WCRP/CLIVAR Working Group on Coupled Modeling (WGCM) Overview and Contribution to the WCRP Crosscut on Anthropogenic Climate Change

WGCM is charged with coordinating experimentation with coupled models that are aimed at understanding natural climate variability on decadal to centennial time scales and its predictability, and at predicting the response of the climate system to changes in natural and anthropogenic forcing. The WCRP Climate Model Intercomparison Project (CMIP) is a major WGCM contribution to the WCRP Anthropogenic Climate Change crosscutting topic.

Other coordinated modeling activities that are directly related to WGCM and its contribution to ACC include the WCRP Stratospheric Processes And their Role in Climate Project (SPARC) Chemistry-Climate Model Validation Activity (CCMVal) and the IGBP Analysis, Integration and Modeling of the Earth System (AIMES) Coupled Climate–Carbon Cycle Model Intercomparison Project (C4MIP). An extensive list of model intercomparison projects is available on the WGCM website (http://www.clivar.org/organization/wgcm/projects.php). WCRP and WGCM have recently formed a Task Force on Regional Climate Downscaling (TF-RCD) that is in the process of developing a White Paper by the end of 2009 on coordinating regional climate modeling (RCM) experiments forced by the CMIP5 climate change scenarios.

Areas of focus for WGCM include understanding emerging high impact uncertainties in the climate system such as the future evolution of ice sheets and their contribution to sea level rise, cloud-climate feedbacks, climate change and impacts on air quality, and abrupt climate change as seen in the paleoclimate record. WGCM works directly with the GEWEX Cloud System Study (GCSS) and with the Working Group on Numerical Experimentation (WGNE) on evaluating and improving climate models, with the International Detection and Attribution Group (IDAG) on understanding climate variability in the recent observational record during increased anthropogenic activity, the Integrated Assessment Modeling (IAM) Consortium on developing future climate forcing scenarios, and with AIMES on integrating coupled carbon/climate/chemistry and human processes into Earth System Models (ESMs).

CMIP Phase 3 (CMIP3)

CMIP introduced the climate science community to a "new era" of climate change research (Meehl et al., 2007). For the first time, the international climate change research community coordinated a set of climate change experiments that were run by all of the international climate modeling groups. This provided a multi-model dataset that included 20th Century simulations with anthropogenic and natural forcings, three 21st Century SRES non-mitigation scenarios for low, medium and high forcing, and three experiments where GHG concentrations were held constant (at year 2000 values, and at year 2100 values for the A1B and B1 experiments) and the models continued to run to quantify climate change commitment (see Fig. 1 for summary of globally averaged temperature changes from the different models and experiments). Output from these model experiments was then collected and archived by PCMDI, and was made openly available to the international climate science community for analysis. This was a new concept for the community (before this, climate change model data had only limited distribution), and opened up climate model analysis to thousands of scientists and students from around the world. This open access has produced hundreds of papers in the peer-reviewed literature, and a sample is listed on the PCMDI web page (http://www-pcmdi.llnl.gov/ipcc/subproject_publications.php).

Of all the multitude of results that have emerged from the CMIP3 analyses, two are illustrated here. For the first time climate change commitment was quantified with particular relevance for the year 2000 stabilized experiment (orange line in Fig. 1). Even when concentrations of GHGs are held constant, the climate continues to warm due to the thermal inertia of the oceans. Committed warming averages 0.1°C per decade for the first two decades of the 21st Century; across all scenarios, the average warming is 0.2°C per decade for that time period (recent observed trend 0.2°C per decade).

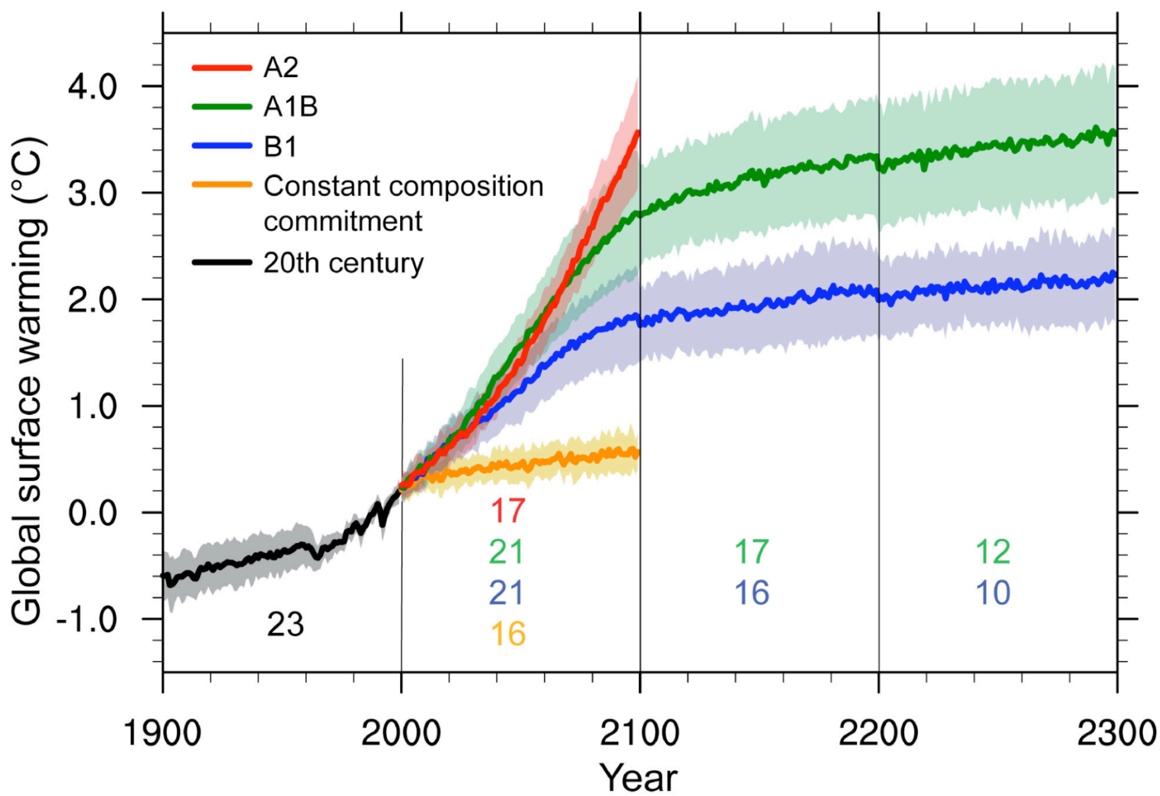


Figure 1: Multi-model means of surface warming (relative to 1980-1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th Century simulation. Values beyond 2100 are for the stabilization scenarios. Linear trends from the corresponding control runs have been removed from these time series. Lines show the multi-model means, shading denotes the +/- standard deviation range of individual model annual means. Discontinuities between different periods have no physical meaning and are caused by the fact that the number of models that have run a given scenario is different for each period and scenario, as indicated by the colored numbers for each period and scenario, at the bottom of the panel. For the same reason, uncertainty across scenarios should not be interpreted from this figure.
(IPCC AR4 WG1 Report, Ch. 10, Fig. 10.4.)

Another aspect that was treated more uniformly was the spatial pattern of warming.

Figure 2 shows a summary of the multi-model results for surface air temperature change. Note that the pattern of warming is very similar for all time periods and all scenarios, but the amplitude differs. Earlier in the experiments, there is little divergence among the forcing from the scenarios, and both the magnitude and pattern of temperature change are similar among the scenarios. But as the 21st Century continues, the amplitude of warming begins to be differentiated among the scenarios, and it is more clearly seen that continents warm more than oceans (an indicator of growing climate change commitment), the high latitude Northern Hemisphere warms more than everywhere else, and there is less warming in the North Atlantic and circumpolar southern ocean.

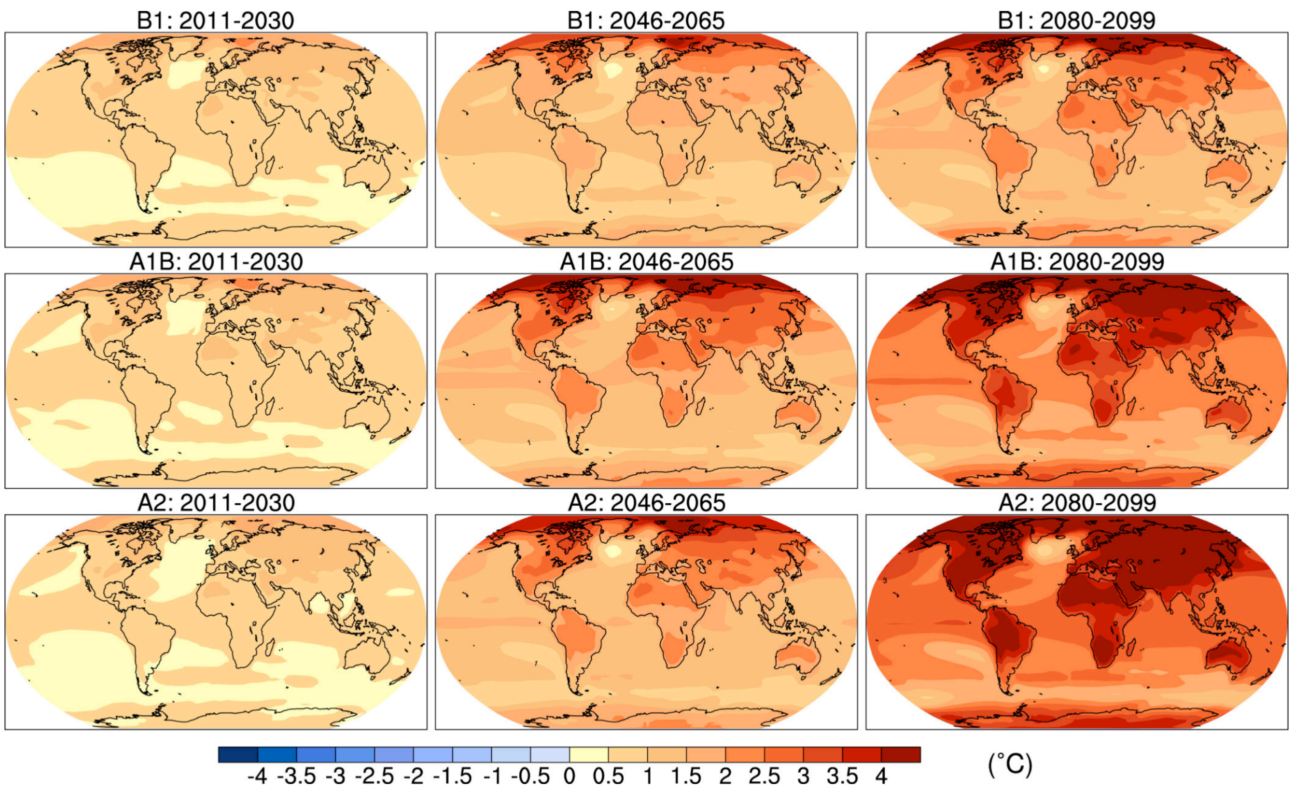


Figure 2: Multi-model mean of annual mean surface warming (surface air temperature change, ^{o}C) for the scenarios B1 (top), A1B (middle) and A2 (bottom) for three time periods, 2011 to 2030 (left), 2046-2065 (middle) and 2080 to 2099 (right). Anomalies are relative to the average of the period 1980 to 1999.
(IPCC AR4 WG1 Report, Ch. 10, Fig. 10.8)

When considering global temperature change, one of the greatest uncertainties on the high end of the range of temperature change was shown to come from carbon cycle feedback. Therefore, one of the main foci in the next phase CMIP5 is to provide a better quantification of the nature and magnitude of carbon cycle feedback. To reduce uncertainties and make the climate model projections and predictions more useful for informing the adaptation and mitigation decisions that our society will need to make, the global climate modeling community is putting effort in three main areas: (1) the understanding and the assessment of climate predictability and predictions at the decadal time scale, (2) the understanding and the assessement of long-term physical and biogeochemical feedbacks in the climate system, and (3) the evaluation and the improvement of climate models to make climate predictions and projections more reliable at all time and space scales. Figure 3 (from Hawkins and Sutton, 2009) shows how the fractional uncertainty of CMIP3 global mean temperature projections due to internal variability (in orange), model uncertainty (in blue) and scenario uncertainty (in green) varies on different spatial and temporal scales.

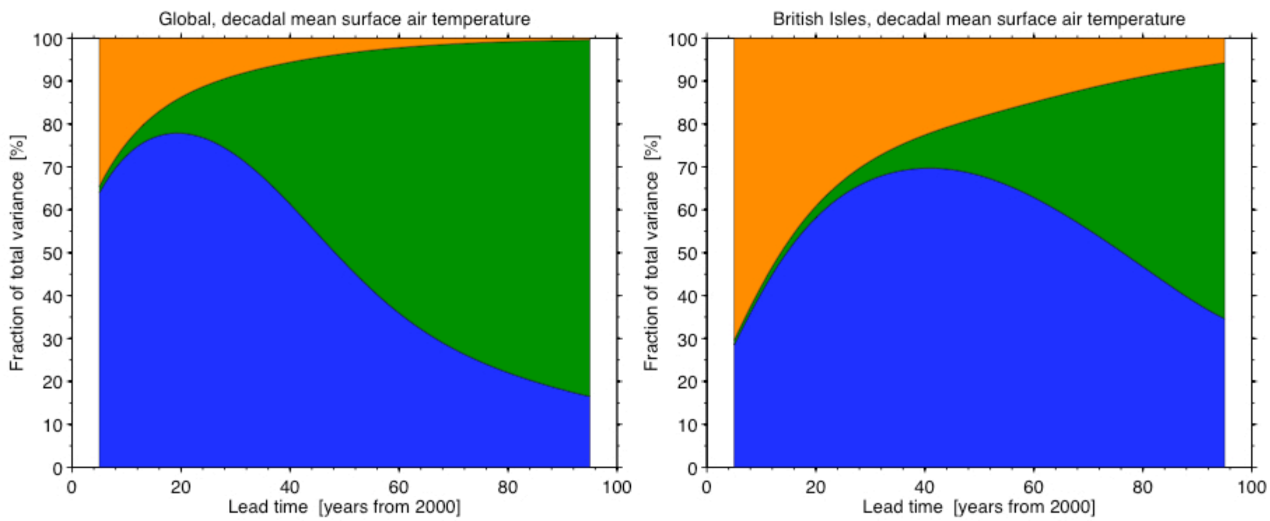
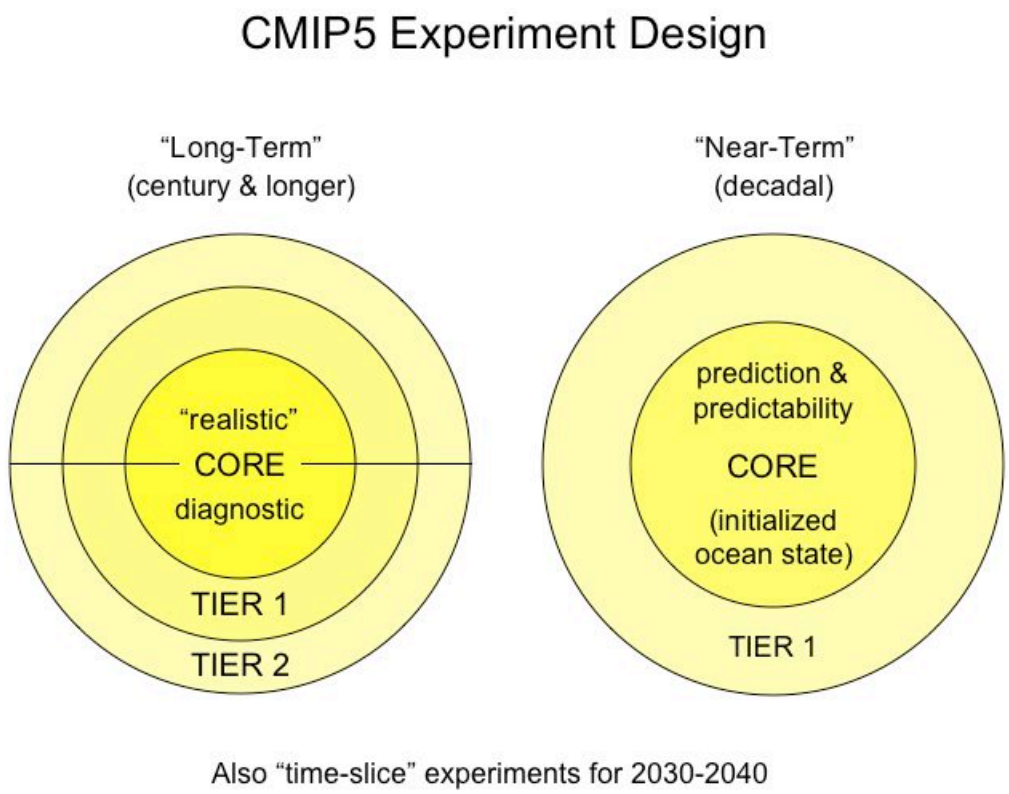


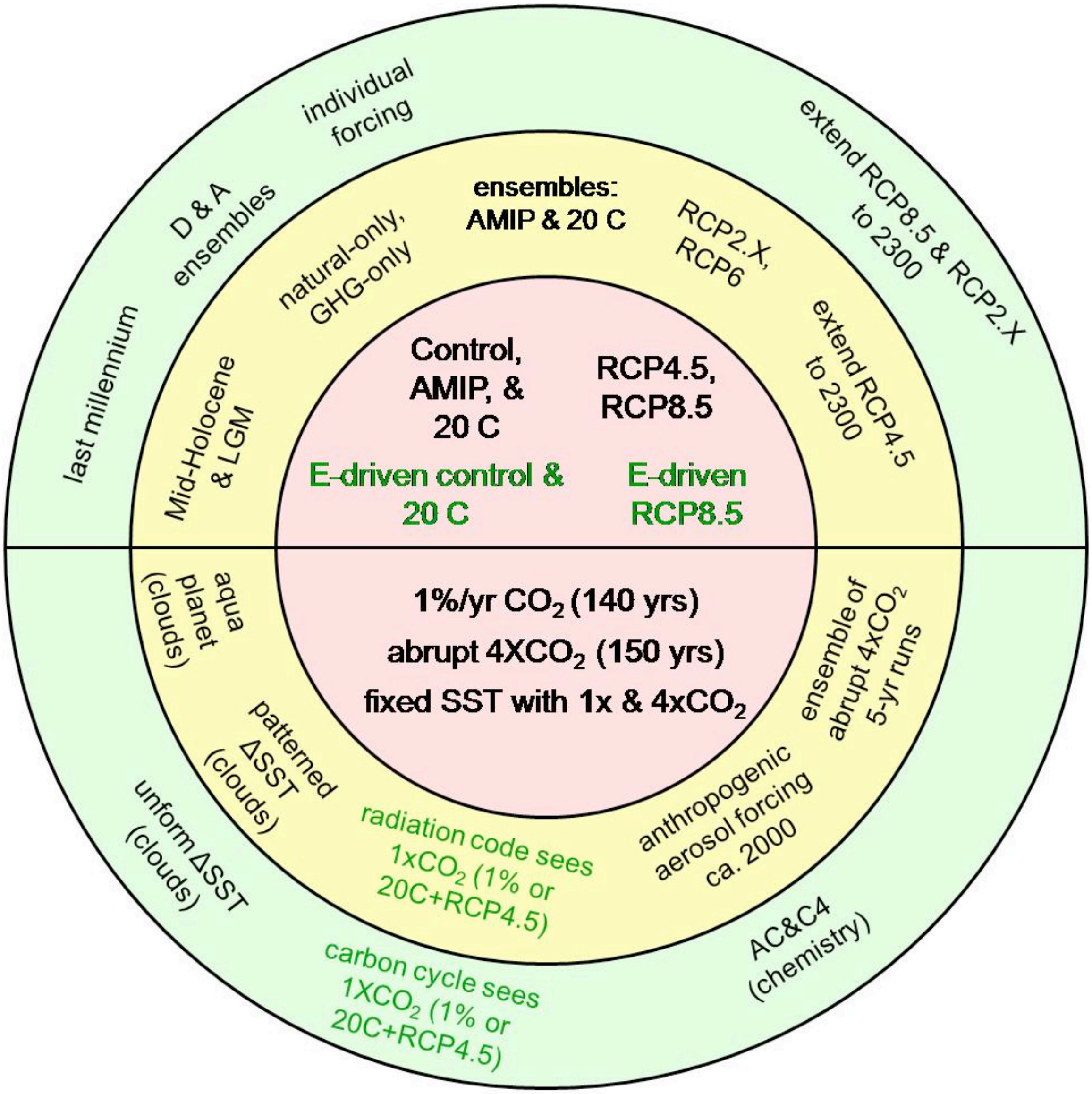
Figure 3: The fractional uncertainty of CMIP3 temperature projections associated with: internal variability (in orange), model uncertainty (in blue), and scenario uncertainty (in green), for the global scale (on the left) and for the regional scale (on the right).
(Fig. 4 c-d from Hawkins and Sutton, 2009)

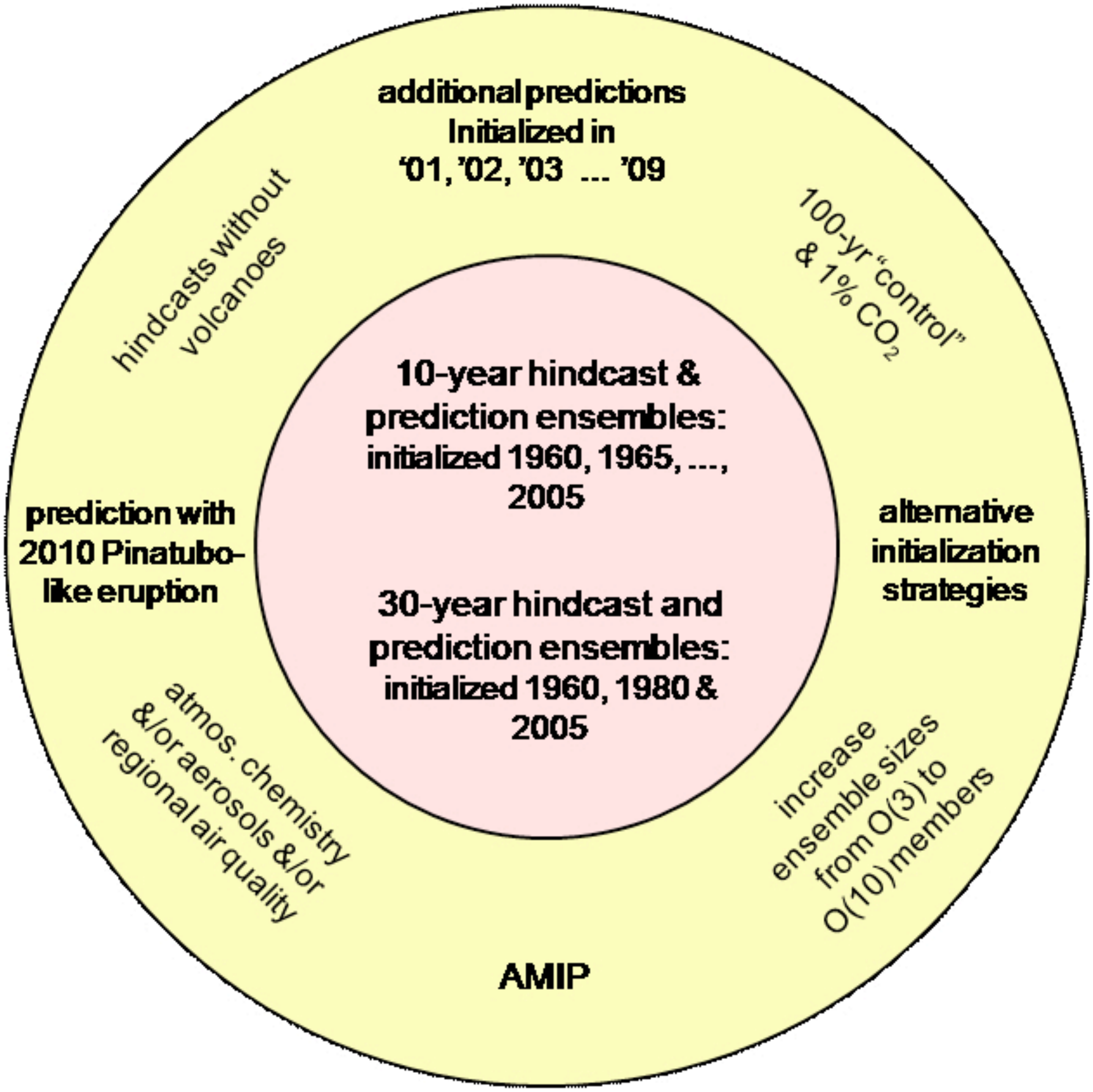
CMIP Phase 5 (CMIP5)
The CMIP3 climate change experiments represented the end of the era of non-mitigation scenarios represented by the SRES suite with the main climate change projection time frame being near the end of the 21st Century. The paradigm shift that occurred after the publication of the IPCC AR4 involved a move toward mitigation scenarios, with implied policy actions, to better quantify various feedbacks, including the carbon cycle, simulations relevant to longer term climate change out to 2100 and beyond, as well as an enhanced focus on shorter term climate change out to about 2035. This paradigm shift grew out of the research assessed for the AR4 that recognized the need to understand and interpret observed climate change in order to understand how much can be attributed to human activity, to internal variability, or to external forcings (natural and anthropogenic). This built on the growing need for climate science to inform adaptation and mitigation decisions.

CMIP5 has two foci, as defined in the CMIP5 strategy (Meehl and Hibbard, 2007; Hibbard *et al.*, 2007) and described in the experimental protocol (Taylor *et al.*, 2009) and summarized in Figure 4. The first is on near-term decadal prediction simulations (10-30 years) and understanding the extent to which future climate depends on the initial ocean-ice state, and to provide higher resolution regional climate change information for adaptation applications. The second is on long-term centennial simulations with both atmosphere-ocean global climate models (AOGCMs) with components of atmosphere, ocean, land surface and sea ice, and Earth-System models (ESMs) that have all the components of AOGCMs with the addition of a fully coupled, interactive carbon cycle. ESMs will examine the sensitivity, feedbacks and related uncertainties of future climate to natural and forced variability due to the carbon cycle. The longer-term simulations will quantify uncertainty across the model responses, as well as examine feedbacks on longer timescales that provide different amplitudes of future climate change.

Figure 4: Summary CMIP5 experimental protocol.
(Taylor *et al*, 2009)




individual forcing
D & A ensembles
last millennium
extend RCP8.5 & RCP2.X to 2300
ensembles: AMIP & 20 C
natural-only, GHG-only
RCP2.X, RCP6
Mid-Holocene & LGM
extend RCP4.5 to 2300
Control, AMIP, & 20 C
RCP4.5, RCP8.5
E-driven control & 20 C
E-driven RCP8.5
1%/yr CO_2 (140 yrs)
abrupt $4XCO_2$ (150 yrs)
fixed SST with 1x & $4xCO_2$
aqua planet (clouds)
patterned ΔSST (clouds)
ensemble of abrupt $4xCO_2$ 5-yr runs
anthropogenic aerosol forcing ca. 2000
radiation code sees $1xCO_2$ (1% or 20C+RCP4.5)
unform ΔSST (clouds)
carbon cycle sees $1XCO_2$ (1% or 20C+RCP4.5)
AC&C4 (chemistry)



For the near term, the CMIP5 experiments will consist of hindcasts to quantify decadal predictability, as well as predictions out to 2035 to address short-term climate change. One of the main science questions involves how best to initialize the ocean, and how much additional regional prediction skill (over and above un-initialized runs) can be obtained from an initialized climate model. This science question bridges the climate change problem to seasonal to interannual prediction, and decadal prediction is bringing together these two communities to address this problem. Another challenging problem related to initialization is how much additional regional predictive skill can be obtained by resolving regional internal decadal variability mechanisms in addition to the climate change produced by commitment and changes in external forcing.

The focus of the long-term integrations is to provide information on how feedbacks in the climate system contribute to the magnitude of climate change in the future for various mitigation strategies. Therefore, these simulations are relevant to mitigation and adaptation, with climate sensitivity in the different models contributing to the size of the feedbacks and the resulting climate change. It is on these longer timescales that sea level rise and the role of the melting of ice sheets will come into play. The combination of the various scenarios and feedbacks will also provide information on possible abrupt climate change. A major source of uncertainty in climate change estimates (climate sensitivity, patterns of regional temperature and precipitation changes, etc) is related to cloud processes and feedbacks (see Figure 5). These will be addressed by experiments led by the Cloud Feedback Model Intercomparison Project (CFMIP) community, as well as by the widespread implementation by models participating in CMIP5 of cloud simulator packages that diagnose from GCM outputs some variables similar to those observed from satellites through passive or active remote sensing.

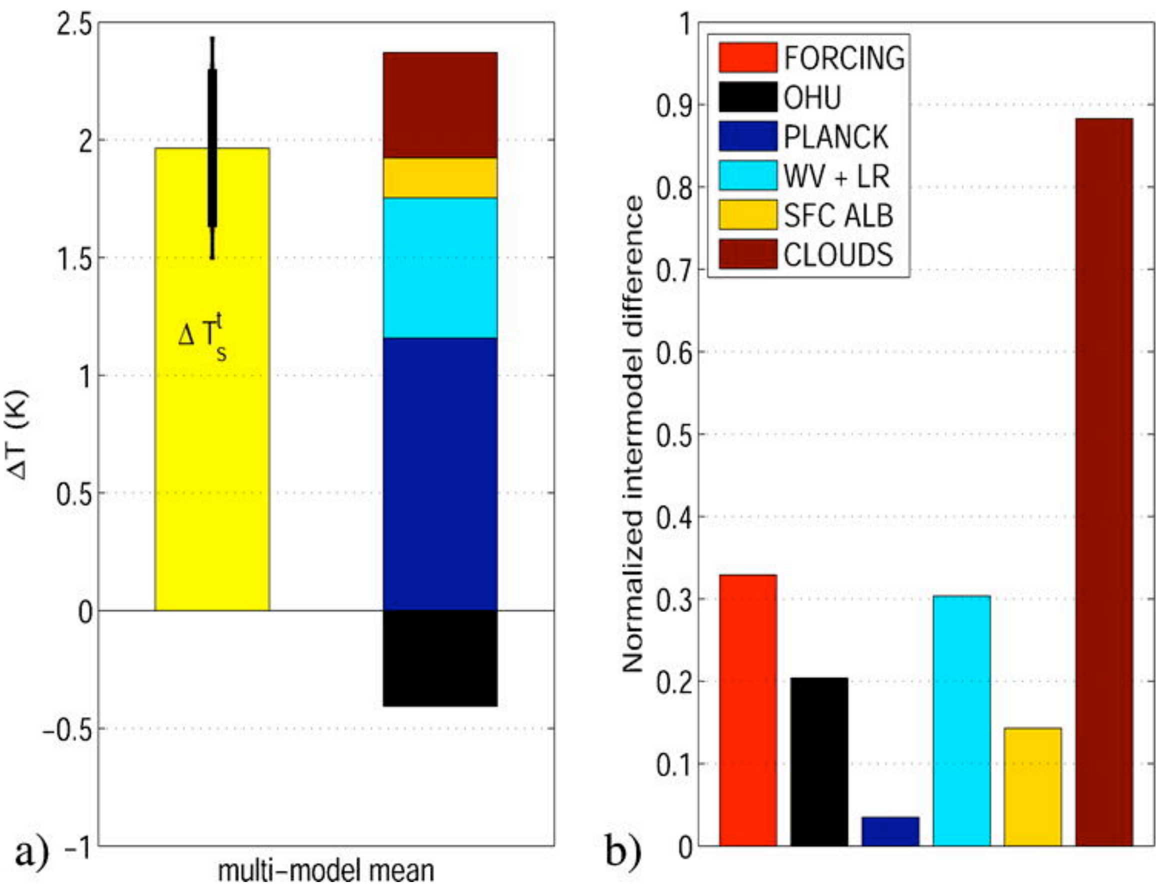


Figure 5: The multi-model spread in Transient Climate Response related to inter-model differences in radiative forcing, feedback and ocean heat uptake. For a CO_2 doubling, (a) multimodel mean ±1 standard deviation (thick line) and 5%–95% interval (thin line) of the transient temperature change (ΔTts) and contributions to this temperature change associated with the Planck response, OHU, combined water vapor and lapse-rate (WV + LR) feedback, surface albedo feedback, and cloud feedback. (b) Intermodel standard deviation of the transient temperature change estimates associated with intermodel differences in radiative forcing, Planck response, ocean heat uptake, and the various feedbacks normalized by the intermodel standard deviation of the transient temperature change ΔT^t_s.

(Dufresne and Bony, 2008)

The Integrated Assessment Model (IAM) Consortium, in collaboration with WGCM and AIMES, has developed four scenarios, called Representation Concentration Pathways (RCPs) for the 21st Century (2005 to 2100) and beyond to 2300, based on future concentrations, emissions and land use changes. One is non-mitigated and the others take into account three levels of mitigation. RCP4.5 and RCP6.0 are the medium mitgation scenarios, RCP2.6 is the low mitigation scenario, and RCP8.5 is the high emissions scenario. RCP4.5, for example, targets an approximate radiative forcing of $4.5 Wm^{-2}$ to be achieved by year 2100 relative to pre-industrial conditions. AOGCMs will be forced by specified concentrations, while ESMs with an interactive, coupled carbon cycle will be additionally forced by emissions, a new approach since CMIP3. The suite of long-term experiments also includes a 1% per year increase in CO_2 to diagnose the transient climate response and an abrupt 4x CO_2 increase experiment to diagnose the equilibrium climate sensitivity due to both forcing and feedbacks. Some participants will also be extending simulations to 2300 to look at the longer-term evolution of future climate. There will be additional experiments to examine "fast" and "slow" responses across the models, and a set of coordinated atmospheric chemistry experiments led by the CCMval community including experiments to diagnose the strength of forcing and the related uncertainties due to aerosols. The simulations leading up to the long term integrations will start in 1850, and will be run from 1850 to 2005 with observed natural (solar and volcano) and anthropogenic (GHG, aerosols, ozone) forcings for analyses relevant to climate change detection/attribution. A new aspect of these 20th Century (and 21st Century) simulations will be specified time-evolving land use change so that, for the first time, the contribution of land use change to local, regional and global climate change can be addressed.

The participation of ESMs with a fully coupled, interactive carbon cycle that will examine the sensitivity, feedbacks and related uncertainties of future climate to natural and forced variability due to the carbon cycle is a major development since CMIP3. These models will run several experiments, also contributing to the next phase of C4MIP. In one experiment the carbon cycle response to climate change will be suppressed so that the carbon cycle only responds to the increasing CO_2 concentrations and not the CO_2-induced changes in the climate's radiative balance. In a parallel experiment, the carbon cycle will be decoupled from the increasing CO_2 concentrations and will only respond to the radiative climate response. The surface CO_2 fluxes from these experiments will be used to derive emissions and compared with those of the fully coupled carbon cycle experiments to diagnose the strength of the carbon cycle feedback, to be expressed in terms of 'allowable emissions', and the implications of uncertainties in the carbon flux estimates. Earth-system Models of Intermediate Complexity (EMICs) and IAMs will also be run to reproduce these ESM results and to develop new future scenarios of human economic activity that will then feed back into the design of future CMIP simulations.

Additionally, there will be several experiments to understand the origin of inter-model differences in the climate response to a given perturbation. Some experiments will allow the diagnosis of climate sensitivity and radiative forcings from coupled models. Idealized experiments (e.g. atmosphere-only experiments forced by prescribed SST perturbations, aqua-planet experiments) will make it possible to assess both the robustness and the uncertainties of the climate change response predicted by coupled models, and to better interpret the origin of inter-model differences in the simulation of clouds, precipitation and large-scale dynamics. As noted above, a set of CMIP5 experiments will be addressing climate feedbacks by isolating components of the climate response according to the ‘fast’ response due to forcing and the ‘slow’ response due to feedbacks. These experiments inhibit the slow response of the ocean and isolate the fast response of the direct impact of increasing CO_2 concentrations on, for example, clouds, land surface, and stratospheric adjustment. Experiments will also be included that use a regression approach to estimate the equilibrium climate sensitivity and strength of feedbacks that are tied to the global mean temperature.

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