AN OVERVIEW OF CMIP5 AND THE EXPERIMENT DESIGN

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The fifth phase of the Climate Model Intercomparison Project (CMIP5), now underway, promises to produce a freely available state-of-the-art multimodel dataset designed to advance our knowledge of climate variability and climate change.

At a September 2008 meeting involving 20 climate modeling groups from around the world, the World Climate Research Programme's (WCRP) Working Group on Coupled Modelling (WGCM), with input from the International Geosphere–Biosphere Programme's (IGBP) Analysis, Integration and Modeling of the Earth System (AIMES) project, agreed to promote a new set of coordinated climate model experiments. These experiments comprise the fifth phase of the Coupled Model Intercomparison Project (CMIP5). The WGCM's endorsement of CMIP5 followed a planning stage involving extensive community input (Meehl and Hibbard 2007; Hibbard et al. 2007) that led to a consensus proposal to perform a suite of climate simulations that focus on major gaps in understanding of past and future climate changes. CMIP5 will notably provide a multimodel context for 1) assessing the mechanisms responsible for model differences in poorly understood feedbacks associated with the carbon cycle and with clouds; 2) examining climate "predictability" and exploring the predictive capabilities of forecast systems on decadal time scales; and, more generally, 3) determining why similarly forced models produce a range of responses. It is expected that some of the scientific questions that arose during preparation of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) will through CMIP5 be addressed in time for evaluation in the Fifth Assessment Report (AR5, scheduled for publication in late 2013). The enhanced set of historical and paleoclimate simulations and the expanded set of model output called for by CMIP5 promise to offer new opportunities for more detailed model evaluation. The four CMIP5 scenario runs, which provide a range of simulated climate futures (characterizing the next few decades to centuries), can be used as the basis for exploring climate change impacts and policy issues of considerable interest and relevance to society.

CMIP5 builds on the successes of earlier phases of CMIP (see Meehl et al. 2000, 2005). In phase 3 (ca. 2004–present), for example, climate model output was for the first time released almost immediately upon completion of the runs so that scientists outside the

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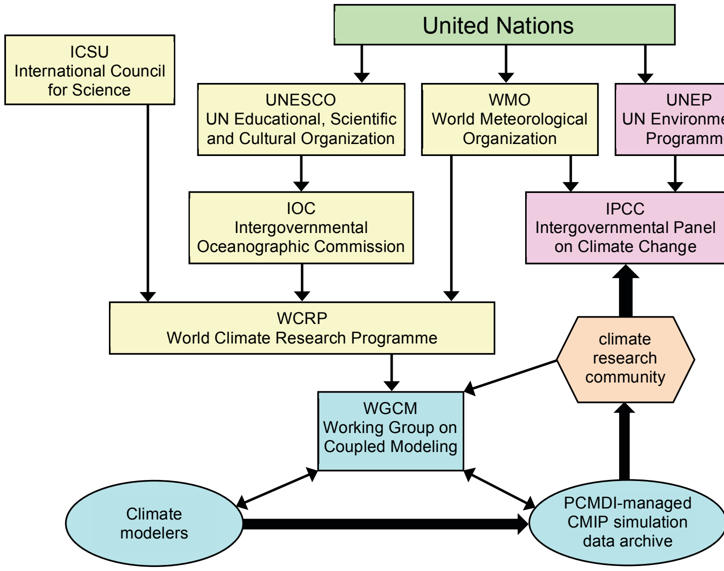

Fig. 1. The relationship of CMIP5 to organizations established to coordinate climate research activities internationally and to the IPCC, the modeling centers, and the climate research community.

modeling groups could provide a more timely and comprehensive analysis of the results. This unprecedented openness ushered in a "new era" in climate change research (Meehl et al. 2007). The CMIP3 multimodel dataset provided the basis for hundreds of peer-reviewed papers and played a prominent role in the IPCC's AR4 assessment of climate variability and climate change. During phase 4 of CMIP (Meehl et al. 2007), additional simulations were performed that could be used to separate anthropogenic and natural influences on twentieth-century climate.

The ongoing CMIP activities are organized by the WGCM, which represents the modeling groups. As part of the planning process, the WGCM received substantial input from potential users of the model output, some of whom are outside the traditional climate research community (e.g., scientists studying climate change impacts and policy makers). The experiments comprising CMIP5 were proposed, discussed, and prioritized by climate modelers working closely with other climate scientists and the biogeochemistry community. Figure 1 shows the international organizations that have a formal interest in CMIP. The WCRP, through the WGCM, coordinates CMIP. The climate research based on CMIP is performed by a broad climate research community, and results of that research can inform major assessment activities, such as the ongoing IPCC process.

The CMIP5 simulations were planned knowing that resource limitations would have to be carefully considered. Clearly, not all possible experiments of interest could be included. Nevertheless, the integrated set of CMIP5 simulations attempt to address major priorities of several different communities and incorporates some of the ideas and suggestions of many individuals and from a number of workshops and meetings.[1] These workshops involved scientists with a wide range of interests, including climate modeling, biogeochemistry modeling, integrated assessment modeling, climate change impacts, climate analysis, climate processes, and climate observations.

With input from these various groups, CMIP5 provides a framework for coordinated climate change experimentation that over the next several years (and well beyond the scheduled publication date of the IPCC AR5) promises to yield new insights about the climate system and the processes responsible for climate change and variability. More than 20 modeling groups are performing CMIP5 simulations using more than 50 models. CMIP5 is not meant to be comprehensive or exclusive. Rather, various groups and interested parties are developing additional experiments that build on or augment the CMIP5 experiments. For example, the Coordinated Regional Downscaling Experiment (CORDEX), after applying a variety of methods, will produce high-resolution "downscaled" climate data based on the CMIP5 simulations (Jones et al. 2011; see also http://wcrp.ipsl.jussieu.fr/SF_RCD_CORDEX.html). An entirely different group of scientists plans to carry out a set of Geoengineering Model Intercomparison Project (GeoMIP) experiments (Kravitz et al. 2011), which,

[1] Notable contributions came from an Aspen Global Change Institute workshop (July 2006), a joint WGCM–AIMES meeting (September 2006), a Snowmass Energy Modeling Forum (July 2007), an IPCC Expert Meeting on New Scenarios (Noordwijkerhout, the Netherlands, in September 2007), an International Detection and Attribution Group (IDAG) meeting (Boulder, Colorado, in January 2008), WGCM meetings (Hamburg, Germany, in September 2007; Paris, France, in September 2008), a Working Group on Numerical Experimentation (WGNE) meeting (Montreal, Quebec, Canada, in November 2008), and individuals who have commented on various versions of Taylor et al. (2009).

building on two of the idealized CMIP5 experiments, explores the effects of possible geoengineering approaches to mitigate climate change.

This paper is intended to provide an overview of CMIP5. The information from Taylor et al. (2009), which specifies the experiment design, is summarized and distilled in a form more suitable for a wide audience; the earlier document can be consulted by those seeking further details. This paper includes an introduction to the CMIP5 experiments, a description on how CMIP5 builds on and goes beyond the previous phases of CMIP, information on how to access CMIP5 model output, an introductory discussion of issues relevant to the interpretation of CMIP5 results, and a summary.

THE CMIP5 EXPERIMENTS. The CMIP5 strategy (Hibbard et al. 2007; Meehl and Hibbard 2007) includes two types of climate change modeling experiments: 1) long-term (century time scale) integrations and 2) near-term integrations (10–30 yr), also called decadal prediction experiments (Meehl et al. 2009). The long-term integrations are usually started from multicentury preindustrial control (quasi equilibrium) integrations, whereas the decadal prediction experiments are initialized with observed ocean and sea ice conditions. Both the long- and near-term experiments are integrated using atmosphere–ocean global climate models (AOGCMs), the "standard" models used in previous CMIP phases. Earth system models of intermediate complexity (EMICs; Petoukhov et al. 2005) can also be used to perform many of the CMIP5 experiments. The AOGCMs and EMICs respond to specified, time-varying concentrations of various atmospheric constituents (e.g., greenhouse gases) and include an interactive representation of the atmosphere, ocean, land, and sea ice. For the long-term simulations, some of the AOGCMs will, for the first time in CMIP, be coupled to biogeochemical components that account for the important fluxes of carbon between the ocean, atmosphere, and terrestrial biosphere carbon reservoirs, thereby "closing" the carbon cycle in the model. These models are called Earth system models (ESMs), and they have the capability of using time-evolving emissions of constituents from which concentrations can be computed interactively. They may in some cases also include interactive prognostic aerosol, chemistry, and dynamical vegetation components. Individual groups may choose to perform either the long-term or the near-term experiments with either AOGCMs or ESMs, or they may do various combinations of each. Application of the EMICs will be limited to the long-term experiments.

CMIP5 also recognizes that some groups may wish to perform simulations with a higher resolution or a more complete treatment of atmospheric chemistry than is typical of AOGCMs or ESMs. In these models, computer resources may be insufficient to allow fully coupled simulations, so CMIP5 includes an option to perform so-called time-slice integrations of both the present-day climate [essentially following the Atmospheric Model Intercomparison Project (AMIP) protocol first described by Gates (1992)] and the future climate (in particular, the decade 2026–35, which allows for direct comparison with the fully coupled experiments). In time-slice simulations of the future, projected changes in sea surface temperature (SST) and sea ice are obtained from a prior integration of a fully coupled AOGCM simulation. In comparison with previous CMIP phases, the time-slice option allows a wider range of modeling groups to participate in CMIP5 (e.g., in weather forecast centers). Some groups may choose to perform additional time-slice experiments for other periods (e.g., late twenty-first century).

The long-term experiments directly build on the CMIP3 experiments but include additional runs to provide a more complete understanding of climate change and variability. The near-term prediction experiments, in contrast, are an entirely new addition to CMIP and therefore are considered more exploratory in nature. In these simulations, the models will not only respond, as in the long-term runs, to climate forcing (e.g., increasing atmospheric CO_2 concentration) but also potentially track to some degree the actual trajectory of climate change, including (within the currently unknown predictability limits of the climate system) the unforced component of climate evolution. Thus, in the near-term experiments CMIP5 models, as part of a forecast system, will attempt a full prediction of climate change, whereas in the long-term experiments the models will provide a projection of the "forced" responses of climate to changing atmospheric composition and land cover. In these long-term projections, the climate change will be obscured to some degree by natural "unforced" variability that only rarely and by coincidence could be expected to match the observable, evolving climate trajectory.

Because of the large numbers of simulations included in the CMIP5 framework, the integrations for both century and decadal time scales are divided (based in part on consensus prioritization) into a "core" set, and then one or two surrounding "tiers" (Figs. 2 and 3). Although a group may choose to perform only the long-term core or only the near-term core of experiments, in each case the complete set of core simulations is expected to be completed. The intent is to generate a sufficiently large set of runs to enable a systematic model intercomparison within each type of experiment and thereby produce a credible multimodel dataset for analysis. The core experiments (located in the innermost circle and shaded pink in Figs. 2 and 3) are critical for evaluating the models, and they provide high-interest information about future climate change as well as help identify reasons for differences in the projections. The tier 1 integrations (surrounding the core and shaded yellow) examine specific aspects of climate model forcing, response, and processes, and tier 2 integrations (shaded green) go deeper into those aspects. Thus, proceeding from core to tier 1 to tier 2 can be seen as a progression from basic to more specialized simulations, exploring multiple aspects of climate system projections and responses. For each suite of experiments, the modeling groups will perform the core integrations first, followed by a selection of the tier 1 and tier 2 integrations, depending on their interests and available resources.

For detailed specifications of all the experiments, the reader is referred to the experiment design document (Taylor et al. 2009), which can be obtained from the CMIP5 website (http://cmip-pcmdi.llnl.gov/cmip5).

Long-term experiments. The core simulations within the suite of CMIP5 long-term experiments (Fig. 2) include an AMIP run, a coupled control run, and a "historical" run forced by observed atmospheric composition changes (reflecting both anthropogenic and natural sources) and, for the first time, including time-evolving land cover. The historical runs cover much of the industrial period (from the midnineteenth century to near present) and are sometimes referred to as "twentieth century" simulations. Within the core set of runs, there are also two future projection simulations forced with specified concentrations [referred to as "representative concentration pathways" (RCPs)], consistent with a high emissions scenario (RCP8.5) and a midrange mitigation emissions scenario (RCP4.5). For AOGCMs and EMICs that have been coupled to a carbon cycle model (i.e., for ESMs), there are control and historical simulations, and the high emissions scenario (RCP8.5). For this set of ESM runs, the time-evolving atmospheric concentration of CO_2, rather than being specified, is calculated by the model.

The CMIP5 projections of climate change are driven by concentration or emission scenarios consistent with the RCPs described in Moss et al. (2010). In contrast to the scenarios described in the IPCC "Special Report on Emissions Scenarios" (SRES) used for CMIP3, which did not include policy intervention,

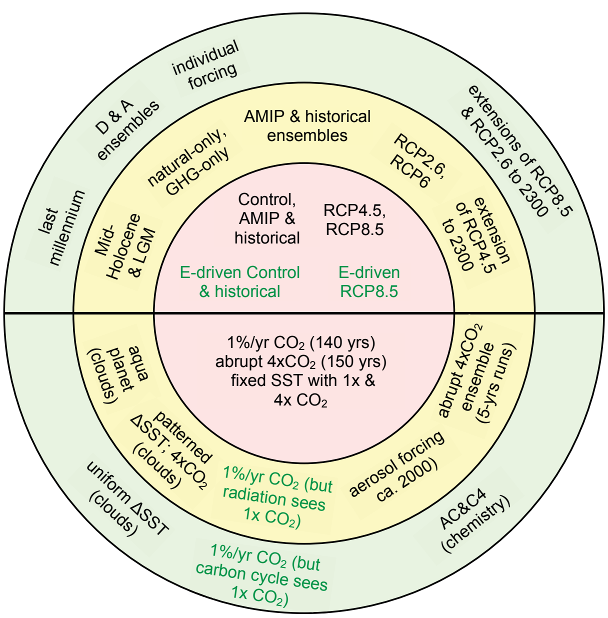

Fig. 2. Schematic summary of CMIP5 long-term experiments with tier 1 and tier 2 experiments organized around a central core. Green font indicates simulations to be performed only by models with carbon cycle representations. Experiments in the upper hemisphere are suitable either for comparison with observations or provide projections, whereas those in the lower hemisphere are either idealized or diagnostic in nature and aim to provide better understanding of the climate system and model behavior.

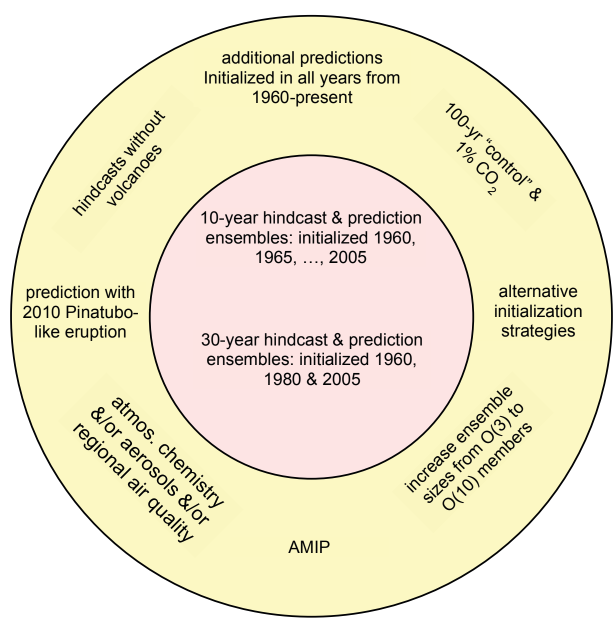

Fig. 3. Schematic summary of CMIP5 decadal prediction integrations.

the RCPs are mitigation scenarios that assume policy actions will be taken to achieve certain emission targets. For CMIP5, four RCPs have been formulated that are based on a range of projections of future population growth, technological development, and societal responses. The labels for the RCPs provide a rough estimate of the radiative forcing in the year 2100 (relative to preindustrial conditions). For example, the radiative forcing in RCP8.5 increases throughout the twenty-first century before reaching a level of about 8.5 W m^{-2} at the end of the century. In addition to this "high" scenario, there are two intermediate scenarios, RCP4.5 and RCP6, and a low so-called peak-and-decay scenario, RCP2.6, in which radiative forcing reaches a maximum near the middle of the twenty-first century before decreasing to an eventual nominal level of 2.6 W m^{-2}.

For the diagnostic core integrations (in the lower hemisphere of Fig. 2), CMIP5 calls for 1) calibration-type runs to diagnose a specific transient climate response (defined as the globally averaged temperature change at the time of CO_2 doubling in a 1% yr^{-1} CO_2 increase experiment; 2) an abrupt CO_2 increase experiment to estimate the equilibrium global mean temperature response to a quadrupling of CO_2 and to quantify both radiative forcing and some of the important feedbacks; and 3) fixed SST experiments to refine the estimates of forcing and help interpret differences in model response.

The tier 1 and tier 2 experiments explore various aspects of the core experiments in further detail. For ESMs, there are two carbon cycle feedback experiments. In the first, climate change is suppressed (by specifying in all radiation code calculations a constant, preindustrial CO_2 concentration), so that the carbon cycle response only reflects changing CO_2 influences unrelated to climate change. In the second, the climate responds to CO_2 increases, but the CO_2 increase is hidden from the carbon cycle. Following an approach found useful in the Coupled Climate–Carbon Cycle Climate Model Intercomparison Project (C4MIP; Friedlingstein et al. 2006), the surface fluxes of CO_2 will be saved in these experiments and then compared with fluxes from the corresponding core experiment (in which the carbon cycle simultaneously responds to both climate and CO_2 concentration changes). From these fluxes, the strength of the carbon–climate feedback can be expressed in terms of a difference in allowable emissions or in airborne fraction.

Some experiments included in CMIP5 were originally conceived as part of other model intercomparison projects. These include the Cloud Feedback Model Intercomparison Project (CFMIP; http://cfmip.metoffice.com/; see also Bony et al. 2011), the Paleoclimate Modelling Intercomparison Project (PMIP; http://pmip3.lsce.ipsl.fr/; see also Braconnot et al. 2011), and earlier CMIP experiments. Thus, in CMIP5 there is a suite of cloud feedback experiments, some paleoclimate experiments to study the response of the models under much different forcing, experiments for climate change detection/attribution studies with only natural forcing or only greenhouse gas (GHG) forcing (as well as some single-forcing experiments), twenty-first century runs with the other two RCPs (RCP2.6 and RCP6), and extensions of the future climate simulations out to year 2300. These twenty-second- and twenty-third-century portions of the projections differ from the twenty-first century segments in that the RCPs were extended without reference to specific underlying societal, technological, or population scenarios (Moss et al. 2010). There are also diagnostic experiments with abbreviated abrupt $4XCO_2$ integrations that should yield more accurate estimates of adjusted CO_2 forcing, an experiment to quantify the magnitude of the aerosol forcing, and a placeholder for an experiment focusing on atmospheric chemistry and climate [Atmospheric Chemistry and Climate Activity 4 ("AC&C4")].

Several of the CMIP5 experiments require specification of concentrations or emissions of various atmospheric constituents (e.g., greenhouse gases and aerosols). The Integrated Assessment Modeling Consortium working with the AC&C community has provided the concentrations, emissions, and time-evolving land use changes that will be prescribed in some of the CMIP5 experiments (e.g., Lamarque et al. 2010).

Near-term experiments (decadal prediction). The near-term experiments have been formally organized through a new collaboration between the WGCM and the Working Group on Seasonal to Interannual Prediction (WGSIP). There are two sets of core near-term integrations, as indicated by Fig. 3. The first is a set of 10-yr hindcasts initialized from observed climate states near the years 1960, 1965, and every 5 yr to 2005. In these 10-yr simulations, it will be possible to assess the skill of the forecast system in predicting climate statistics for times when the initial climate state may exert some detectable influence. The other core integrations extend the 10-yr simulations initialized in 1960, 1980, and 2005 by an additional 20 yr, ending up with two 30-yr hindcasts, and one 30-yr prediction to the year 2035. At this somewhat longer time scale, the external forcing from increasing GHGs could very well dominate the response, but some residual influence of the initial conditions might still be detectable. It is desired that a minimum of three ensemble members be generated for each of the core integrations.

The tier 1 near-term experiments also include predictions with 1) additional initial states to include both recent years when, as a result of the widespread introduction of Argo floats (www.argo.ucsd.edu), ocean temperature and salinity data become spatially more complete and of better quality, and also earlier years to obtain more robust estimates of the bias adjustment and other statistical calculations; 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 (not indicated in Fig. 3) of performing time-slice experiments with high-resolution models or models with computationally expensive atmospheric chemistry treatments. A relatively short "control" run (e.g., about 100 yr) and a 1% yr^{-1} CO_2 increase experiment are also called for within the near-term suite of experiments to provide a calibration of the model's internal climate variability and response to increasing CO_2 (these runs would, of course, be redundant and would be omitted if the model were used to perform the suite of long-term experiments) Finally, there is also the possibility of an atmospheric chemistry/pollutant experiment.

Users of CMIP5 model output should take note that decadal predictions with climate models are in an exploratory stage. A number of different methods are being tried to assimilate ocean observations into the models, and no single method has gained widespread acceptance. Moreover, the quality and completeness of ocean observations may be insufficient to realize but a fraction of the predictability inherent in the system. Thus, the forecast systems being assembled for CMIP5 are clearly not considered operational, nor will they necessarily provide more realistic simulations than the long-term simulations. Rather, the experiments aim to advance understanding of predictability, expose the relative merits of various data assimilation approaches, and reveal the limitations of the existing ocean observational network. Overall predictive skill of a forecast system will be determined by the quality of the observations, the capabilities of the assimilation method, and the skill of the model itself.

CMIP3/CMIP5 DIFFERENCES. As discussed earlier, relative to CMIP3, CMIP5 includes more comprehensive models and calls for a broader set of experiments that address a wider variety of scientific questions. CMIP5 also differs from earlier phases in that generally higher-spatial-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 (as described in the next section).

The spatial resolution of CMIP5 coupled models will likely range for the atmosphere component from 0.5° to 4° and for the ocean component from 0.2° to 2°. For the handful of atmospheric models that fall into the "computationally demanding" class (which will not be coupled to ocean models), the resolution may approach 0.2°. For CMIP5 roughly half of the atmospheric models will have an average latitudinal resolution finer than 1.3°, whereas in CMIP3 only one model fell into this category. Similarly, whereas about half the CMIP3 ocean models had an average latitudinal resolution coarser than 1°, for CMIP5 only 2 out of more than 30 models will have a resolution this coarse.

Of substantial importance to analysts will be the greatly expanded list of model output that will be archived from CMIP5 simulations. Through a multiyear process during which input on which variables should be saved was solicited from various potential users, a final list of "requested" output was compiled (consistent with practical constraints on data storage and transfer). Many of the atmospheric variables had been requested in earlier phases of CMIP; in CMIP5, however, a much more complete set of ocean fields is included, as called for in a WCRP report by Griffies et al. (2009). For other aspects of the climate system, ad hoc groups of interested individuals pooled their expertise and eventually reached a consensus on the most important variables to archive. These various groups were largely responsible for the list of aerosol, biogeochemical, and cryospheric fields included in CMIP5. In the case of clouds, many models now can produce a whole new set of variables using specialized "satellite simulator" codes. Encouraged by community acceptance of the CFMIP diagnostic plans, CMIP5 includes a request for variables produced by the CFMIP Observation Simulator Package (COSP), which, for example, facilitates a comparison with *CloudSat*/*Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations* (*CALIPSO*)[2] and International Satellite

[2] CloudSat and *CALIPSO* are complementary satellites that together provide a 3D perspective of how clouds and aerosols form, evolve, and affect weather and climate.

Cloud Climatology Project (ISCCP) observations (Bodas-Salcedo et al. 2011). These new model output variables will greatly facilitate an evaluation of the representation of clouds in climate models.

It would clearly be impossible to satisfy all the needs of potential users of model output, so the CMIP5 "requested output" list is far from exhaustive. The IPCC's Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA), for example, suggested that a few fields be sampled hourly (see IPCC TGICA 2007). This request was in the end rejected, partly because the modelers have little confidence in the ability to represent behavior accurately at hourly time scales and partly for practical reasons (i.e., the data volume would be overwhelming).

Despite these limitations, the CMIP5 requested output (see http://cmip-pcmdi.llnl.gov/cmip5/output_req.html) includes an unprecedented variety of output fields. The number of variables that is being collected for different parts of the climate system appears in parentheses in the following list: atmosphere (60), ocean (77), land surface and carbon cycle (58), ocean biogeochemistry (74), sea ice (38), land ice and snow (14), and clouds (100). Many of these fields are only being saved as monthly means (390), but data for some variables are also being reported as annual means (57), daily means (53), or sampled every 3 or 6 h (23 and 6, respectively). Some of the ocean properties are being saved as annual cycle climatologies (22). Not all variables are being collected for all CMIP5 experiments, and some variables are being saved for only selected periods of the simulations.

One of the limitations of CMIP3 was that documentation of the models and details of the experiment conditions (e.g., which greenhouse gases were included in which models) were difficult to obtain. For CMIP5 there is an increased emphasis on providing better documentation. Compared to CMIP3, the model output files themselves include more complete descriptions of the experiment conditions (e.g., a list of "forcings" and a record of which "parent" simulation provided the initial conditions). The Common Metadata for Climate Modelling Digital Repositories (METAFOR) project (see http://metaforclimate.eu/; Guilyardi et al. 2011) has taken the lead in creating a conceptual framework for organizing additional detailed information about the models and their simulations, and has created a questionnaire that the modeling groups are filling out to input the information into a searchable database.

Finally, it is of interest to note that for CMIP3, each modeling group submitted on average 1,750 yr of model output from the first member of what was often a multimember ensemble of runs. If *all* ensemble members are considered, then nearly 2,800 yr on average were simulated per CMIP3 model, but the total years varied substantially from one model to another (500–8,400 yr with a median of 2,200 yr). The total amount of CMIP3 model data archived was about 36 TB. In contrast for CMIP5, the long-term and near-term core experiments alone call for, at minimum, ~2,300 yr, approximately matching the number of years in CMIP3. The additional tier 1 and tier 2 experiments, however, add considerably to the total number of years. Furthermore, the generally higher resolution of the CMIP5 models, the larger number of models participating, and the greatly expanded requested output list leads to an estimate of total data volume exceeding 3 PB (1 PB = 10^6 GB), nearly 100 times the volume of CMIP3 data.

OBTAINING CMIP5 MODEL OUTPUT. The enormous volume of model output expected from CMIP5 has required a rethinking of the traditional strategy for sharing data across the research community. In CMIP3, modeling centers restructured and rewrote their model output in a standard way and then shipped it to a central repository managed by the Program for Climate Model Diagnosis and Intercomparison (PCMDI). Researchers and other users could then download it and analyze it in a uniform way. For CMIP5, the output will again be formatted in a common way; however, to reduce shipment of huge data volumes, the data will be archived in data nodes distributed at modeling centers and data centers near where the model output is produced. The nodes will be linked together and the model output will be freely accessible through data portals (or gateways) integrated in a way that retains much of the convenience of a single repository.

The international effort to create this "federated archive" was initiated under the Earth System Grid (ESG) project (http://esg-pcmdi.llnl.gov) led by PCMDI and is being advanced through the Earth System Grid Federation (ESGF; http://esgf.org/wiki/ESGF_Overview; Williams et al. 2011), established under the Global Organization for Earth System Science Portals (GO-ESSP; http://go-essp.gfdl.noaa.gov/).

For earlier CMIP phases, the model output was primarily meant for use by researchers studying the physical climate system and for assessment, subsequently, by Working Group 1 (WG1) of the IPCC. To serve scientists working in areas more typically associated with WG2 and WG3 of the IPCC (i.e., impacts, adaptation, and mitigation), a subset of the

TABLE 1. List of experiments with official CMIP5 identifying labels, type of model(s) used to perform experiments, and major purposes (with the overall purpose of all experiments being to further scientific understanding of the climate system).

Experiment description	CMIP5 label	AOGCM	ESM or EMIC	High resolution[a]	Major purposes
Preindustrial control run	piControl	X	X		Evaluation, unforced variability
Past ~1.5 centuries (1850–2005)	historical	X	X		Evaluation
AMIP run (observed SSTs and sea ice prescribed for 1979–present)	amip	X	X	X	Evaluation
Future projection (2006–2300) forced by RCP4.5	rcp45	X	X		Projection
Future projection (2006–2300) forced by RCP8.5	rcp85	X	X		Projection
Future projection (2006–2300) forced by RCP2.6	rcp26	X	X		Projection
Future projection (2006–2100) forced by RCP6	rcp60	X	X		Projection
Benchmark 1% yr^{-1} increase in CO_2 (to quadrupling)	1pctCO2	X	X		Climate sensitivity, feedbacks
Quadruple CO_2 abruptly, then hold fixed	abrupt4xCO2	X	X		Climate sensitivity, feedbacks, fast responses[b]
Climatological SSTs and sea ice imposed from piControl	sstClim	X	X		Fast responses[b]
As in sstClim, but with $4XCO_2$ imposed	sstClim4xCO2	X	X		Fast responses[b]
As in sstClim, but with aerosols specified from year 2000 of the historical run	sstClimAerosol	X	X		Fast responses[b]
As in sstClim, but with sulfate aerosols specified from year 2000 of the historical run	sstClimSulfate	X	X		Fast responses[b]
Preindustrial conditions imposed as in piControl, but with atmospheric CO_2 determined by the model itself	esmControl		X		Evaluation, carbon cycle
Simulation of past, as in historical, but driven by CO_2 emissions rather than concentrations	esmHistorical		X		Evaluation, carbon cycle
Future projection as in rcp85, but driven by CO_2 emissions rather than concentrations	esmrcp85		X		Projection
Radiation code sees piControl CO_2 concentration, but carbon cycle sees 1% yr^{-1} rise	esmFixClim1[c]		X		Carbon feedback
Carbon cycle sees piControl CO_2 concentration, but radiation sees 1% yr^{-1} rise	esmFdbk1[c]		X		Carbon feedback
As in AMIP, but with radiation code seeing $4 \times CO_2$	amip4xCO_2	X	X	X	Clouds, fast responses[b]
Patterned SST anomalies added to AMIP conditions (as called for by CFMIP)	amipFuture	X	X	X	Cloud feedbacks
Zonally uniform SSTs imposed on an ocean-covered Earth (as called for by CFMIP)	aquaControl	X	X	X	Clouds
As in aquaControl, but with 4 × CO2	aqua4xCO2	X	X	X	Clouds, fast responses[b]
As in aquaControl, but with a uniform 4-K increase in SST	aqua4K	X	X	X	Cloud feedbacks
As in AMIP, but with a uniform 4-K increase in SST	amip4K	X	X	X	Cloud feedbacks
Historical simulation but with natural forcing only	historicalNat	X	X		Detection and attribution
Historical simulation but with GHG forcing only	historicalGHG	X	X		Detection and attribution
Historical simulation but with other individual forcing agents or combinations of forcings	historicalMisc	X	X		Detection and attribution
Extension of historical through year 2012	historicalExt	X	X		Evaluation, detection, attribution

Table 1. Continued.

Experiment description	CMIP5 label	AOGCM	ESM or EMIC	High resolution[a]	Major purposes
Mid-Holocene conditions (as called for by PMIP)	midHolocene	X	X		Evaluation
Last Glacial Maximum conditions (as called for by PMIP)	lgm	X	X		Evaluation
Natural forcing for 850–1850 (as called for by PMIP)	past1000	X	X		Evaluation, natural variability
Decadal hindcasts/predictions, some extended to 30 yr	decadalXXXX[d]	X			Predictability, prediction, evaluation
Hindcasts but without volcanoes	noVolcXXXX[d]	X			Predictability
Decadal forecast with Pinatubo-like eruption in year 2010	volcIn2010	X			Predictability, prediction
SST and some other conditions for 2026–35 specified from a coupled model experiment	sst2030			X	Projection

[a] High resolution identifies atmospheric models with resolutions higher than normally used in climate simulations or models that in some other way require exceptional computational resources (e.g., models with comprehensive treatments of atmospheric chemistry).

[b] Fast responses," as discussed, for example, in Gregory and Webb (2008), are the climate system responses that occur on time scales that are short when compared to the response time of the mixed layer of the ocean. In the case of an increase in CO_2, the fast response is dominated by the immediate radiative response to atmospheric composition changes (typically referred to as "radiative forcing"); however, it is also affected, for example, by stratospheric temperature responses ("stratospheric adjustment") and fast cloud responses. Together, the fast responses produce an "effective" radiative forcing somewhat different from the instantaneous radiative effect of abruptly increasing CO_2 concentration.

[c] There are two additional simulations not listed here, identified in CMIP5 as "esmFixClim2" and "esmFdbk2," that are similar to "esmFixClim1" and "esmFdbk1" but are designed to determine the strength of carbon cycle feedback for the historical period and the RCP4.5 future run.

[d] The "XXXX" is a generic representation of the year in which the decadal prediction was initiated. As an example, a simulation focusing on the 10-yr period from Jan 1966 to Dec 1975 will typically be initiated sometime between 1 Sep 1965 and 1 Jan 1966 and would be labeled "decadal1965."

CMIP model output was transferred to the IPCC Data Distribution Centre, where it was jointly hosted by the British Atmospheric Data Centre (BADC) and Deutsches Klimarechenzentrum (DKRZ). For CMIP5, PCMDI has again been given responsibility for the model output archive. To serve all three IPCC working groups, PCMDI has been working with BADC, DKRZ and other climate data centers to establish a unified data archive. This alliance of major data centers promises to reduce past delays in making model output available to scientists outside the WG1 climate research community.

To obtain output from the CMIP5 archive, users must first register, indicating how the data will be used and agreeing to specific "terms of use" (see http://cmip-pcmdi.llnl.gov/cmip5/terms.html). Some of the modeling groups will release their data for "unrestricted" use, whereas others will limit use to "noncommercial research and educational" purposes. A user who is planning to engage in some commercial activity using the data will be given access only to model output that is meant for unrestricted use. Through the registration mechanism, it will be possible to inform users of errors found in model output and of data that have been retracted or updated.

Once registered, a user can access CMIP5 model output through the PCMDI data portal (http://pcmdi3.llnl.gov/esgcet/home.htm) or through any of the other ESG federated gateways. The ESG data portal web pages make it possible to search for the specific output of interest to a user. A user may search using any combination of model, variable, experiment, frequency (e.g., monthly, daily, 3 hourly), and modeling realm (e.g., atmosphere, ocean, sea ice). To assist the user in identifying which experiments might be of most interest, Table 1 provides a very brief description of each CMIP5 experiment, along with an indication of which model types will be used. Users need to become familiar with the experiment "labels" given in the table, since these names will be displayed by the ESG search engine and will appear in the CMIP5 data archive.

Before beginning to download model output, users should consider how the data will be used. For example, if there is interest only in a global mean time series or in some climate index, then it is possible that instead of downloading the full spatial fields, one might find the condensed information has already been calculated by the ESG Federation and can be obtained through the data portals. Also, there soon will be enhanced capabilities to do some "server side" calculations, which, for example, will make it possible to extract data from a limited region or to compute means (zonal, temporal, etc.), thereby substantially reducing the data volume before downloading it.

The above-mentioned description is meant to provide a brief overview of how data will be served. Detailed step-by-step instructions on how to register and access CMIP5 model output are available (at http://cmip-pcmdi.llnl.gov/cmip5/data_getting_started.html).

SOME BASIC CONSIDERATIONS FOR USERS OF CMIP5 DATA. As described earlier, the variety of models and the complexity of the CMIP5 experiment design will confront researchers with what initially may seem like a baffling collection of model output. The key to finding data and experiments of interest is to become familiar with the simulations listed in Table 1 and with the kinds of models carrying out those simulations (also indicated in the table). If misuse of the data is to be avoided, then it is also important to understand some of the fundamental limitations of the simulations produced by the models. Here four potentially complicating issues are briefly discussed.

Unforced variability. In addition to responding to "external" forcing (attributable both to natural causes, such as volcanic eruptions, and to anthropogenic activities, such as fossil fuel burning), climate exhibits variations solely due to internal interactions within the complex nonlinear climate system. These unforced variations must be taken into account to sensibly analyze the CMIP5 output. Examples of quasi-regular internal climate variations of this sort are the El Niño events, the North Atlantic Oscillation (NAO), and, on shorter timescales, the Madden–Julian oscillation (MJO). There are, however, other variations occurring on a variety of time scales that may be much less regular (e.g., a record cold December).

A realistic climate model should exhibit internal variability with spatial and temporal structure like the observed. In the long-term simulations, however, the timing of individual unforced climate events will only by coincidence match observations. For example, the El Niño years in a "historical" climate simulation will rarely (and only by chance) coincide with years when El Niños have actually occurred. This is because the historical runs are initiated from an arbitrary point of a quasi-equilibrium control run, so internal variations (even if they were perfectly predictable) would not be expected to occur at the same time as those found in the observational record. Analysts comparing model simulations with observations should take this expected discrepancy into account and not naively attribute it to model errors. In contrast, in the AMIP simulations, sea surface temperatures are specified, based on observations, which guarantees that the occurrences of simulated historical El Niño events coincide with observations. In these runs it is possible to directly compare with observations a model's atmospheric manifestations of El Niño conditions, but agreement will still be limited by atmospheric variability not tightly coupled to SSTs.

As discussed earlier, the decadal prediction experiments are designed to explore the extent to which some of the unforced variations are in fact predictable and whether the models can make skillful probabilistic predictions over the near term. Since these runs are initialized using observations, these models may be able to track for some limited period of time the actual unforced component of climate change. It should be stressed once again, however, that this relatively new and exciting area of climate research has yet to reveal how far into the future useful information can be obtained through the initialization strategy.

Climate drift and bias correction. Below the seasonal thermocline, the ocean requires thousands of years to fully adjust to any change in external forcing. This means that the typical several-hundred-year CMIP5 control simulation, which attempts to determine the equilibrium climate for preindustrial conditions, is generally too short to eliminate residual drift (toward an eventual equilibrium). The drift may or may not significantly affect analysis of any particular aspect of the CMIP5 runs, but users should not *prima facie* assume the drift is inconsequential. If, for example, one were interested in examining how much historical warming has occurred according to some model, then the period in the control run that corresponded to the historical period would need to be examined to see if climate drift might explain part of the simulated trend. The usual approach is to assume that drift in the control run is also identically present in the corresponding period of the historical run, so simple subtraction yields trends without the artifact of residual drift. The drift will likely be most evident in variables linked to deep ocean conditions, but users should not assume the drift is negligible anywhere.

In the decadal prediction runs, a similar, but likely more significant, problem is expected. Because climate models are not perfect, their simulated equilibrium mean climate states will differ somewhat from the observed. When these models are initialized from observations, they will initially be forced away from their equilibrium states to match the observations. The model will subsequently tend to drift back toward its natural, but "biased," equilibrium state. With the exception of the deep ocean, the initial drift will be much more severe than in the long-term runs, and this will be confounded with the climate evolution that is being predicted. In contrast to the long-term simulations, drift in the near-term simulations will in complicated ways almost certainly affect nearly all variables considered. Consequently, it will be essential to correct for drifts by applying a more sophisticated "bias correction" than for the long-term runs. There is no single, accepted approach for doing this (see, e.g., CMIP–WGCM–WGSIP Decadal Climate Prediction Panel 2011). Most users will find it difficult to bias correct the decadal prediction runs; it is therefore recommended that analysis of the near-term simulations be limited to the four variables that the modeling groups themselves plan to bias correct: near-surface air temperature, surface temperature, precipitation rate, and sea level pressure.

Climate noise and "downscaling." As noted earlier, the models used in CMIP5 have grid cells typically measuring about 100 km on a side. Consequently, comparing model results to observations at point locations (e.g., at weather station sites) must account for the mismatch in the spatial representativeness of data values; an observation usually represents much more localized conditions than the model's gridcell value. Among the factors affecting the comparison are surface elevation differences, local surface characteristics affecting climate, and differences in the variability characteristics at different spatial scales.

Unforced variability (discussed earlier and sometimes referred to as "climate noise") is a reflection of natural chaotic tendencies of the climate system. It occurs across all spatial scales from local to global. Because some of the local variations offset each other when spatially averaged, the variability at the larger scales is generally smaller than it is locally. Somewhat in contrast, the climate change "signal" induced, for example, by increasing atmospheric concentrations of CO_2, tends to be spatially rather more uniform, so the local manifestation of the climate signal can often be about the same magnitude as the global signal. A consequence of the different scale dependencies of signal and noise is that their ratio generally decreases as smaller scales are considered. Thus, local climate change will more often be judged as statistically insignificant (in the context of climate noise) compared to a global-scale change of the same magnitude.

In any single climate simulation (or in observations), both the signal and noise contribute to the apparent climate change, so the signal will always be obscured to some extent by the noise. To better characterize projected climate change and, more generally, to separate signal from noise, the CMIP5 experiment design stipulates that modeling groups should perform an *ensemble* of simulations for some of the experiments. All members of an ensemble are run under identical experiment conditions, but they differ in how they have been initialized. Within a given model's ensemble of historical runs, for example, all members are forced in the same way, but each is initiated from a different point in the preindustrial control run. The different initial conditions produce different climate trajectories, with each realization assumed to be an equally likely outcome. If the observed evolving climate state were to fall within the envelope of the ensemble of model trajectories, then the model would be judged to be consistent with observations. If, however, the observed trajectory strayed far from the ensemble, then the model would be judged to be inconsistent with observations. In general these single-model ensembles of simulations can be used to assess the statistical significance of apparent differences.

One increasing demand placed on models is to provide climate change information on finer and finer spatial scales. Because of the existence of climate noise, satisfying these demands would not be trivial even with a perfect model. Nevertheless, a number of downscaling techniques (i.e., taking global climate model output and providing information of added value on scales smaller than the size of the model's grid cells) have been developed that attempt to provide information that—if accurate—would be of enormous value (e.g., to researchers studying the potential impacts of climate change on vegetation or to planners attempting to build infrastructure appropriate for climates of the future). The obvious statement that the downscaled information can be no more reliable than the climate model simulation that underlies it cannot be overemphasized; more detail does not automatically imply better information. A prudent approach by those making use of downscaled data is to consider various downscaling methods and output from multiple CMIP5 models. The spread of results found will provide some perspective concerning uncertainty. In general, careful researchers may wish to avoid consideration of downscaled information from the CMIP5 models unless they have become sufficiently aware of the limitations of both the global models and the downscaling methods.

Multimodel ensemble. The benefits of considering results from the multimodel CMIP5 ensemble is different from the value of the ensembles of simulations produced by individual models. The multimodel ensemble represents a variety of best-effort attempts to simulate the climate system. To the extent that these attempts are at least somewhat independent and that the collection of models is not systematically biased on the whole, the ensemble can be used to provide both a consensus representation of the climate system and, based on the spread of model results, provide some measure of how much confidence might be placed in that consensus.

The specific causes of the spread in any set of CMIP5 model simulations will, in general, be difficult to isolate. The variety of model formulations and model resolutions will provide a partial, and often the primary, explanation for differences in simulations. Knowing this fact, however, may not be all that enlightening since models differ in so many respects. There will also be variations in the way that the CMIP5 experiment conditions are applied in different models. In the historical experiment, for example, not all models will include exactly the same suite of aerosols. Some of the CMIP5 model experiments have been designed to determine the extent to which differences of this sort might matter, but relatively little information will be available about most differences of this kind. Finally, some of the differences among the model simulations will be due to climate "noise," which, as discussed earlier, can be quantified using initial condition ensembles produced by individual models. In general, users of CMIP5 output will have to become familiar with all the model differences and variations on the experimental conditions before attempting an explanation of the spread in simulation results.

SUMMARY. CMIP5, as in earlier CMIP phases, calls for integrated sets of experiments that offer a multimodel perspective of simulated climate change and climate variability. Most modeling groups worldwide are participating in CMIP5, and their simulations are expected not only to be useful to research scientists in a variety of climate-related disciplines but also of relevance to national and international assessments of climate science (e.g., the IPCC AR5).

The CMIP5 experiment design focuses on two time scales: one, the long-term, spanning from the midnineteenth century through the twenty-first century and beyond, and the other, the nearer term out to 2035. The long-term experiments build on the design of past phases of CMIP and include, for example, runs for studying unforced variability, climate change over the historical period, and projected climate change to the end of the century and beyond. For the first time in CMIP, these traditional long-term experiments will be performed by ESMs, as well as by AOGCMs and EMICs. The ESMs, which include at least a full representation of the carbon cycle, will in some experiments be driven by prescribed concentrations of CO_2 so that their results can be compared directly to the AOGCMs. Additional ESM simulations will be driven by prescribed emissions of CO_2. Both types of experiments can be used to study carbon feedbacks on climate change and the impacts of climate change on terrestrial and marine ecosystems.

The near-term decadal prediction experiments are an entirely new addition to CMIP. They will be initialized from observed states of the climate system to explore climate predictability and prediction on decadal to multidecadal time scales. One of the aims of CMIP5 is to identify the variables that can be skillfully predicted and to determine for each variable how long (following initialization) some predictive skill remains evident. The near-term predictive skill will not only depend on the skill of the models but also on the methods used to initialize them and the quality and coverage of the ocean observations.

The CMIP5 model output is freely available to all researchers through gateways linked to modeling and data centers worldwide, where the data will be archived. Compared to previous phases of CMIP, not only will a more comprehensive set of output be produced but better documentation will be made available. A key to CMIP5's usefulness is that all model output conforms to community standards and is placed in an archive that appears to users as a single unified database. This makes analysis of the multimodel ensemble nearly as easy as analysis of a single model.

CMIP5 will ultimately be judged on the research it enables. If scientists can successfully obtain CMIP5 model output from the archive and use it to address fundamental scientific questions concerning climate and climate change, and if results of that research are published and inform key scientific assessments (e.g., the IPCC AR5), then CMIP5 should be considered a success. Thus, the scientific impact of CMIP5 depends on the interest of and contributions by scientists who are analyzing this rich set of climate model results. In addition, if these scientists discover aspects of a simulation that are surprising, puzzling, or simply at odds with observations, then they are under obligation to report this information back to the responsible modeling group. In this way, those whose research benefits from CMIP5 can assist scientists at the modeling centers who are working to devise and implement model improvements necessary for the further advancement of climate science.

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