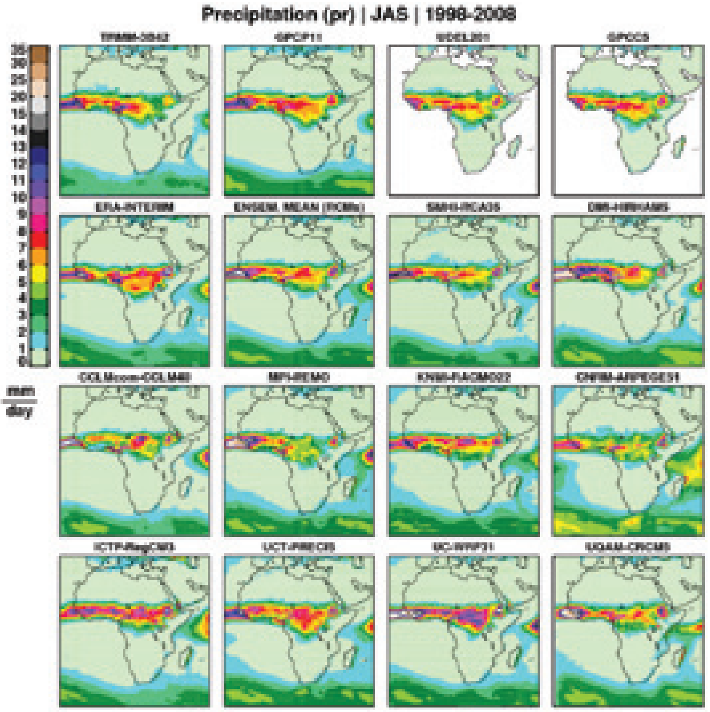

Figure 2 provides an example of the type of data that will become available through CORDEX, both for Africa and other regions of the world. We plot the July to September mean precipitation for 1998-2008. Four observational estimates are shown; the combined satellite-gauge data sets from TRMM and GPCP11, plus land-only gauge data from the University of Delaware and GPCC5, also shown is the accumulated 12-24 hour forecast precipitation from ERA-interim. We then plot the ensemble mean precipitation (from 10 RCMs) and the individual results from each model.

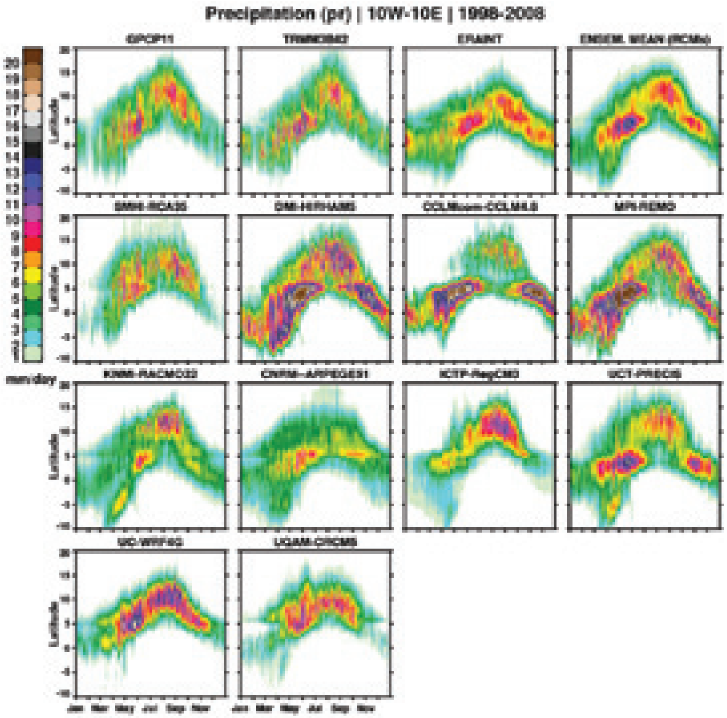

Figure 3 presents a more user-oriented region-specific output, where we assess the ability of the RCMs to simulate the onset and seasonal progression of the West African monsoon. Figure 3 shows pentad-mean rainfall, averaged over the longitude band 10°W to 10°E, plotted as a function of the annual cycle and latitude from 10°S to 20°N, averaged over 1998-2008. On the top row we plot TRMM and GPCP11 estimates, followed by the ERA-interim forecast precipitation and the RCM ensemble mean. The individual RCM results are plotted below.

collaboration over the coming 1-3 years, with an aim to produce a significant matrix of regional climate change projections, both to support the 5th Assessment report of the IPCC (IPCC AR5) and to provide useful climate information to decision-makers involved in climate risk management and adaptation planning. Africa was selected for a number of reasons. First, Africa is particularly vulnerable to climate change, because of the adverse impacts of changing climate variability on a number of vital sectors (e.g agriculture, water management, health) and because of the relatively low adaptive capacity of its economies. Second, climate change may have significant impacts on temperature and precipitation patterns over Africa which in turn can interact with other environmental stressors such as land-use change, desertification and aerosol emissions, further exacerbating the stresses on human and natural populations.

As an initial step, 10 RCM groups have downscaled ERA-interim data for 1989-2008 on the common Africa CORDEX grid. All these groups have also committed to making at least one climate projection run for the CORDEX-Africa domain, with some groups planning more than one with different CGCM forcing. A model evaluation/diagnostic team has now been formed for Africa, consisting of 30 scientists from a range of disciplines and representing the majority of sub-Saharan Africa. Similar teams are in the process of being formed for the other CORDEX domains in Asia and South America.

While there are inter-model differences, the majority of the RCMs capture the ITCZ well, with accurate estimates of seasonal rainfall amounts. In fact the ensemble mean bias, when calculated against any one of the four observation data sets, is of similar magnitude, or smaller, to the differences across the 4 observations. The main message we wish to convey at this early stage is that a lot of high quality simulated climate information will be available for the African continent within the next 12 months.

For practical use in West Africa it is important that models can simulate the onset date of the monsoon, as well as the monsoon duration, intra-seasonal variability within the monsoon season and its north-south propagation. A number of the RCMs simulate the overall monsoon cycle quite accurately, with a few capturing the northward jump in the monsoon seen in early July in the observations, the ensemble mean having a particularly good representation of this phenomenon. A feature common to a number of the RCMs is that during the southward march of the monsoon, in October to November, precipitation rates are overestimated. More work is required to fully characterize the ability of the CORDEX RCMs to simulate climate variability over Africa. This effort is underway now, in preparation for the climate projection phase of CORDEX, which will begin for Africa and other regions in the coming months.

4. Summary and conclusions

We have presented a new framework for regional climate modeling and downscaling, CORDEX, with the aims of 1) developing a coordinated framework for evaluating and improving RCD techniques; 2) producing a new generation of RCD-based fine scale climate projections for regions worldwide and 3) to promote increased interaction between the climate modeling and IAV communities. Past experience has shown that coordinated experiments, such as CMIP5, have proven invaluable to the global modeling community, both in terms of improving models and generating credible climate change projections to support international assessments. CORDEX is structured to play a similar role for the RCD community, with the extra task of developing a sustainable and productive 2-way interaction with regional and national user communities.

We have presented the basic structure and aims of CORDEX, with some preliminary example results from CORDEX-Africa, which is the first region targeted for intensive international collaboration. This selection was taken with the specific aim to deliver useable regional climate change information for Africa on the timescale of the IPCC AR5 and beyond. While an initial focus is on Africa, a number of other domains have also become rapidly active and will likely also deliver regional projections of interest to the AR5. It is however intended that CORDEX will provide a framework for RCD development and application activities well beyond AR5 and a continuous link between the climate modeling community and regional to national IAV researchers and decision-makers. We anticipate that CORDEX and associated activities will result in further development of regional networks of climate experts, who can serve as an interface between the research community and decision makers. Together these efforts aim to enhance the use of WCRP-coordinated climate simulations and information by an expanded group of practitioners, towards understanding and coping with the impacts of climate variability and change on economic and societal sectors of importance to the regions

Acknowledgements

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References

Christensen J-H and O. Christensen, 2007: A summary of the PRUDENCE model projections of changes in European climate by the end of this century. Climatic Change 81, Supplement 1, 7-30, DOI: 10.1007/s10584-006-9210-7.

Christensen, J.H., T.R. Carter, M. Rummukainen and G. Amanatidis, 2007: Evaluating the performance and utility of regional climate models: the PRUDENCE project. Climatic Change, 81, 1-6.
Deque, M. and J.P. Piedelievre, 1995: High resolution climate simulation over Europe. Climate Dynamics, 11, 321-339.

Giorgi, F., 2006: Regional climate modeling: Status and Perspectives. Journal de Physique, IV, 139, 101-118.

Giorgi, F. and L.O. Mearns, 1991: Approaches to the simulation of regional climate change: a review. Reviews of Geophysics, 29, 191–216.

Giorgi, F., and L. O. Mearns, 1999: Introduction to special section: Regional climate modeling revisited. Journal of Geophysical Research, 104, 6335- 6352.

Giorgi, F., et al., 2001: Regional Climate Information – Evaluation and Projections. Chapter 10 of: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T.,et al., eds.]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 583-638.

Giorgi, F, et al. 2008: Exploring uncertainties in regional climate change: The Regional Climate Change Hyper-Matrix Framework. EOS, 89, 445-446.

Hewitson, B.C. and R.G. Crane, 1996: Climate downscaling: Techniques and application. Climate Research, 7, 85-95.

Hewitson, B.C. and R.G. Crane, 2006: Consensus between GCM climate change projections with empirical downscaling: precipitation downscaling over South Africa. International Journal of Climatology, 26, 1315-1337.

Huntingford, C., and J. Gash, 2005: Climate equity for all. Science, 309, 1789.

IPCC 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., et al., eds.]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 940 pp.

Jung, T., Gulev, S., Rudeva, I. and Soloviov, V. 2006: Sensitivity of extratropical cyclone characteristics to horizontal resolution in the ECMWF model. Q. J. R. Meteorol. Soc., 132, 1839–1857.

Laprise, R., et al., 2008: Challenging some tenets of Regional Climate Modelling. Meteorology and Atmospheric Physics, 100, 3-22.

Leung, L.R., L.O. Mearns, F. Giorgi and R.L. Wilby, 2003: Regional climate research: Needs and opportunities. Bulletin of the American Meteorological Society, 82, 89-95.

Mearns, L.O., et al., 2003: Guidelines for use of climate scenarios developed from regional climate model experiments. TGCIA-IPCC report. Available from http://ipcc-ddc.cru.uea.ac.uk/guidelines/RCM6.Guidelines.October03.pdf, 38 pp.

Mearns, L. O., W. J. Gutowski, R. Jones, L.-Y. Leung, S. McGinnis, A. M. B. Nunes, and Y. Qian: A regional climate change assessment program for North America. EOS, Vol. 90, No. 36, 8 September 2009, pp. 311-312.

Meehl, G.A., et al., 2007: The WCRP CMIP3 multimodel ensemble – A new era in climate change research. Bulletin of the American Meteorological Society, 88, 1383-1394.

Murphy, J., 1999: An evaluation of statistical and dynamical techniques for downscaling local climate. Journal of Climate, 12, 2256–2284.Oouchi K, et al. 2006: Tropical cyclone climatology in a global-warming climate as simulated in a 20 km-mesh global atmospheric model: frequency and wind intensity analyses. J Meteorol Soc Jpn 84:259\u2013276

Schmidli, J., et al., 2007: Statistical and dynamical downscaling of precipitation: An evaluation and comparison of scenarios for the European Alps. Journal of Geophysical Research, 112, D04105.

Solman S.A, Nunez M.N and M.F. Cabré 2008: Regional climate change experiments over southern South America. I: present climate. Climate Dynamics Volume 30, Number 5, 533-552, DOI: 10.1007/s00382-007-0304-3.

Taylor, K. E., R. J. Stouffer and G. A. Meehl, 2009: A summary of the CMIP5 Experimental Design. http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2011: The CMIP5 Experiment Design. Bull. Amer. Meteorol. Soc., submitted.

Uppala S, D. Dee, S. Kobayashi, P. Berrisford and A. Simmons, 2008: Towards a climate adapt assimilation system: Status update of ERA-Interim, ECMWF Newsletter, 115, 12-18.

Van der Linden. P and J.F.B. Mitchell (eds). 2009: ENSEMBLES: Climate Change and its Impacts: Summary of Research and Results from the ENSEMBLES Project. Met Office Hadley Centre: Exeter.

Wang, Y., et al., 2004: Regional climate modeling: progress challenges and prospects. Journal of the Meteorological Society of Japan, 82, 1599-1628.

Wilby, R. L., and T. M. L. Wigley, 2000: Precipitation predictors for downscaling: Observed and General Circulation Model relationships. International Journal of Climatol., 20, 641–661,

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The Earth System Grid Federation: Software Framework Supporting CMIP5 Data Analysis and Dissemination

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5 German Climate Computing Centre (DKRZ).
6 National Centre for Atmospheric Science / British Atmospheric Data Centre (BADC).
7 National Center for Atmospheric Research (NCAR).

The Earth System Grid Federation (ESGF) is a coordinated international collaboration of individuals and institutions that is developing, deploying and maintaining software infrastructure for the management of model output and observational data. The goal of this effort is to facilitate advancements in Earth System Science. Through the ESGF alliance, governed under the Global Organization for Earth System Science Portals (GO-ESSP), the team has developed an operational system for serving climate data from multiple locations and sources. Model simulations, satellite observations, and reanalysis products will all be served from a distributed data archive. Researchers worldwide can now access ESGF data holdings through any of the gateways hosted by ESGF partners, including laboratories in the U.S. funded by the Department of Energy (DOE), the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration (NOAA), and at laboratories elsewhere, for example at the Australian National University (ANU) National Computational Infrastructure (NCI), the British Atmospheric Data Center (BADC), the Max Planck Institute for Meteorology (MPI-M) German Climate Computing Centre (DKRZ). A good place to start if one wants access to CMIP5 output is the CMIP5 website and the “getting started” document .

In planning for CMIP5, the ESGF has built on the success of the earlier Earth System Grid (ESG) project, which served CMIP3 model output and with US DOE support was led by the Program for Climate Model Diagnosis and Intercomparison (PCMDI). CMIP5 has driven all ESGF development work and has attracted the interest of others seeking to make their data widely available and easy to use (e.g., CORDEX and satellite measurements for CMIP5, discussed elsewhere in this publication (see Jones et al. and Teixeira et al., this issue).   The ESGF aims to:

- Support the current CMIP5 activity, and prepare for future assessments;
- Develop data and metadata facilities for inclusion of observations and reanalysis products in CMIP5;
- Enhance and improve current climate research infrastructure capabilities through involvement of the software development community and through adherence to sound software principles;
- Foster collaboration across agency and political boundaries;
- Integrate and interoperate with other software designed to meet the objectives of ESG: e.g., software developed by NASA, NOAA, ESIP, and the European ES-INES;
- Create software infrastructure and tools that facilitate scientific advancements.

The software deployed in ESGF has been developed using an open-source approach, and all participants are encouraged to contribute to the ongoing development of the infrastructure.

A detailed view of the components and capabilities provided by the ESGF is shown and described in Figure 1.

Not all aspects of the end-to-end preparation and archiving of CMIP5 model output are formally organized as part of the ESGF, but the entire process will be briefly summarized here . It starts with the individual modeling groups running models, following the CMIP5 experiment specifications described in Taylor et al. (2009, 2011). The CMIP5 output structure and metadata requirements ensure that analysts can read and interpret output from all models in a uniform way and is perhaps the most valuable aspect of CMIP5. A software library, called CMOR (Climate Model Output Rewriter), helps insure conformance with the requirements, while somewhat reducing the burden imposed on the modeling groups in preparing output. The simulation data, stored in files using the netCDF library and consistent with the Climate and Forecast (CF) metadata conventions , are then placed on an ESGF data node located either at the modeling center or one of the ESGF data centers. The data is then "published", which is a procedure that records information in the ESGF catalog and makes the data visible to users through ESGF gateways.

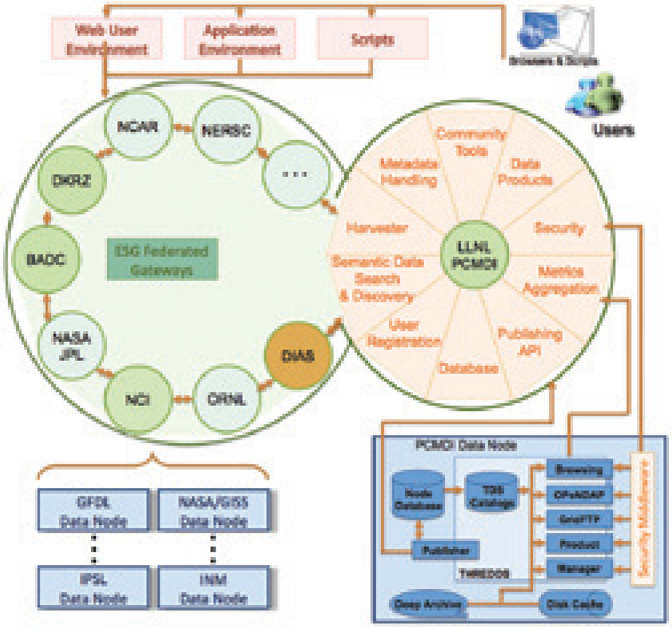

Figure 1: The figure shows how users can access ESGF data using web browsers, scripts, and soon by client applications. Conceptually, ESGF is composed of two interacting parts: ESGF gateways (indicated in green) and ESGF data nodes (indicated in blue). The expanded view shown for the gateway and data node hosted by PCMDI provides a more detailed picture of the various components and capabilities that are duplicated at the other the sites. Gateways handle user registration and management and allow users to search, discover, and request data. Data nodes are located where the data resides, allowing data to be "published" (or exposed) on disk or through tertiary mass store (i.e., tape archive) to any gateway. In addition, some advanced data nodes can handle data reduction, analysis, and visualization. ESGF currently comprises eight gateways, and four of these (indicated by darker shade of green) are special because they host replicas of a substantial number of the CMIP data sets. Users have access to all data from the federation regardless of which gateway is used.

As the modeling groups prepare the simulation output, they are expected to complete the METAFOR questionnaire (described by Guilyardi et al., this issue) whereby information is gathered to document the models and the simulations. The documentation is subsequently made accessible to users through the ESGF gateways using software developed collaboratively by the Curator, METAFOR, and ESG projects. An important new addition to CMIP5 is that a three-step quality control (QC) procedure is being applied to all model output. If the ESGF software can successfully read and obtain catalog information from the data files during "publication", then Level 1 of the QC procedure is passed. Level 2 QC involves extensive examination of metadata and data for self-consistency and conformance to standards. These quality checks are performed using the "QC Tool" developed at DKRZ. For example, a variable must have a recognized CF "standard name" attribute and its data values are checked to determine whether they fall within a range of values expected for the variable. Level 3 QC provides a few additional self-consistency checks and is passed only when the modeling group providing the data has agreed that the data should be permanently entered into the ESGF data holding (although it can subsequently be flagged as being flawed). DKRZ maintains a database of the results for every QC check performed by their tool anywhere within the ESGF archive.

For CMIP5, the ESGF may eventually archive 3 petabytes (PB, 1 PB = 10^{15} bytes) or more of officially requested data . Some simulation output is expected to be of interest to only a handful of specialists, whereas a few fields are likely to attract widespread interest (e.g., surface temperature and precipitation). To assure the high interest data are preserved and that this subset of output is readily accessible worldwide, it will be replicated by one or more of the ESGF partners. Replication does not proceed until QC Level 2 is passed.

The final step (after QC Level 3 has been passed) is to assign a Digital Object Identifier (DOI) to each dataset within the CMIP5 collection. To give appropriate credit to the data providers, these DOI's should be cited when results are published based on the CMIP5 model output.

Although some CMIP5 model simulations were completed in early 2010, it was not until March of 2011 that the first model output was published and made available to users. By May of 2011 some simulation output was available from modeling groups in the UK, Russia, France, and the U.S.A. A current list of models that have contributed to the CMIP5 archive can be found at the CMIP5 website . There are also observational datasets that will become available soon through ESGF which have been written in the same structure with similar metadata conventions as the CMIP5 model output. Teixeira et al. (this issue) describe one such effort.
At present the available CMIP5 model output can be viewed only via web browsers hosted by the following ESGF gateways, with data centers planning to replicate a significant subset of the model output highlighted by the asterisks:

- PCMDI*: http://pcmdi3.llnl.gov/esgcet/home.htm
- BADC*: http://cmip-gw.badc.rl.ac.uk/home.htm
- DKRZ*: http://ipcc-ar5.dkrz.de/home.htm
- JPL: http://esg-gateway.jpl.nasa.gov/home.htm
- NCAR: http://www.earthsystemgrid.org

- NCI*: http://esg.nci.org.au/esgcet/home.htm
- NERSC: http://esg.nersc.gov/esgcet/home.htm
- ORNL: http://esg.ccs.ornl.gov/esgcet/home.htm

Note that regardless of where data may be located, all holdings are visible at any ESGF gateway that is configured to display it. Thus a user can browse the federation's holdings from any gateway and obtain the data of interest. A help desk staffed by ESGF collaborators provides support to CMIP5 users across the federated system.

With CMIP5 data now being served, the ESGF federation is working to improve various aspects of the system by adding new capabilities that should better meet the needs of users. Among the improvements expected over the next several months are:

1. A simpler scripting method for downloading files;
2. An enhanced search capability;
3. An automatically updated table showing which simulations have been archived by each model;
4. A notification service to advise users when errors are found in datasets;
5. A straight-forward method to report errors discovered in the data and to provide feedback to the modeling groups about their simulations;
6. A list of publications based on CMIP5 model output, as recorded by users through a web form;
7. General system enhancements related to scaling to millions of datasets and petabytes of data volume;
8. An online visualization capability that will allow users quick inspection and comparison of datasets from multiple locations;
9. An enhanced capability to perform server-side data reduction and calculations, which will reduce the volume of data transferred to the users via the Internet.

References

Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2009: A summary of the CMIP5 Experimental Design. http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf.

Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2011: An Overview of CMIP5 and the Experiment Design. Bull. Amer. Meteor. Soc., submitted.

The CMIP5 model and simulation documentation: a new standard for climate modelling metadata

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9 CERFACS, Toulouse, France

Together with the data transformation towards a standard format and the archiving of output files in the distributed ESG Federation, the standard model and simulation documentation process is an essential part of the CMIP5 process. The development of the associated metadata and web questionnaire is described in this article.

Climate modelling metadata: sharing the climate scientist's notebook

The outputs of climate models are increasingly used, not only by the climate scientists that produce them, but also the growing number of stakeholders which study climate change as well as policy-makers and the enlightened public. Climate modelling data is stored in huge and complex digital repositories (Overpeck et al., 2011). Hence, archiving, locating, assessing and making sense of this unique resource requires accurate and complete metadata (data describing data). Climate model simulations, such as those prepared for CMIP5 , involve several component models (atmosphere, ocean, sea-ice, land surface, land ice, ocean biogeochemistry, atmosphere chemistry) coupled together that follow a common experimental protocol (Taylor et al., 2009; 2011). Each of these component models can be configured in many different ways, including not only different parameter values but also changes to the source code itself. Component models, or even compositions of component models, can have multiple versions, and individual component models can be coupled together and run in a myriad of different ways. The range of possibility is immense. Until now, this key information can only be found in the climate scientist's experimental notebooks, hence largely under-documented in the output data itself. Community multi-model database provided the first incentive for a common description, as for instance initially proposed for CMIP3 .

When dealing with multi-model databases, scientists and other stakeholders are increasingly faced with questions about the suitability of that data for their purposes, a question that was not addressed by these initial documentation efforts. For example, what is the difference between model A and model B? Which simulations of the 20th century have daily output data and use Turbulent Kinetic Energy (TKE) vertical mixing in the ocean? What is the grid resolution near the equator or over Europe? How does this model conform to the CMIP aerosols protocol? Are volcanoes included and how? The climate modelling community identified early the need for comprehensive and standard metadata for climate modelling to address such questions (as in the European Network for Earth System Modelling, ENES, http://enes.org). The whys and wherefores and issues associated with any particular simulation form the scientist's experiment notebook and sharing this key information widely is also a quality and transparency insurance. Proper and comprehensive climate modelling documentation will further re-enforce the maturity, credibility and openness of our science, under increased pressure from society (Carlson, 2011; Kleiner, 2011).

The EU-funded Metafor project (see Box 1) specifically addresses these challenges. Its central aim is the development of a Common Information Model (CIM) to describe climate data and the models that produce it in a standard way . The CIM is a formal model of the climate modelling process. It includes descriptions of the experiments being undertaken, the simulations being run in support of these experiments, the software models and tools being used to implement the simulations and the data generated by the software. The CIM is organised into two components: one normative artefact the UML (Universal Modelling Language) model called CONCIM or conceptual CIM and a derived XSD/XML generated automatically called the APPCIM, or application CIM. The CONCIM is independent of the application and its concepts are organised into several packages to separate different aspects of the climate modelling process: data, software, activity, grids, quality, shared (Lawrence et al., 2011).

Following this high-level work, Metafor has been charged by the Working Group on Coupled Modelling (WGCM) via the Coupled Model Inter-comparison Project (CMIP) panel to define and collect model and experiment metadata for CMIP5. Integrated in the ESG Federation, the CMIP5 metadata pipeline is described in Figure 1 and summarized below.

Developing and using the CMIP5 metadata questionnaire

The Metafor team has developed a web-based questionnaire to collect information and metadata from the CMIP5 climate modelling groups on the details of the climate models used, how the simulations were carried out, and how the models conformed to the CMIP5 protocol requirements.

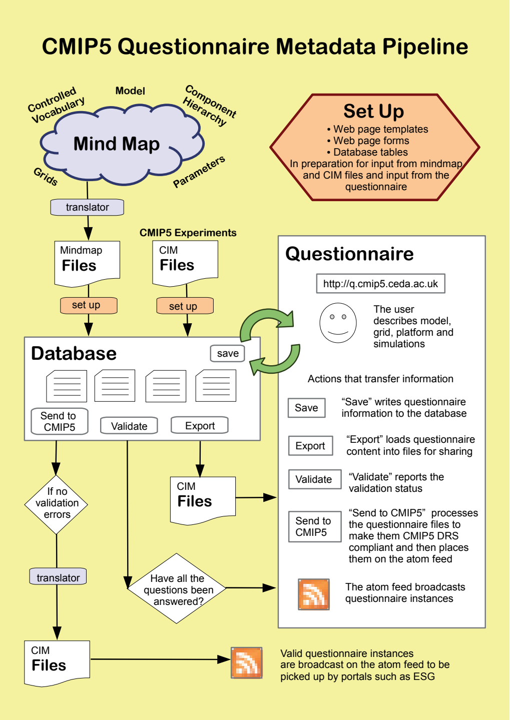

Figure 1. CMIP5 questionnaire metadata pipeline. Interviews with climate scientists helped collect basic information needed to understand models, e.g. structured and controlled vocabulary, captured in mind maps. The mind maps together with the CMIP5 protocol description are automatically transformed into a web questionnaire. Once the questionnaire is completed and validated, instances (CIM files in XML), are broadcasted and harvested by several portals (ESG Gateway, Metafor portal, vERC portal), in which the binding with the CMIP5 data files is made. See also Lawrence et al. (2011).

■ Developing standard model description with the climate modelling community

The content and structure of the model description section of the questionnaire was developed via a series of interviews with numerous climate modellers. The aim of these interviews was to find out the information that scientists need to know to be able to compare climate model simulations. Care was taken not to try to propose standards in areas where there is still active research as community agreed "standards" have yet to emerge. Besides identifying the proper questions, providing standardised responses requires specific knowledge and expertise as well as a wide community perspective. Converging on a first version proved relatively straightforward and debates among experts were easily addressed.

The interviews with domain experts were interactively summarised as mind map diagrams (Figure 2) that allowed the Metafor team to capture both the questions and the standard responses that are referred to as controlled vocabularies (CV, Moine et al., 2011). Symbols on mind map elements indicated how questions should be posed in terms of whether the users should provide one answer or many. The mind maps allowed the Metafor team not only to build up lists of controlled vocabulary, but also to build a structure for the

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[1] The Coupled Model Inter-comparison Project, Phase 5

[2] www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php

[3] "A METAFOR for climate change", International Innovation, Environment, October 2010, Research Media Ltd.

way the information about climate models would be collected. Branches in the mind maps were used to illustrate model component hierarchies, and additional formatting was used to distinguish between questions about model components, questions about individual parameters or to indicate where user input should be numeric or text (Figure 2).

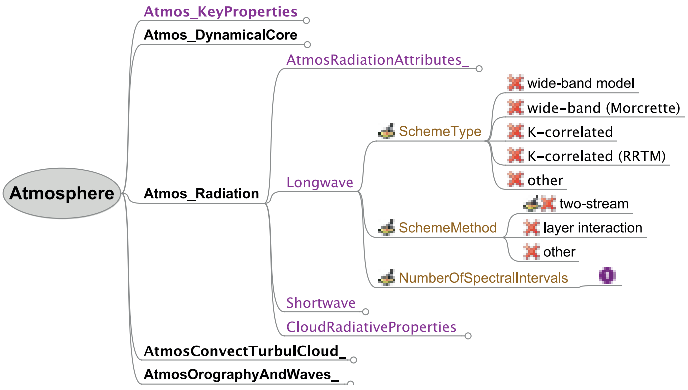
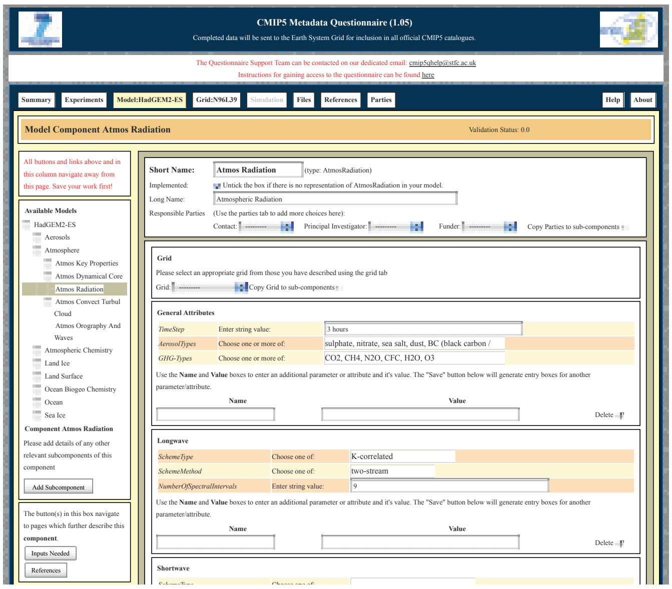


Figure 2. Example mind map for the Atmosphere longwave radiation component. Red crosses indicate that the questions about Scheme Type and Method require only one answer and the number adjacent to NumberOfSpectralIntervals indicates that numeric user input is required.

The intuitive format of the mind map diagrams enabled the scientists interviewed to give direct feedback about both the structure and content of the questionnaire and this feedback could be integrated quickly without exposing any of the questionnaire code. The current mind maps mapping the 8 realms defined by CMIP5 can be found and interactively explored under http://metaforclimate.eu/trac/browser/controlled_vocabularies/trunk/Software. This first attempt to comprehensively describe the science of an Earth System Model (it include more than 550 properties) is a unique community resource that can also be used for educational and training purposes.

■ Building the CMIP5 questionnaire

The mind maps, together with the precise CMIP5 experiment protocol description provided directly by the CMIP panel, were integrated into a web-based questionnaire. Automatic python parsing tools rendered the mind maps structure, questions and controlled vocabulary directly into the questionnaire (Figure 3) clearly separating climate science and IT concerns. The branching structure of the mind maps generated the hierarchy of model components, each with an associated web form. The branching structure also drove the tree navigator (to the left in Figure 3), which allows users to navigate directly to a particular model component. The controlled vocabulary captured in the mind maps generated the questions about the model components and also populated the drop-down lists of standardised responses for each web form. Attached notes in the mind maps appear as explanation tool tips in the questionnaire.



CMIP5 Metadata Questionnaire (1.05)

Completed data will be sent to the Earth System Grid for inclusion in all official CMIP5 catalogues.

The Questionnaire Support Team can be contacted on our dedicated email: cmip5qhelp@stfc.ac.uk

Instructions for gaining access to the questionnaire can be found here

Model Component Atmos Radiation Validation Status: 0.0

All buttons and links above and in this column navigate away from this page. Save your work first!

Available Models

- HadGEM2-ES
  - Aerosols
  - Atmosphere
    - Atmos Key Properties
    - Atmos Dynamical Core
    - Atmos Radiation
    - Atmos Convect Turbul Cloud
    - Atmos Orography And Waves
  - Atmospheric Chemistry
  - Land Ice
  - Land Surface
  - Ocean Biogeo Chemistry
  - Ocean
  - Sea Ice

Component Atmos Radiation

Please add details of any other relevant subcomponents of this component

The button(s) in this box navigate to pages which further describe this **component**.

Short Name: Atmos Radiation (type: AtmosRadiation)

Implemented: Untick the box if there is no representation of AtmosRadiation in your model.

Long Name: Atmospheric Radiation

Responsible Parties (Use the parties tab to add more choices here):

Contact: --------- Principal Investigator: --------- Funder: --------- Copy Parties to sub-components

Grid

Please select an appropriate grid from those you have described using the grid tab

Grid: --------- Copy Grid to sub-components

General Attributes

TimeStep	Enter string value:	3 hours
AerosolTypes	Choose one or more of:	sulphate, nitrate, sea salt, dust, BC (black carbon /
GHG-Types	Choose one or more of:	CO2, CH4, N2O, CFC, H2O, O3

Use the **Name** and **Value** boxes to enter an additional parameter or attribute and it's value. The "Save" button below will generate entry boxes for another parameter/attribute.

Name **Value** Delete

Longwave

SchemeType	Choose one of:	K-correlated
SchemeMethod	Choose one of:	two-stream
NumberOfSpectralIntervals	Enter string value:	9

Use the **Name** and **Value** boxes to enter an additional parameter or attribute and it's value. The "Save" button below will generate entry boxes for another parameter/attribute.

Name **Value** Delete

Shortwave

Figure 3: Screen shot of the CMIP5 questionnaire. This screen shot shows part of the entry form for describing the longwave atmosphere radiation scheme; it is generated from the mind map shown in Figure 2.

The questionnaire also allows users to enter descriptions of components that are not covered by the mind maps (see "blank" forms in Figure 3). The mind map controlled sections of the questionnaire ensure that a standardised set of metadata about each of the CMIP5 model is collected. However the questionnaire is flexible enough to allow users to describe their models in more detail if they wish. Additional terms entered by users will inform the future externally governed controlled vocabularies used by the Metafor Common Information Model (CIM).

Detailed technical information about the questionnaire and its implementation can be found in the questionnaire help documentation, in the Metafor document repository (http://metaforclimate.eu/Documents.htm) and in Moine et al. (2011). The separation of concerns described above, coupled with the generic implementation of the questionnaire as a whole, allows the questionnaire to be 'specialised' for other metadata collection projects through the supply of different controlled vocabularies, as currently developed within the Metafor and IS-ENES European projects for non-CMIP5 applications.

- Using the CMIP5 questionnaire

The CMIP5 metadata questionnaire was launched in Nov 2010 (http://q.cmip5.ceda.ac.uk), and is now in use by most of the CMIP5 modelling centres. Box 2 presents a short introduction to questionnaire use. The process to gather the required information represents a significant investment from modelling groups. First experience by several groups indicates that several weeks of interviews of many experts are likely needed, even though the process of filling up the questionnaire once that information is obtain is relatively straightforward. This information will represent the public documentation of the models and simulations provided by the modelling groups to the wider community and stakeholders. To ensure this metadata is provided in time for the analysis stage of CMIP5, Metafor offers comprehensive user support. Help systems and documentation have been developed by a dedicated team to support the users of the questionnaire. These include a dedicated email address solely for questionnaire issues (cmip5qhelp@stfc.ac.uk) and webcasts and interactive web seminars to publicise and train users of the questionnaire. A CMIP5 Questionnaire helpdesk handles all queries relating to the metadata requirements for CMIP5 and ensures replies within two working days.
Once a questionnaire instance has been completed, it is validated against a set of validation rules. The first of these is to ensure completeness of the information so that a comprehensive description is provided, while the second is to ensure consistency between related elements of metadata so that this description is meaningful. Validation may be performed at any point during the completion of a questionnaire and provides the user with an indication of the extent to which the metadata provided constitutes a valid metadata record, and a guide as to how much more information will be required before this is the case.

Once questionnaire instances have been validated into CIM XML standard instances, they are made freely available on the questionnaire atom feeds (Figure 1). The content of the questionnaire instances will be hosted and displayed in the ESG Gateway hosted by the Program for Climate Model Diagnosis and Intercomparison (http://pcmdi3.llnl.gov/esgcet/). The Curator project has worked closely with the ESG team and METAFOR to develop a metadata display for ESG, and to complete a metadata pipeline that takes questionnaire output and propagates it through the PCMDI or other (ENES's vERC, Metafor) portals (Figure 1).

Looking ahead

This first comprehensive metadata collection for climate modelling is an ambitious undertaking by the community and, used for CMIP5, will provide the most comprehensive metadata of any climate model inter-comparison project. Because it is a pilot project, many aspects will need to be revisited after this first experience, coupled with the need for a governance structure to both maintain and develop the CIM and the associated controlled vocabularies. Discussions are underway on how to best organise this important legacy of the EU Metafor and US Curator projects. Looking beyond CMIP5, the CIM and the associated standards have the ambition to become more ingrained within modelling groups (as with netCDF/CF) as a means of automatic documenting of model configurations and simulation runs (as currently planned by the Hadley Centre, NCAR, IPSL and other modelling.

Acknowledgements

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References

Carlson, D., 2011: A lesson in sharing. Nature, 469, 293, doi:10.1038/469293a.

Kleiner, K., 2011: Data on demand. Nature Climate Change 1, 10–12. doi:10.1038/nclimate1057.

Overpeck, J.T., G. A. Meehl, S. Bony, and D. R. Easterling, 2011: Climate Data Challenges in the 21st Century. Science, 331, 700-702, doi: 10.1126/science.1197869.

Moine, M.P., C. Pascoe, A. Alias, V. Balaji, P. Bentley, G. Devine, R. Ford, E. Guilyardi, B. N. Lawrence, S. Valcke, 2011: Development and Exploitation of a Controlled Vocabulary in support of Climate Modelling, IEEE, submitted.

Lawrence, B.N., V. Balaji, P. Bentley, S. Callaghan, C. DeLuca, S. Denvil, G. Devine, M. Elkington, R. Ford, E. Guilyardi, M. Lautenschlager, M. Morgan, M.-P. Moine, S. Murphy, C. Pascoe, H. Ramthun, P. Slavin, L. Stenman-Clark, F. Toussaint, A. Treshansky and S. Valcke, 2011: Describing Earth System Simulations, IEEE, submitted.

Taylor, K. E., R. J. Stouffer and G. A. Meehl, 2009: A summary of the CMIP5 Experimental Design. http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2011: The CMIP5 Experiment Design. Bull. Amer. Meteorol. Soc., submitted.

Box 1: The METAFOR project

"The Common Metadata For Climate Modelling Digital Repositories" (METAFOR http://metaforclimate.eu, 2008-2011) is a Europe-US collaboration project that seeks to address the problems associated with metadata (data describing data) identification, assessment and usage. This 2.5 M€ project, which groups 12 institutions, is led by Prof. Eric Guilyardi from NCAS-Climate/University of Reading and managed by Dr. Sarah Callaghan from BADC. Metafor has developed a Common Information Model (CIM, currently at version 1.5) to standardise descriptions of climate data and the models that produce it. METAFOR has secured a mandate from the World Climate Research Programme's Working Group on Coupled Modelling (WGCM) to define and collect model and experimental metadata for the Coupled Model Intercomparison Project Phase 5 (CMIP5) project. METAFOR is taking the first step in doing for climate data what search engines have done for the Internet: putting users of climate data in touch with the information they need.

Box 2: Filling up the CMIP5 metadata questionnaire: a user perspective

Charlotte Pascoe and Gerry Devine, in charge of the CMIP5 questionnaire user support group.

The CMIP5 metadata questionnaire can be accessed at http://q.cmip5.ceda.ac.uk. Although the different sections of the questionnaire can, to some degree, be completed in any order, following a suggested route can significantly reduce the time needed. Initially users are advised to complete their range of auxiliary information, namely references (publications, web pages etc), files (that have been used as inputs to models for example), and details of those responsible parties, whether an institution or individual scientists, involved in the centre's CMIP5 simulations. Having this information completed prior to filling out the more complex sections of the questionnaire means that this information is on hand to attach directly to, for example, the different component sections of the model.

Having completed the auxiliary information, it is then suggested that users complete the descriptions of the different grids that they have used as well as the computing platforms on which their simulations have been deployed. The next step is to complete the description of the climate model itself and, naturally, is where the largest investment of time will occur. Within the model section of the questionnaire, the users will be able to navigate the different components using the navigation tree on the left-hand panel. Users are free to fill out the details of each component in any order they see fit and will in general, for each component, be asked to provide some high-level information, name, description, references etc, more intricate questions about the properties of each component (driven primarily by the mind maps), and details of how this component is traditionally coupled to other components. There are currently 8 top-level 'realm' components each of which has on average approximately 6 or 7 sub-components.

The final stage of the questionnaire is to complete the information about the climate simulation itself. To do so, it is required that the model and platform description have already been initiated. In the simulation section, the user will fill out the 'specifics' of the modelling workflow, e.g. the particular CMIP5 experiment that the model was run, details of how long, or over what time period, the model was run for, any configured model settings imposed for this particular model run, as well as giving details of how the simulation conformed to those requirements that the CMIP5 experiment requested.

At any stage of the process, the user can return to a 'summary' page that details all the grids, platforms, models, and simulations that are currently being documented for that particular centre. From this same page, a user can create a duplicate copy of, for example, a previously completed grid, to act as a starting point for a new, but similar in nature, grid description.

The questionnaire has a "Test centre" area where users can experiment before filling out information in their own respective centre pages, and a read-only "Example centre" which gives examples of the sorts of information that is expected. The Test and Example centres are freely accessible but only those users who have an OpenID issued by an ESG Federation OpenID provider can request access to individual modelling centre pages. The Example centre contains a read-only example of elements of the questionnaire (kindly provided by the UK Met Office Hadley Centre which already completed the description of its models and several experiments).

Satellite Observations for CMIP5 Simulations

Joao Teixeira[1], Duane Waliser[1], Robert Ferraro[1], Peter Gleckler[2], Gerald Potter[3] and colleagues

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3 NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Summary

The objective of this project is to provide the community of researchers that will access and evaluate the CMIP5 climate model results access to analogous sets (in terms of variables, temporal and spatial frequency, and periods) of satellite observational data. This activity is being carried out in close coordination with corresponding CMIP5 modeling activities and directly engages the observational (e.g. mission and instrument) science teams to facilitate production of the corresponding data sets and associated documentation.

Background

Observations play an essential role in the development and evaluation of climate modeling systems. In particular, observations from satellite platforms often provide a global depiction of the climate system that is uniquely suited for these purposes.

The goal of this project, funded by the National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE), is to provide selected satellite observations for the diverse research that will result from the 5th phase of the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP5). This standard experimental protocol facilitates the community-based study of coupled earth system model simulations, and is expected to be a centralizing resource for the upcoming 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5).

Taylor et al (2009) describe in detail the protocol for CMIP5, which defines the scope of the simulations that will be undertaken by the participating modeling groups. For several of the prescribed retrospective simulations (e.g, decadal hindcasts, AMIP and 20th Century coupled simulations), observational data sets can be used to evaluate and diagnose the simulation outputs.

However, the pertinent observational data sets to perform these particular evaluations have not been optimally identified and coordinated to readily enable their use in the context of CMIP5

Main Tasks

Given the importance of the observations to the assessment process, along with the range and complexity of the observational datasets needed for a robust assessment, a simple framework to identify, organize and disseminate them for CMIP5 is currently underway in this project.

The CMIP5 simulation protocol (Taylor et al., 2009; 2011) is utilized as the guideline for deciding which observations to stage in parallel to the model simulations – in particular: which variables, and for what periods, temporal frequencies, and spatial resolutions. A planning workshop sponsored by NASA and the DOE, that brought together experts in satellite observations and in climate model diagnostics, was organized at the Program for Climate Model Diagnosis and Intercomparison (PCMDI) at Lawrence Livermore National Laboratory in October 2010 (Gleckler et al., 2011).

The main tasks of the project have been defined as:

(i) To work with the modeling, observational and assessment communities to identify the potential data sets for model evaluation and diagnostics;

(ii) To work with the observational teams to establish the necessary metadata information for the candidate observational datasets while documenting as best as possible the relative quality of the observations and their applicability for direct comparison to model quantities, and producing a technical document addressing these issues;

(iii) To work with the observational science teams to facilitate production of the identified datasets, with the needed characteristics (variables, periods, resolutions) and formats (e.g. CF compliant);

(iv) To organize these datasets and provide a strategy for accessing them that closely parallels the model data archive.

These goals are being achieved by directly involving the large variety of groups that are the originators of these observational datasets. A variety of instrument/mission and data products is being considered and are currently being worked on. The technical documentation synthesizing the most essential information needed by analysts such as 'measurement-to-product' processing, sampling influences, and known uncertainties is being produced. The initial set of satellite observations from this activity – which is expected to grow over time and for future assessments - will be directly accessible from the Earth System Grid supporting CMIP5, providing a readily accessible and focused resource for climate model evaluation. Along with the desire to have this activity serve as a means for observations to inform model development and evaluation, it is hoped that it will lead to more feedback from the model development community into the formulation of new satellite observational systems.

References

Gleckler, P., R. Ferraro and D. Waliser, 2011: Better use of satellite data in evaluating climate models contributing to CMIP and assessed by IPCC: Joint DOE-NASA workshop; LLNL, October 12-13, 2010. EOS, in press.

Taylor, K. E., R. J. Stouffer and G. A. Meehl, 2009: A summary of the CMIP5 Experimental Design. http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2011: The CMIP5 Experiment Design. Bull. Amer. Meteorol. Soc., submitted.

ESA Climate Change Initiative: Challenging climate models with observations

Paul van der Linden[1] and Roger Saunders [1]

1 Met Office, UK

Summary

The European Space Agency (ESA) under its Climate Change Initiative (CCI) is leading a project that aims to produce high-resolution temporal and spatial climate observations from satellite data, for more than ten variables. The climate observations output is being produced for use by climate research scientists in general and climate modellers in particular. An interface between the teams in the CCI, who are processing the satellite data to produce climate observations, and the climate modelling community is provided through the Climate Modelling User Group (CMUG). The CMUG are working closely with the all parties to ensure the expectations of the climate modelling community are met.

Climate Modelling User Group

The Climate Modelling User Group (CMUG) consists of a consortium of European climate modelling and reanalysis centres which are the Met Office Hadley Centre, Max Planck Institute for Meteorology, MétéoFrance and ECMWF. It ensures a climate system perspective at the centre of the ESA CCI by providing a forum for the climate observation dataset producers and the climate modelling community to help develop the products in meeting user expectations. A core activity is for the CMUG to assess the climate observation datasets generated by the CCI projects for climate research applications by using them for model validation, assimilation and long term trend analysis. Also the CMUG will play the role of highlighting the benefits of the new CCI datasets to the climate modelling community to ensure they are exploited as soon as possible once released.

Project Overview

The CMUG has six main areas of activity as follows:

1. Refining of scientific requirements derived from the Global Climate Observing System (GCOS) for climate modellers

The starting point for CMUG was the set of user requirements generated by GCOS who canvassed the needs of the climate research community with respect to satellite-derived observational datasets. Given that the needs and expectations of climate modellers for satellite observational data will change over time, the CMUG conducted an in depth survey across this user group at individual, institutional, programme and international organisational levels.

2. Provide technical feedback to CCI projects

The ten individual CCI projects have also generated their own user requirements and product specifications, and the CMUG has started providing feedback to ESA on them from the point of view of climate modelling applications. One important requirement was the inclusion of error characteristics in the products that need to be well defined and consistent for all the climate observation data produced.

3. Assess the global satellite climate data records (CDRs) produced from the 10 CCI projects

The climate data records produced by the CCI projects will be assessed in terms of their suitability for climate modelling applications. For some datasets observation simulators will be developed to optimally compare the satellite product with the model equivalent variable.

4. Look specifically at required consistencies across CDRs from a user viewpoint

There are several ways in which the CMUG is working with the CCI projects to ensure consistency. Firstly through ensuring common input datasets are used for CDR creation and in some cases common pre-processing (e.g. geolocation, land/sea mask, cloud detection). Secondly through comparisons of CDRs for different projects (e.g. SST, sea-level, sea-ice and ocean colour) to make sure major phenomena (e.g. El-Nino, polar vortex, etc) are consistent between ECV datasets. Thirdly through comparisons of CDRs with model fields (e.g. GHG and Ozone CDRs and MACC model profiles/total column amounts). Fourthly through studying teleconnections (e.g. El-Nino SST shows consistent impact on cloud fields, fires, etc) and finally through assimilation of CDRs and assessment of their impact on the model analyses and predictions (e.g. SST in ERA-Interim).

5. Interact with related climate modelling and reanalysis initiatives

There are a number of important activities the CMUG aims to provide input to, for example a precursor data set is being produced to support the model intercomparison assessment in the fifth phase of the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP5). The next generation reanalysis (ERA-CLIM) is now underway at ECMWF and these new datasets will provide an important input for assimilation or specification of the model boundary conditions.

6. Promote and report on the use of the CCI datasets by climate modellers

Once the new satellite datasets are available the CMUG will promote their use to the climate modelling community through demonstrating their unique qualities, ease of use and initial successes. A workshop is planned in 2013 at the end of the initial 3 year phase of the CCI projects to increase awareness of the datasets to the climate modelling community.

Requirements of the climate modelling community

One of the initial tasks of the CMUG was to consult the climate modelling community to gather its requirements. These requirements were then compared with the GCOS requirements and those gathered by the CCI projects. The main message from this combined result is that the majority of climate modellers want to use the CCI datasets for model validation, process studies and development, some for initilisation and prescribed conditions, and only a few for climate monitoring activities.

All users canvassed expressed the need for the observation datasets to include uncertainty estimates. Some users want access to raw level 1 products in addition to the level 2 products as provided by the CCI projects. While another clear message is for the CCI datasets to be provided in NetCDF–CF format with parameter naming following the convention developed in the CMIP5 project. Requirements for map projections, metadata and easy data access have also been described by users

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An update from the CLIVAR global modeling working groups: WGCM, WGSIP and WGOMD

Anna Pirani[1]

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1 CLIVAR, hosted by ICTP, Italy

JSC/CLIVAR Working Group on Coupled Modeling (WGCM)

The 14th Session of WGCM took place on 4-6 October 2010, hosted by the UK Met Office, Exeter, UK. The presentations and report are available here: http://www.clivar.org/organization/wgcm/wgcm-14/wgcm14.php. WGCM's partners (including IGBP-AIMES, CLIVAR, GEWEX, SPARC, CliC, WGNE, WOAP, IDAG) and the global modelling centres reported on their activities of relevance to CMIP5 and progress in model development. The CMIP5 discussion included the prospects and coordination of analyses across the different CMIP5 components and recommendations for analysts. WGCM encouraged the CMIP5 partners to pledge introductory/overview papers on the components of CMIP5 that they are leading in an effort to facilitate the assessment process by IPCC author teams in the IPCC Fifth Assessment Report (AR5).

In addition to the CMIP5 suite of experiments, the following are WGCM-endorsed community coordinated projects that are modeling activities encouraged by WGCM and synergistically built on the CMIP5 experiment framework:

- Atmospheric Chemistry and Climate MIP (ACC-MIP)
- Climate-system Historical Forecast Project (CHFP)
- Cloud Feedback Model Intercomparison Project (CFMIP)
- Coordinated Regional climate Downscaling Experiment (CORDEX)

- Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP)
- Geoengineering Model Intercomparison Project (GeoMIP)
- Paleoclimate Modelling Intercomparison Project (PMIP)
- Transpose Atmposphere Model Intercomparison Project (Transpose-AMIP)

Many of these projects have contributed a set of core experiments to the CMIP5 suite of experiments (see some contributions in this issue, for example) for all modelling groups to participate in.

Discussions also addressed how to promote and facilitate model development, how to benefit from CMIP5 analyses and the implications for WCRP modelling coordination. Model errors and biases are key limitations of the skill of model predictions over a wide range of time and space scales. This is not a new story and increased resolution and the addition of complexity in ESMs have not solved the problem. Identifying these errors and understanding their root cause constitutes a prerequisite for the planning of model improvement activities. For this purpose WGCM and the WCRP/CAS Working Group on Numerical Experimentation (WGNE) initiated in 2009 a WCRP-WWRP-THORPEX[1] "bottom-up survey" about the key deficiencies of numerical weather prediction (NWP) and climate models. The survey solicited input on problems identified in operational NWP and seasonal prediction centers as well as deficiencies identified for the current generation of climate models by modelers and analysts of CMIP3 simulations.

Some general issues that were raised in the responses are the imbalance between visibility and effort between work on hot new topics compared to long-standing errors, that resolution is often portrayed as the solution to everything, while it can lead to new problems, the imbalance in the maturity and size of efforts in evaluating model components (e.g. atmosphere vs. biogeochemistry) and the need for more interdisciplinary interactions. The survey sought to identify what are the key uncertainties and deficiencies of current models, for example in terms of parameterizations and interactions among processes, where the key areas that should be prioritized by the modeling, process study and observations communities and whether there are resources, such as new observations or results, that should be exploited by the wider community.

The survey received over 120 responses, with about 20 group- or lab-wide responses. The majority of the individual responses came from outside the WCRP panels and working groups; an encouraging result for a survey that aimed to consult the baseline scientific community. The promotion of growth of the model development community was clearly encouraged, as was increased synergy across climate to weather prediction scales and across the modeling, process study and observations communities. The survey results are being analyzed and presented, but the survey will continue to remain open to additional contributions.

CLIVAR Working Group on Seasonal to Interannual Prediction (WGSIP)

The 13th Session of WGSIP was held on 29-31 July 2010, in Buenos Aires, Argentina, hosted by the Comisión Nacional de Actividades Espaciales (CONAE), the Servicio Meteorológico Nacional (SMN), and the Instituto Tecnológico Buenos Aires (ITBA). The meeting took place simultaneously with the 13th Session of the CLIVAR Variability of the American Monsoon System (VAMOS) panel, with the two groups meeting for a joint session on the final day. The presentations and report are available here: http://www.clivar.org/organization/wgsip/wgsip13/wgsip13.php.

The main topics for discussion were the Climate-system Historical Forecast Project (CHFP) and the coordination of decadal prediction experiments as part of CMIP5, in collaboration with WGCM. The CHFP data set is being hosted by the Centro de Investigaciones del Mar y la Atmósfera (CIMA), Argentina and will be available in 2011. Links to WWRP TIGGE[2] were discussed in relation to the development of 1-90 day prediction capabilities. The use and need for seasonal to interannual data by seasonal applications, WMO Regional Climate Outlook Fora (RCOF) and climate services were also discussed. The joint WGSIP-VAMOS meeting focused on the implementation of the VAMOS Modeling Plan and on initiating VAMOS-WGSIP collaboration in the analysis of the CHFP over the Americas.

The CHFP is a WCRP-wide, multi-model hindcast experiment incorporating all physical elements of the climate system, designed to test the hypothesis that maximum predictability has not been reached yet by seasonal forecast systems. The project is exploring additional sources of predictability from initializing the land surface, cryosphere, and stratosphere. These experiments provide a baseline assessment of current seasonal prediction capabilities using the best available models of the climate system and data for initialisation, as well as of climate models in seasonal prediction mode. They provide a framework for assessing of current and planned observing systems, and a test bed for integrating process studies and field campaigns into model improvements.

There are various components of the CHFP. The Stratosphere-HFP will be an assessment of the impact on surface forecast skill of raising the atmospheric model lid for a more accurate representation of the stratosphere and its initialization. These experiments will also be comparable to CMIP5 simulations that will have both high and low top models. The Global Land-Atmosphere Coupling Experiment (GLACE-2) is an international project aimed at quantifying the soil moisture impacts on prediction skill and is the GEWEX contribution to the CHFP. The overall goal of GLACE-2 is to determine the degree to which realistic land surface (soil moisture) initialization contributes to forecast skill (rainfall, temperature) at 1-2 month leads, using a wide array of state-of-the-art forecast systems. The results highlight the potential usefulness of improved land surface state observational networks for prediction. The Sea ice-HFP is a

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[1] World Climate Research Programme (WCRP)-World Weather Research Programme (WWRP)- The Observing System Research and Predictability Experiment (THORPEX)

[2] TIGGE – the THORPEX Interactive Grand Global Ensemble

preliminary study on the impact of initializing aspects of the cryosphere. Some simple sea-ice experiments have been proposed of parallel runs with and without initialization. An analysis of what is being done by groups that are participating in CHFP, together with idealized experiments where the initialization is used or switched off of case study years, for example with high or low Arctic Ocean sea ice area, will provide an evaluation of current initialization capabilities. For more information on the CHFP, see: http://www.clivar.org/organization/wgsip/chfp/chfp.php.

WGSIP and WGCM share a common interest in the decadal prediction problem. A limited lifetime panel of experts has been set up with representatives from both working groups to oversee the CMIP5 decadal prediction experiments: the WGCM-WGSIP Decadal Climate Prediction Panel (DCPP). The DCPP will act as a point of contact for questions related to CMIP5 decadal climate prediction, for example on methods, validation, evaluation, scores, etc. The DCPP will also distribute relevant recommendations from WGCM and WGSIP to the broader community. It will aid the coordination of meetings and workshops, including the 2011 Aspen Global Change Institute workshop on decadal prediction and the analysis of the CMIP5 decadal climate prediction results by fostering collaboration with other CLIVAR Working Groups and Panels. It will provide input to the IPCC Chapter 11 on Near-term Climate Change: Projections and Predictability. For more information see here: http://www.wcrp-climate.org/decadal/index.shtml.

Several centres are now contributing real time decadal prediction information to an experimental forecast exchange initiative initiated by the UK Met Office. This experimental activity will help to identify the level of consistency and multimodel spread in decadal predictions. It compliments the CMIP5 initiative described above which deals mainly with hindcast information.

Anther area of focus for WGSIP is the integration of seasonal forecast systems with applications models. The integration of dynamic disease models with seasonal lead-time ensemble prediction systems has been developed over the last 10 years, particularly for malaria. The knowledge of integrating disease and climate models has been transferred to projections of diseases such as blue tongue, and seamless ensemble prediction systems ranging across days to decades are being developed for use with disease models. As a result of this work, there is more interaction with users than in the past. However more is needed to widen participation through the use of state of the art climate datasets. Many users continue to use older datasets, often supplied through an intermediary. In addition to the challenge of facilitating access to climate data, emphasis should be placed on the recommendation that applications models should use multi-model ensembles where possible. These issues are inextricably linked to the development of Climate Services at a national and international level. WGSIP can contribute, sharing good practice recommendations, climate datasets and helping to connect the Climate Services agenda with the impacts community building on experiences learned from operational seasonal prediction services.

CLIVAR Working Group on Ocean Model Development (WGOMD)

The 9th WGOMD meeting was held on 23-25 September 2010 at NCAR in Boulder, USA. The presentations and reports are available here: http://www.clivar.org/organization/wgomd/wgomd9/wgomd_ncar.php. The meeting focused on the Co-ordinated Ocean-ice Reference Experiments (CORE), particularly on the CORE-II protocol and plans for coordinated analysis, as well as the status and developments of the CORE interannual forcing (IAF) dataset and the Repository for Evaluating Ocean Simulations (REOS). The WGOMD meeting was preceded by the WGOMD-GSOP[3] Workshop on Decadal Variability, Predictability and Predictions: Understanding the Role of the Ocean, which was held on 20-23 September 2010 (www.clivar.org/decadal.php).

WGOMD also had joint sessions with the DIMES Project[4] and the US CLIVAR Working Group on Decadal Predictability (WGDP). The former brought together modelers and observationalists and stimulated an exchange of information about how current models treat isopycnal and diapycnal mixing and what the state of observations is in the Southern Ocean. The joint session with WGDP gave an overview of some proposed decadal variability diagnostics and a discussion possible uses of CORE-II forced experiments.

The CORE-II experiment consists of ocean-only or ocean-sea-ice hindcast simulations forced with the CORE interannually varying atmpospheric forcing data set. See here for more information: http://www.clivar.org/organization/wgomd/core/core.php. The atmospheric forcing data set covers the 1948-2007 period and provides a common framework for assessing the robustness of model solutions subject to identical forcing data sets. Moreover, the hindcast solutions at particular dates can be used to initialize ocean and sea-ice models for decadal prediction experiments as an alternative to the reanalysis approach. The CORE-II baseline experiments will be complemented by sensitivity studies on model numerics, physics, and various aspects of the forcing. Particular attention will be paid to the period after 1984 – as all the forcing fields have true interannual variability only after this date – providing comparisons to available ocean state estimates and observations. The analysis will cover time-mean diagnostics over 1988-2007, variability defined with respect to the 1988-2007 mean, and trends and changes over this period. Regional case studies will contribute to understanding of observed variability, such as changes in the strength of the Atlantic sub-polar gyre, dynamic-thermodynamic induced variations in sea level, the role of spatial model resolution, and variability of the Atlantic Meridional Overturning Circulation. These CORE-II simulations can also explore sensitivity in the climate system, for example due to changes to precipitation at high latitudes, changes in zonal wind trend over the Southern Ocean, and the role of buoyancy and mechanical forcing for abrupt climate shifts.

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[3] CLIVAR Global Synthesis and Observations Panel (GSOP)

[4] Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES)

The World Climate Research Programme (WCRP) will hold an Open Science Conference (OSC) with the theme of "Climate Research in Service to Society" and will commemorate the 30th anniversary of WCRP. This large and unique assembly of the international scientific community will identify key scientific challenges and opportunities to advance understanding and prediction of variability and change of Earth's climate system on all space and time scales. It will also stimulate new projects and initiatives to help WCRP coordinate national efforts and advance its scientific objectives.

Specifically, the OSC will:

- Identify key opportunities and challenges in observations, modeling, analysis and research required to understand and predict responses of the Earth system to climate variability and change;
- Provide an internationally-based "state of knowledge" for the upcoming fifth assessment report of Inter-governmental Panel on Climate Change (IPCC);
- Facilitate cross-coordination among scientific disciplines involved in the WCRP, as well as with other international research programmes, including the Earth System Science Partnership (ESSP); the World Weather Research Programme (WWRP) and other global changes research programs; and
- Help WCRP identify the information needs required to reduce vulnerability of people, ecosystems and infrastructure to high impact weather and climate events and to build more sustainable systems.

CONFERENCE PROGRAM

The WCRP OSC is organized around daily themes that reflect integrative aspects of the WCRP programme, as well as connections to other international research programmes. Each day will consist of plenary presentations and discussions by leading scientists and conference participants who are informed by community-based position papers. The plenary sessions will be followed by parallel and poster sessions, which will be the primary means for conference participants to present their research findings. The poster sessions will have their own dedicated time for viewing and one-on-one discussions with authors, thus avoiding overlap with the plenary and parallel sessions. Moreover, groups are encouraged to self-organize and submit cluster of posters addressing a specific topic, preferably as part of one of the planned sessions. All sessions are structured to foster discussion and dialogue.

DAILY THEMES

- The Climate System Components and Their Interactions
- Observation and Analysis of the Climate System
- Assessing and Improving Model and Predictive Capabilities
- Climate Assessments and Future Challenges
- Translating Scientific Understanding of Climate System into Climate Information for Decision Makers

OPPORTUNITIES AND SUPPORT FOR STUDENTS, EARLY CAREER SCIENTISTS AND SCIENTISTS FROM DEVELOPING COUNTRIES

As part of WCRP's ongoing commitment to education and capacity development and to train the next generation of climate experts, grants are available to enable and support participation of students, early career scientists and scientists from developing countries to attend the conference. Please consult the OSC web site for further information. **The deadline for submitting a request for support to attend the OSC is 15 April, 2011.**

IMPORTANT DATES

April 15, 2011

- Last day to submit request for travel support
- Last day to submit abstract for those requesting travel support

May 15, 2011

- Last day to submit abstracts (everyone!)

July 12, 2011

- Early registration deadline

FOR MORE INFORMATION

Please visit the conference webpage: http://conference2011. wcrp-climate.org

Exchanges

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