meeting summary

The Coupled Model Intercomparison Project (CMIP)

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ABSTRACT

The Coupled Model Intercomparison Project (CMIP) was established to study and intercompare climate simulations made with coupled ocean–atmosphere–cryosphere–land GCMs. There are two main phases (CMIP1 and CMIP2), which study, respectively, 1) the ability of models to simulate current climate, and 2) model simulations of climate change due to an idealized change in forcing (a 1% per year CO_2 increase). Results from a number of CMIP projects were reported at the first CMIP Workshop held in Melbourne, Australia, in October 1998. Some recent advances in global coupled modeling related to CMIP were also reported. Presentations were based on preliminary unpublished results. Key outcomes from the workshop were that 1) many observed aspects of climate variability are simulated in global coupled models including the North Atlantic oscillation and its linkages to North Atlantic SSTs, El Niño–like events, and monsoon interannual variability; 2) the amplitude of both high- and low-frequency global mean surface temperature variability in many global coupled models is less than that observed, with the former due in part to simulated ENSO in the models being generally weaker than observed, and the latter likely to be at least partially due to the uncertainty in the estimates of past radiative forcing; 3) an El Niño–like pattern in the mean SST response with greater surface warming in the eastern equatorial Pacific than the western equatorial Pacific is found by a number of models in global warming climate change experiments, but other models have a more spatially uniform or even a La Niña–like, response; 4) flux adjustment, by definition, improves the simulation of mean present-day climate over oceans, does not guarantee a drift-free climate, but can produce a stable base state in some models to enable very long term (1000 yr and longer) integrations—in these models it does not appear to have a major effect on model processes or model responses to increasing CO_2; and 5) recent multicentury integrations show that a stable surface climate can be attained without flux adjustment (though still with some systematic simulation errors).

1. Introduction

The first gathering of the international global coupled climate modeling community was at a workshop held at Scripps Institution of Oceanography in La Jolla, California, in October 1994 organized under the auspices of the World Climate Research Programme (WCRP). The meeting was convened specifically to examine the state of the art in global coupled climate modeling. It was recommended that an "intercomparison . . . be performed for the . . . set of models [then] in use" (Meehl 1995). At about the same time, data from many of these models were collected and analyzed by S. Lambert and G.J. Boer for the Intergovernmental Panel on Climate Change Second Assessment Report (Gates et al. 1996).

The Coupled Model Intercomparison Project (CMIP) was initiated by the Climate Variability and Predictability (CLIVAR) Numerical Experimentation Group 2 (NEG2, subsequently reconstituted as the WCRP Working Group on Coupled Models, WGCM) late in 1995, partially as an outgrowth of these two ef-

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TABLE 1. Model participation in CMIP1. Asterisks denote those models also participating in CMIP2.

Model	Flux correction	Run length (yr)	Comments
*BMRC	none	105	no std dev or ocean data
*CCCMA	heat, water	150	
*CCSR	heat, water	40	
*CERFACS	none	40	
COLA	none	50	
*CSIRO	heat, water, momentum	100	
*DOE PCM	none	300	
ECHAM1+LSG	heat, water, momentum	960	temperature time series data only
*ECHAM3+LSG	heat, water, momentum	1000	no flux-correction fields
ECHAM4+OPYC3	heat, water (ann. mean)	240	
*GFDL	heat, water	1000	
GISS (Miller)	none	89	
*GISS (Russell)	none	98	no decadal std dev or barotropic stream function
*IAP/LASG	*sea surface salinity restored to obs*	50	
*LMD/IPSL	none	24	no decadal std dev
*MRI	heat, water	100	no ocean heat transports
*NCAR (CSM)	none	300	
*NCAR (Wash. & Meehl)	none	100	
*NRL	*sea ice prescribed to obs*	36	
*UKMO (HadCM2)	heat, water	1085	
*UKMO (HadCM3)	none	80	in CMIP2 only

forts. The next year under the first phase of CMIP (CMIP1), model data from unforced climate from 21 global coupled atmosphere–ocean–ice models were archived at the U.S. Department of Energy Program for Climate Model Diagnosis and Intercomparison (PCMDI) at the Lawrence Livermore National Laboratory (Table 1). This set represented virtually every global coupled model in existence at the time (Meehl et al. 1997). About half of the models use some form of flux adjustment or anomaly coupling (whereby the fluxes of heat, water, and momentum, either singly or in combination, are adjusted at the air–sea interface to compensate for errors in the model components and to minimize climate drift). The second phase of CMIP (CMIP2) was designed to compare the climate changes simulated by the models for an idealized change in forcing of 1% per year increase in CO_2. CMIP2 was initiated in early 1997, and data were collected from 17 of the CMIP1 models (Table 1).

The analysis of the data is largely undertaken through "diagnostic subprojects," which concentrate on a particular aspect of climate and model behavior and that attempt to entrain analysis expertise from outside of the modeling community. Diagnostic subprojects were initiated for CMIP1 starting in February 1997 and for CMIP2 starting in February 1998. Currently there are 10 CMIP1 subprojects and 11 CMIP2 subprojects, as indicated in Table 2.

The first CMIP workshop, hosted by the Bureau of Meteorology Research Centre (BMRC), was held in Melbourne, Australia, 14–15 October 1998. The purpose of the workshop was to update the status of global coupled modeling in the context of CMIP, and to discuss future directions for coupled model intercomparison studies.Results and status reports from the CMIP subprojects were presented, in addition to the latest results from global coupled models related to the goals of CMIP.

2. Topics from the workshop

A variety of studies of features and processes in the control climates of the CMIP1 models were reported.

1) Flux adjusted and nonflux adjusted models were compared in terms of their simulated tropical Pacific El Niño–like variability.
2) The decadal timescale surface air temperature variability was examined to look for "potential local predictability" (e.g., places where the local variability is significantly larger than what is expected from a red noise fit to the power spectrum).
3) High-frequency (timescales less than 10 yr) surface temperature variability and interhemispheric temperature correlations were compared to observations.
4) Low-frequency variability of surface temperature on the multidecadal timescale was analyzed.
5) Evidence for the presence of the Antarctic Circumpolar Wave (a decadal timescale propagation of SST anomalies around the circumpolar southern ocean) in coupled models was shown.
6) The results for CMIP1 models were displayed in various ways including the calculation of systematic model errors and the spread of model results via intermodel standard deviations for both atmospheric and oceanic quantities.
7) The seasonal cycle of zonal mean surface temperature was analyzed in both nonflux adjusted models and flux adjusted models, and possible linkages between climate sensitivity and seasonal cycle amplitude were shown (see also Covey et al. 1999, manuscript submitted to *Climate Dyn.*).

As noted above, CMIP2 subprojects consider the models' responses to increasing the CO_2 concentration by 1% per year (corresponding to a linear increase in radiative forcing). The CMIP2 subproject announcement was only sent out in early 1998, so a number of the approved subprojects were in the very early stages of analysis. However, some preliminary analyses were discussed.

1) An analysis of simulated climate change was performed over northern Europe to examine relationships between regional precipitation and temperature changes related to global mean quantities.
2) The dynamical ocean response was studied in terms of a possible feedback that could alter and even amplify the warming of the climate system associated with an increase of CO_2. The possible causes for the collapse of the thermohaline circulation in the North Atlantic in response to global warming were examined.

Other results presented were related to the more general goals of CMIP.

a. *Model improvements*

- Nonflux adjusted models are now being integrated in control-run modes for longer and longer periods of time, the latest in excess of 800 yr, with comparatively little surface drift. This strongly indicates a significant reduction of the systematic errors in the component models, and an advance in our ability to more accurately model the climate system.
- Improvements to the simulation of tropical Pacific phenomena were related to better atmospheric convection schemes and improved upper ocean mixed layer formulations.

TABLE 2. List of CMIP1 and CMIP2 subprojects with main points of contact.

CMIP1 subprojects	CMIP2 subprojects
1) Analysis of variance in the CMIP coupled models Tim Barnett UCSD/Scripps Institution of Oceanography, La Jolla, CA	1) East Asia climate change Wei-Chyung Wang University at Albany, State University of New York, Albany, NY
2) North Atlantic oscillation (NAO) variability (NAOMIP) David Stephenson University Paul Sabatier, Laboratoire de Statistique, Toulouse, France	2) Signal detection in the CMIP2 model integrations Tim Barnett UCSD/Scripps Institution of Oceanography, La Jolla, CA
3) Documentation of interannual variability and coupled processes Marc Pontaud Direction InterRegionale de Météo-France en Polynesie Francaise, Tahiti, French Polynesia	3) Dynamic response of the ocean to global warming Scott Power Bureau of Meteorology Research Centre, Melbourne, Australia
4) Simulation of the cryosphere in coupled models Gregory M. Flato Canadian Centre for Climate Modelling and Analysis, Victoria, BC, Canada	4) Climate change in northern Europe Jouni Räisänen Rossby Centre, Norrköping, Sweden
5) Potential predictability of the coupled system at long timescales George J. Boer and Francis Zwiers Canadian Centre for Climate Modelling and Analysis, Victoria, BC, Canada	5) Energetics of coupled models: Role of oceanic heat transport on climate and climate change Emmanuelle Cohen-Solal and Jean-Louis Dufresne LMD, Paris, France
6) Autocorrelation analysis of the hemisphere O/AGCM control-run temperature data Tom Wigley National Center for Atmospheric Research, Boulder, CO Richard Smith and Ben Santer Lawrence Livermore National Laboratory, Livermore, CA	6) The correlation between oceanic structure, ocean circulation, and heat transport in coupled models Yanli Jia and David Webb Southampton Oceanography Centre, Southampton, United Kingdom
7) East Asia climate Wei-Chyung Wang University at Albany, State University of New York, Albany, NY	7) Biospheric carbon cycle response to global warming Pierre Friedlingstein LSCE, Paris, France
8) Southern mid-to-high-latitude variability Wenju Cai CSIRO, Aspendale, Australia	8) Effective climate sensitivity Sarah Raper Climatic Research Unit, UEA, East Anglia, United Kingdom
9) Analysis of coupled model variance David Ritson Stanford University, Palo Alto, CA	9) Ocean thermal expansion and heat uptake in climate change experiments Jonathan Gregory Hadley Centre, Bracknell, United Kingdom
10) Effect of flux adjustments on interannual and decadal variability in the CMIP ocean–atmosphere climate models P. B. Duffy and Curt Covey Lawrence Livermore National Laboratory, Livermore, CA Jason Bell University of California, Santa Cruz, Santa Cruz, CA	10) Vertical structure of warming in CO_2 climate change experiments S. Fred Singer SEPP, Fairfax, VA
	11) Analysis of climate variability and change using simple global indices David Karoly CRC for Southern Hemisphere Meteorology, Clayton, Australia

- Versions of a global coupled model using the same atmospheric component coupled to different ocean model components allow a comparison of the effects of different ocean dynamics on coupled simulations.
- A spinup technique that couples components in sequence, with each equilibrating to the forcing from the other model components in turn, reduces climate drift in a fully coupled model.

b. Detection/attribution

- A comparison of the local radiative forcing to the local response in a global coupled model showed that an accounting of global forcing could provide a first-order indicator of the local response.
- Time-evolving solar forcing (in which forcing changes are substantial at frequencies lower than the 11-yr solar cycle) could account for about one-third of the global warming observed over the instrumental record consistent with previous experimental results. However, the estimates of the past solar radiative forcing are highly uncertain as is the climate model response to that solar forcing.

c. Processes (El Niño, decadal variability, etc.)

- An El Niño–like pattern in the SST response to increased CO_2, with greater mean surface warming in the eastern equatorial Pacific than in the western equatorial Pacific, has been seen in some global coupled models. This response is related in part to cloud feedbacks that produce asymmetric cloud radiative forcing across the Pacific, with a consequent slackening of the west–east SST gradient and associated eastward shifts of precipitation. However, some global coupled models do not show the El Niño–like response to increasing CO_2; some even show a La Niña–like response where mean surface temperatures warm more in the western Pacific than the east.
- The larger-scale implications of the El Niño–like response (described above) were associated with changes in precipitation and evaporation patterns. These changes lead to a decrease of salinity in the tropical Pacific and an increase in the Atlantic, with possible implications for the strength of the meridional overturning circulation in the North Atlantic.
- Analyses have been performed to examine future changes in amplitude of El Niño events, though inherent low-frequency variability of tropical Pacific surface temperature makes such changes difficult to diagnose in most models.
- Models generally simulated a decrease of the meridional overturning circulation in the Atlantic with CO_2-induced climate change consistent with earlier coupled model simulations, but the amount of decrease varied markedly from model to model.
- On longer timescales, decadal oscillations of the North Atlantic gyre in a global coupled model were linked to ocean advection reinforced by latent heat flux variations.
- A Decadal Pacific Oscillation Index was studied in relation to similar timescale fluctuations in the connections between Australian rainfall and the Southern Oscillation index.

d. Model responses to forcings

- The "commitment" to further warming when increasing CO_2 concentrations are stabilized was analyzed.
- The collapse of the Antarctic overturning cell in the ocean (and associated Antarctic bottom water formation) was simulated in some models with increasing CO_2, but the levels of equivalent CO_2 required for this to occur in the models differs, and could also be a function of the ocean parameterizations.

e. Paleoclimate

- A coupled model simulation of mid-Holocene climate was analyzed to study the strength of the African monsoon related to paleoclimatic data.

3. Summary

Presentations at the workshop generally reinforced the results of earlier analyses (with different models) already published in the scientific literature. Other results, however, were new. Many of these results were preliminary and are subject to revision upon further study and analysis. These preliminary results and analyses, however, highlight the directions of current research. They suggest the following:

1) Many observed large-scale climate processes are represented in the global coupled models, including the North Atlantic oscillation, the Antarctic Circumpolar Wave, El Niño–like events, and monsoon interannual variability. The continued study of these phenomena are basic aspects of model evaluation.
2) The high-frequency surface air temperature variability is typically underestimated due in part to the

ENSO in the models having too small an amplitude. This is associated with the coarse resolution and simplified parameterizations used in this class of climate models. There are some suggestions that the low-frequency variability is also underestimated in the models, though there is uncertainty in the estimates of past radiative forcing that warrants caution in such studies.

3) In global warming climate change experiments, an El Niño–like pattern in the mean SST response such that eastern equatorial Pacific SSTs warm faster than western equatorial Pacific SSTs, is simulated by a number of models. Other models simulate a more spatially uniform, or even a La Niña–like, response. Understanding this reason for the different responses has implications for possible future climate change anomalies in the Pacific region and in extratropical regions where El Niño influences are important.
4) Comparison of results of global coupled models with and without flux adjustment indicates that flux adjustment, by definition, generally improves the simulation of mean present-day climate over ocean areas, and can produce a stable base state in some models to enable very long term (1000 yr and longer) integrations. Yet some flux adjusted models still exhibit considerable drift, while some newer models with no flux adjustment have comparatively little drift. Overall, model responses do not appear to be influenced by flux adjustment in a major way.
5) Coupled models continue to evolve rapidly, with enhanced resolution (some atmospheric GCMs are now at about 2.5° latitude–longitude resolution, and some ocean GCMs at about 1° latitude–longitude resolution), and better physical parameterizations (e.g., clouds, convection, etc.). Recent multicentury integrations that produce a stable surface climate without flux adjustment (though still with some systematic simulation errors) are a sign of the benefits of these improvements in the model components.

4. Future CMIP activities

1) Additional CMIP integrations (present-day climate control runs and 1% per year CO_2 increase simulations) will continue to be collected for intercomparison by diagnostic subprojects.
2) A CMIP pilot project is being initiated to intercompare global coupled model simulations of intraseasonal variability (the Madden–Julian oscillation). This activity is intended to facilitate, under the auspices of CLIVAR, a transfer of knowledge derived from TOGA COARE to the global coupled modeling community in order to apply that knowledge to the improvement of the models.
3) Future CMIP initiatives will consider collecting more elaborate climate change scenario integrations (over and above 1% per year increase of CO_2) for intercomparison studies, along with a wider range of model variables with increased time resolution.

For more information, see the CMIP Web site (http://www-pcmdi.llnl.gov/cmip).

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References

Gates, W.L., and Coauthors, 1996: Climate models—Evaluation. *Climate Change 1995: The Science of Climate Change,* J.T. Houghton et al., Eds., Cambridge University Press, 229–284.

Meehl, G.A., 1995: Global coupled general circulation models. *Bull. Amer. Meteor. Soc.,* **76,** 951–957.

——, G.J. Boer, C. Covey, M. Latif, and R.J. Stouffer, 1997: Intercomparison makes for a better climate model. *Eos, Trans. Amer. Geophys. Union,* **78,** 445–446, 451.