Coupled Climate Model Appraisal: A Benchmark for Future Studies

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Studies of future climate scenarios, such as those conducted in support of the Intergovernmental Panel on Climate Change (IPCC, http://www.ipcc.ch/), rely heavily on numerical experiments performed with coupled ocean-atmosphere general circulation models (OAGCMs). In order to assess the results of such climate change experiments, a benchmark for evaluating model performance is required. To provide this benchmark, Lawrence Livermore National Laboratory's Program for Climate Model Diagnosis and Intercomparison (PCMDI) conducted an extensive appraisal of multidecadal climate simulations by 11 coupled OAGCMs that were developed during the period of 1995–2002 [*Bader et al.,* 2004].

While diverse representations of atmosphere, ocean, sea ice, land, and of their respective couplings were employed (see Table 1), all of these climate models were run with current values of solar and greenhouse gas radiative forcings. Thus, by comparing details of the OAGCM simulations with analogous facets of climate observations, the needed model-performance benchmark can be obtained. If, for instance, a model simulation closely replicates the salient features of the present climate, a necessary (though not sufficient) condition is met for placing some confidence in the model's projections of the climate of the next several decades.

OAGCMs were selected for inclusion in the coupled model appraisal by virtue of their participation in the most recent phase of the Coupled Model Intercomparison Project (CMIP, http://www-pcmdi.llnl.gov/cmip/index.php), which was coordinated by PCMDI under the auspices of the World Climate Research Programme's Working Group on Coupled Modelling. Model sponsors participating in this 'CMIP2+' phase of the intercomparison agreed to supply all available output variables from their simulations of the present climate. The appraisal focused on three facets of these CMIP2+ simulations: (1) century-scale trends in climatic time series; (2) decadal-scale climatologies of ocean/atmosphere fields; and (3) intradecadal modes of climatic variability. Highlights of these aspects of the CMIP2+ simulations are briefly discussed here.

Century-Scale Trends

The coupled atmosphere-ocean climate state at the start of a given CMIP2+ simulation was achieved in a model-specific way. The initial uncoupled state of the ocean component model was specified from Levitus World Ocean Atlas observations (http://www.cdc.noaa.gov/cdc/data.nodc.woa98.html). The uncoupled atmospheric state was obtained by running the model atmosphere for one to two decades with prescribed seasonally varying ocean surface temperatures, which were specified somewhat differently for each CMIP2+ model. Then the atmospheric and oceanic components were coupled and run for various 'spin-up' periods (see Table 1) prior to the nominal start of a given CMIP2+ simulation. In most of the coupled runs, various ad hoc surface flux adjustments also were applied (see Table 1) so as to minimize a problematical model behavior known as 'climate drift,' where aspects of the evolving coupled simulation (e.g., sea surface temperatures) diverge increasingly from a realistic equilibrium state.

To identify instances of climate drift, century-scale trends were examined in the simulated time series of surface temperatures, sea ice extents, and deep-ocean temperatures and salinities. No substantial climate drift was found in any simulation of surface temperature, even for models that did not employ flux adjustments. While larger trends were present in sea ice extents and deep-ocean

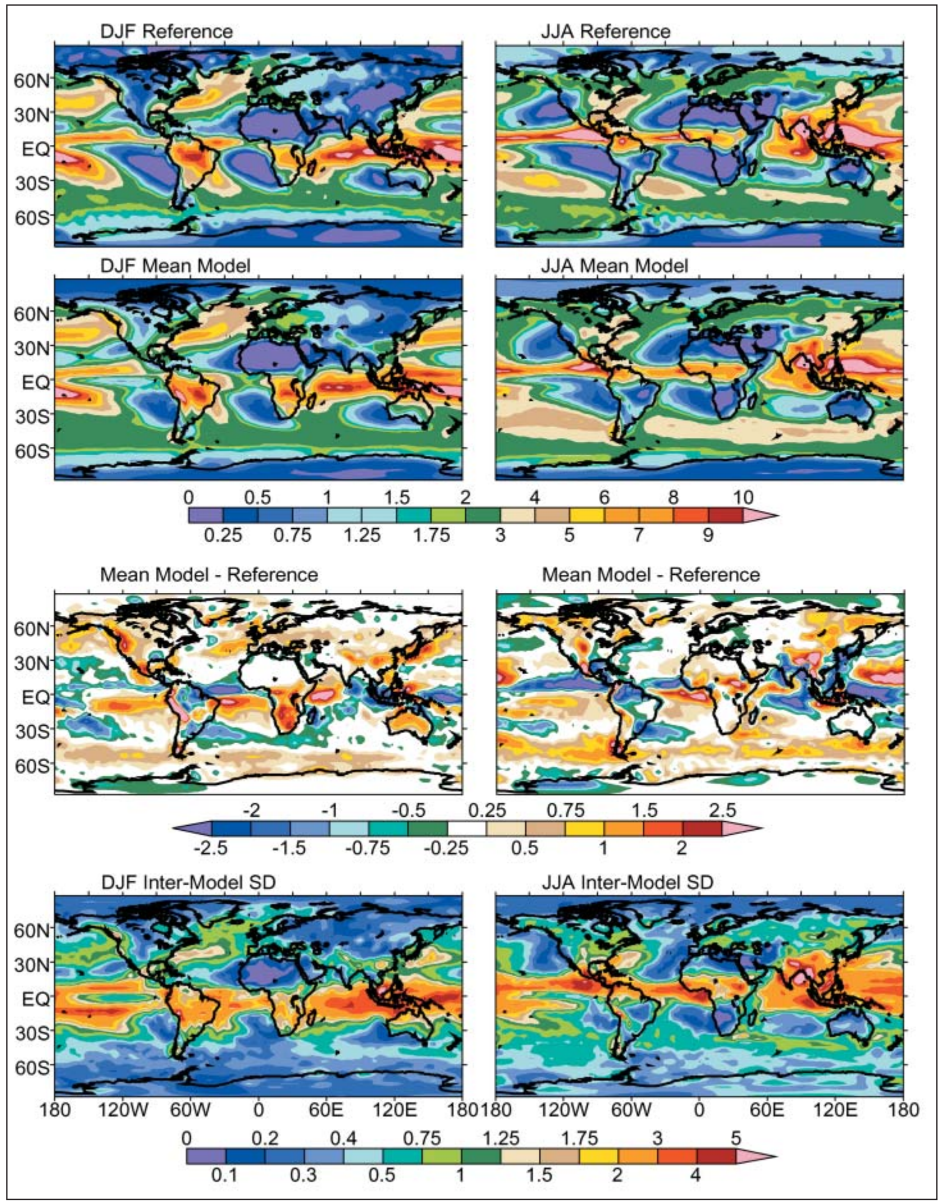

Fig. 1. Simulation-observation comparisons of December-January-February (DJF) and June-July-August (JJA) total precipitation (in millimeters per day). (top row) Climatic Prediction Center (CPC) merged analysis of precipitation (CMAP) observation-based data (http://www.cdc.noaa.gov/cdc/data.cmap.html). (second row) Multimodel ensemble mean (BCM02 model data not included). (third row) Multimodel ensemble-mean departures from CMAP. (bottom row) Ensemble cross-model standard deviation. Note that nonlinear scales are used for all plots and that the multimodel ensemble statistics and observational estimates are interpolated to a common (~3 × 3 degree) grid.

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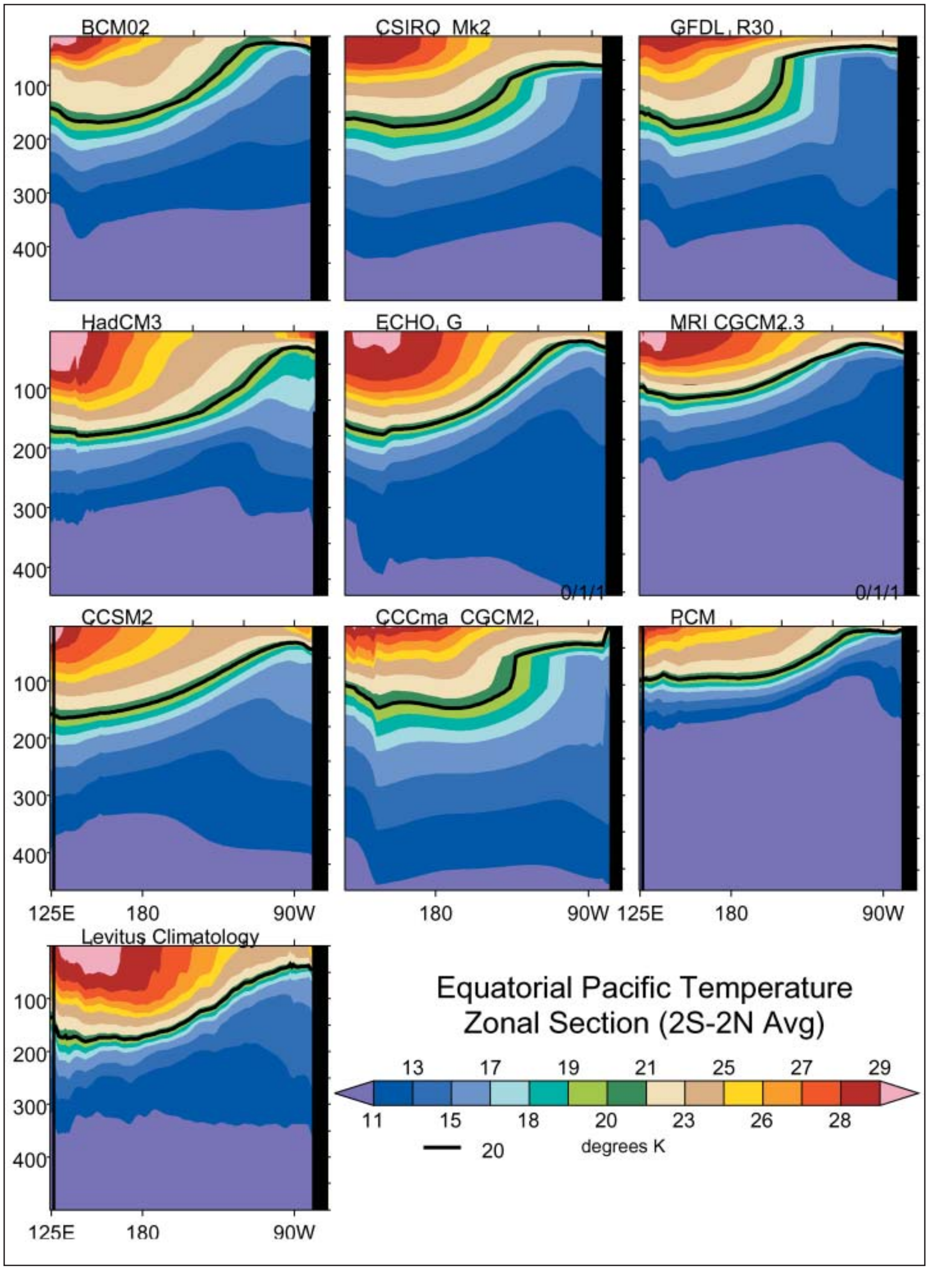

Fig. 2. Equatorial Pacific (averaged 2°S–2°N) simulations of 20-year climatologies of upper ocean temperature in CMIP2+ models (ECHAM4_OPYC and HadCM2 models (see Table 1) not included) compared with the Levitus observations.

Table 1. Salient Features of the CMIP2+ Models and Respective Simulations of the Present Climate[a]

Model, Vintage	Institutional Sponsor, Country	Atmosphere: Resolution TOA pressure	Ocean: Resolution Vertical Coordinates	Sea Ice: Dynamics Structure	Land: Soil Plants	Coupling: Spin-Up Duration Flux Adjustments
BCM02,2002	University of Bergen, Norway	1.9° × 1.9° L31 10 hPa	2.4° × 2.4° L24 density	rheology leads	layers canopy	25 years heat, freshwater
CCCma_CGCM2,2002	Canadian Centre for Climate Modelling and Analysis, Canada	3.7° × 3.7°L10 5 hPa	1.9° × 1.9° L29 depth	rheology leads	bucket no canopy	50 years heat, freshwater
CCSM2.0, 2002	National Center for Atmospheric Research, U.S.	2.8° × 2.8°L26 2.9 hPa	1.0° × 1.0° L40 depth	rheology leads	layers canopy	350 years no adjustments
CSIRO_Mk2,1997	Commonwealth Scientific and Industrial Research Organisation, Australia	3.2° × 5.6° L9 21 hPa	3.2° × 5.6° L21 depth	rheology leads	layers canopy	105 years heat, freshwater, momentum
ECHAM4_OPYC3, 1996	Max Planck Institute for Meteorology, Germany	2.8° × 2.8° L19 10 hPa	2.8° × 2.8° L11 density	rheology leads	bucket canopy	100 years heat, freshwater
ECHO-G, 1999	Model and Data Group, Germany	3.8° × 3.8° L19 10 hPa	3.8° × 3.8° L20 depth	rheology leads	bucket canopy	310 years heat and freshwater anomalies
GFDL_R30_c, 1996	Geophysical Fluid Dynamics Laboratory, U.S.	2.3° × 3.8° L14 15 hPa	1.9° × 2.3° L18 depth	no rheology no leads	bucket no canopy	900 years heat, freshwater
HadCM2, 1995	Hadley Centre, Met Office, U.K.	2.5° × 3.8° L19 5 hPa	2.5° × 3.8° L20 depth	no rheology leads	layers canopy	~ 500 years heat, freshwater
HadCM3, 1997		2.5° × 3.8° L19 5 hPa	1.5° × 1.5° L20 depth	no rheology leads	layers canopy	400 years no adjustments
MRI_CGCM2.3, 2002	Meteorological Research Institute, Japan	2.8° × 2.8° L30 0.4 hPa	2.0° × 2.5° L23 depth	no rheology leads	layers canopy	95 years heat, freshwater
PCM, 1999	Department of Energy, U.S.	2.8° × 2.8° L18 2.9 hPa	0.7° × 0.7° L32 depth	rheology leads	layers canopy	50 years no adjustments

[a]Among the included features are the approximate year of model development ('vintage'), and the institutional sponsor and country. Also listed are the horizontal and vertical resolution of the model atmosphere and ocean (approximate latitude × longitude size of a grid cell and the number of vertical levels L) as well as the pressure model top-of-atmosphere (TOA) (in units of hectopascals, hPa) and the vertical coordinate (depth or density) of the model ocean. The representation of sea ice dynamics and structure (explicit rheology, inclusion of ice leads), and of land hydrology (single-layer 'bucket' or layered soil column) and vegetation (inclusion of canopy biophysics) also are indicated. In addition, selected aspects of the ocean-atmosphere coupling are noted, including the duration of the coupled spin-up period prior to the nominal start of each simulation and the application of surface flux adjustments (in heat, freshwater, or momentum) designed to ameliorate model 'climate drift.'

variables, these were small enough to imply that each model had achieved a coupled climate state which was sufficiently equilibrated for simulation statistics to be compared with recent climate observations [*Covey et al.,* 2006].

Decadal-Scale Climatologies

As a key measure of OAGCM performance, twenty-year statistical means (climatologies) of diverse model atmospheric and oceanic fields were compared to those derived from global observations of recent decades (most since about 1980). For atmospheric variables, the multimodel ensemble mean of each field was evaluated after remapping to a common (~3 × 3 degree) grid. Owing to partial cancellation of errors in this averaging over different models, the ensemble-mean field usually agreed better with observations than any single simulation. Thus, deviations of the multimodel means from reference data were symptomatic of general problems in the CMIP2+ models.

For instance, while seasonal climatologies of ensemble-mean precipitation agreed fairly well with large-scale observed patterns, their magnitudes were deficient in the tropical convergence zones but excessive in the subtropical eastern oceans (Figure 1). Intermodel variations were also large in tropical convergence zones and to some extent in the midlatitude storm tracks, indicating substantial differences in the individual simulations of finer-scale features.

Each model's combination of annual-mean continental precipitation and surface air temperature also was regionally categorized according to Köppen geographical climatic regimes (tropical, desert/steppe, temperate, snowy, and polar). Comparison with observed regimes was fairly good over most regions, and was better still for the ensemble-mean model climatology (M. Fiorino, An assessment of climate model performance using the Köppen classification system, submitted to *Climate Dynamics,* 2005).

In addition, spatiotemporal measures of similarity with observations [*Taylor,* 2001] were calculated for diverse ensemble-mean atmospheric fields. The greatest similarity was seen in fields of midtropospheric geopotential height, lower tropospheric humidity, mean sea level pressure, outgoing longwave radiation, surface air temperature, and upper tropospheric winds. The least agreement with observations was displayed by simulated fields of surface sensible and latent heat fluxes, total cloud cover, and upper tropospheric temperatures.

For each CMIP2+ ocean model, profiles of abyssal temperature and salinity climatologies in the major basins were compared with the Levitus observations, which also had been used to initialize each ocean model. Because the typical abyssal ocean model requires many centuries of coupled spin-up to evolve to a substantially different climatic state, qualitative similarities remained between the CMIP2+ ocean simulations and the Levitus observations in many basins. A notable exception was the Arctic Ocean, where the generally poor quality of the simulations (not shown) may have been due to flawed model representations of heat/salinity transport, vertical mixing, and/or the insulating effects of sea ice.

In some areas, the simulated upper oceans also differed noticeably from the Levitus data, as seen in cross sections of simulated equatorial Pacific upper ocean temperatures (Figure 2). While all models displayed the correct sign of the east-west equatorial temperature gradient (warm west Pacific and cold east Pacific), they showed mixed success in replicating its observed steepness. Different tropical north-south ocean temperature gradients also produced sizeable deviations of model equatorial Pacific currents from observationally based analyses.

Intradecadal Modes of Climatic Variability

Analyzed modes of climatic variability included the Madden-Julian Oscillation which displays a distinct atmospheric signature on intraseasonal time scales in the tropics, as well as the lower-frequency North Atlantic Oscillation and El Niño–Southern Oscillation (ENSO).

In the case of ENSO, most models displayed the observed seasonal phase-locking of their composite warm events, with maximum amplitude during northern winter (Figure 3a). However, the ENSO amplitudes of some models fell outside the one-standard-deviation envelope of the observed warm events. Models with weak simulated events failed to reproduce the observed ENSO periodicity of two to seven years, while the peak power of overly strong events mostly occurred at the lower end of this range (Figure 3b). Compared with ENSO simulations of antecedent CMIP models, the CMIP2+ models exhibited greater realism, and current-generation

OAGCMs generally show still better agreement with observations [*AchutaRao and Sperber,* 2006].

Future Studies

While the PCMDI appraisal is more extensive than previous analyses of this type, it renders only a performance snapshot of models that are undergoing continual development. The appraisal's enduring value is that it provides a standard against which to measure the performance of new OAGCMs.

Especially significant for further studies of this type are the multiple OAGCM simulations of historical climate and future climate scenarios that were recently produced in support of the IPCC's Fourth Assessment Report, which is scheduled for publication in 2007. These include a greater amount of model output data than were previously available and thus will require unprecedented cooperative efforts to analyze.

To this end, PCMDI is providing storage facilities and associated infrastructural support for disseminating these model data to contributing climate scientists (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). This commitment demands the continuing enhancement and refinement of PCMDI's working set of diagnostic methods, data management tools, and visualization/computation software.

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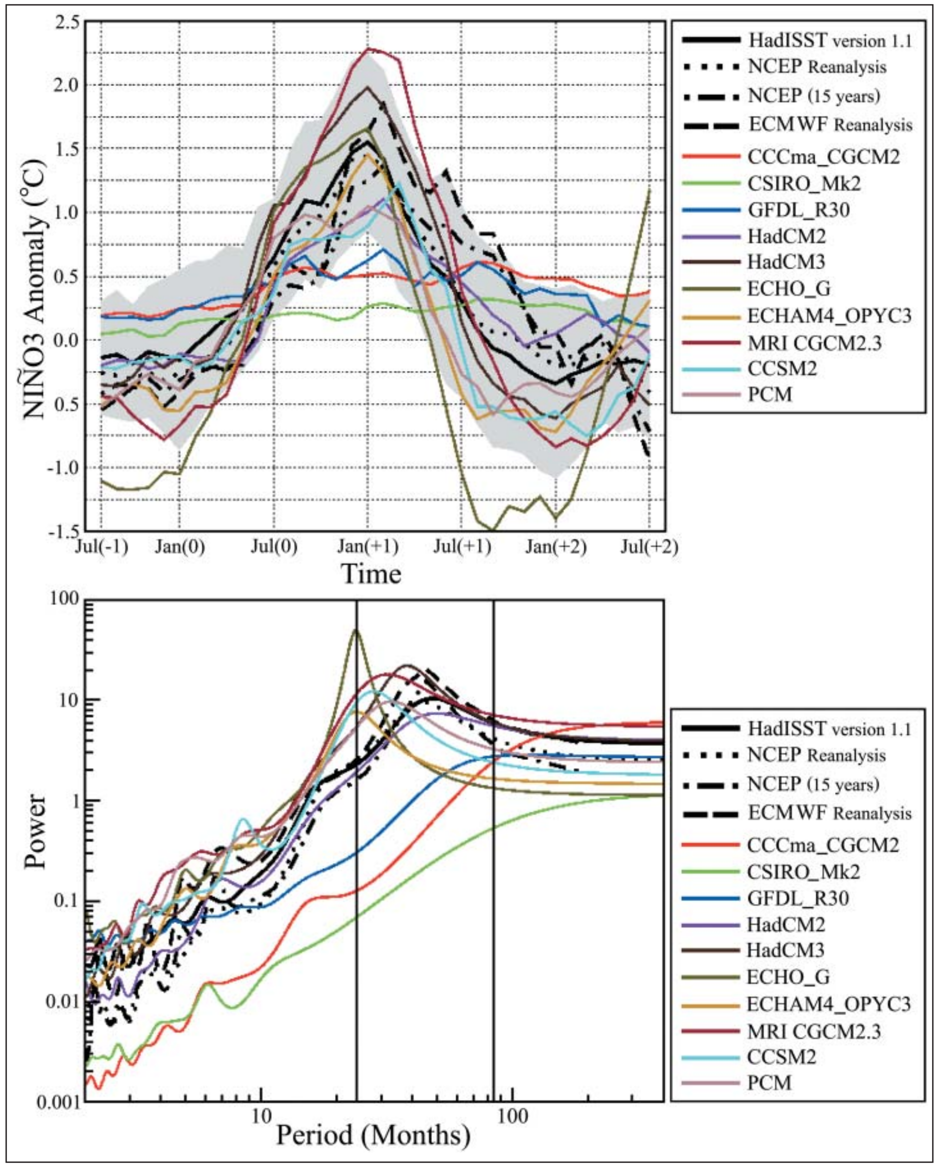

Fig. 3. Aspects of CMIP2+ model simulations of the ENSO compared with observation-based estimates. (a) The evolution of the surface air temperature anomaly in the NIÑO3 region (5°S–5°N and 150°W–90°W) is shown for a composite warm event in 10 models (BCM02 data not included), in reanalyses of the National Centers for Environmental Prediction (http://www.cdc.noaa.gov/cdc/reanalysis/ reanalysis.shtml) and the European Centre for Medium-Range Weather Forecasts (http://www.ecmwf.int/research/era/ERA-15/), as well as in the HadISST 1.1 sea surface temperature data set (http://badc.nerc.ac.uk/data/hadisst/). The shaded area represents the one-standard-deviation envelope of the observed NIÑO3 sea surface temperature anomaly for warm events in the HadISST 1.1 data set. (b) The maximum entropy power spectra calculated from the available CMIP2+ model monthly mean surface air temperature anomalies are compared with that obtained from HadISST1.1 sea surface temperature anomalies, both for the NIÑO3 region (BCM02 model data not included). Vertical lines correspond to two- and seven-year periods, respectively.

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