THE WCRP CMIP3 MULTIMODEL DATASET

A New Era in Climate Change Research

BY GERALD A. MEEHL, CURT COVEY, THOMAS DELWORTH, MOJIB LATIF, BRYANT MCAVANEY, JOHN F. B. MITCHELL, RONALD J. STOUFFER, AND KARL E. TAYLOR

Open access to an unprecedented, comprehensive coordinated set of global coupled climate model experiments for twentieth and twenty-first century climate and other experiments is changing the way researchers and students analyze and learn about climate.

The history of climate change modeling was first characterized in the 1980s by a number of distinct groups developing, running, and analyzing model output from their own models with little opportunity for anyone outside of those groups to have access to the model data. This was partly a consequence of relatively primitive computer networking and data transfer capabilities, along with the daunting task of collecting and storing such large amounts ▶

of model data (Meehl 1995). Starting in the mid-1990s, a World Climate Research Programme (WCRP) committee [now named the WCRP/Climate Variability and Predictability (CLIVAR) Working Group on Coupled Models (WGCM)] organized the first global coupled climate model intercomparison exercise whereby modeling groups performed control runs and idealized 1% yr^{-1} CO_2 increase experiments (Meehl et al. 1997). A subset of model data was then collected and archived at the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and made available to researchers outside the modeling groups. Subsequently there were several additional phases of the Coupled Model Intercomparison Project (CMIP), termed CMIP2 and CMIP2+ (Meehl et al. 2000, 2005b; Covey et al. 2003). The latter marked the first time that every field from each model component (atmosphere, ocean, land, and sea ice) from the control and 1% CO_2 increase experiments was collected and made available for analysis. However, only output from the control runs and 1% CO_2 experiments were collected because those represented the most scientifically straightforward response of the climate system to an unambiguous change in external forcing. Limitations in data transfer and storage still restricted the collection of output from the early climate change scenario experiments [e.g., experiments using the IS92a scenario as described in the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report; Kattenberg et al. 1996]. It was recognized that such an exercise would certainly be useful at some stage to open up the output of state-of-the-art climate change scenario experiments for analysis by the wider community.

AFFILIATIONS: Meehl—National Center for Atmospheric Research,* Boulder, Colorado; Covey and Taylor—Program for Climate Model Diagnosis and Intercomparison, Livermore, California; Delworth and Stouffer—Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey; Latif—Leibniz-Institut fuer Meereswissenschaften, Kiel, Germany; McAvaney—Bureau of Meteorology, Research Centre, Melbourne, Australia; Mitchell—Hadley Centre, Exeter, United Kingdom
*The National Center for Atmospheric Research is sponsored by the National Science Foundation
CORRESPONDING AUTHOR: Gerald A. Meehl, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307
E-mail: meehl@ncar.ucar.edu

During the lead-up to the IPCC Third Assessment Report (TAR) in the late 1990s, a set of emission scenarios for twenty-first-century climate was produced and documented in the Special Report on Emission Scenarios (typically referred to as the SRES emission scenarios; Nakicenovic et al. 2000). The climate modeling community was asked to perform experiments with these scenarios for assessment in the TAR. The late date and the large number of scenarios (numbering about 30 at the time) dictated that only two (A2 and B2) could be run by a limited number of groups that had the wherewithal to perform such experiments with the associated considerable computing requirements on such short notice. There was little time to analyze these data, and only a few fields were collected and assessed by the authors of the TAR to illustrate possible future climate changes (Cubasch et al. 2001; Giorgi et al. 2001). Subsequently, output from some of these experiments was collected by the IPCC Data Distribution Centre in Hamburg, Germany (http://cera-www.dkrz.de/IPCC_DDC/), and made available to the climate change impacts community. But, this still amounted to only a few models and experiments, and was aimed at a limited segment of the climate science community.

As planning for the IPCC Fourth Assessment Report (AR4) commenced in 2003, the climate modeling community, as represented at the international level by WGCM, recognized that this process had to be better organized and carefully coordinated. Not only must there be more lead time for the modeling groups to be able to marshal improved model versions and the requisite computing resources to participate, but there should also be time and capability for the model data to be analyzed by a larger group of researchers. In this way, it was desired that more studies based on these model experiments could be performed by more scientists in time for the AR4, thus providing a better assessment of the state of human knowledge on climate variability and climate change from the models.

THE INITIATION OF THE WCRP CMIP3 MULTIMODEL DATASET. In consulating with the IPCC Working Group 1 cochairs, in late 2003 WGCM embarked on a process to coordinate a set of experiments covering many aspects of climate variability and change that could be performed by as many modeling groups as possible with state-of-the-art global coupled climate models [sometimes referred to as atmosphere–ocean general circulation models (AOGCMs)]. The model data were then collected and made available for analysis (Meehl et al. 2004, 2005b). However, a crucial part of this effort was to archive

and actually organize the data so that they were readily available to the international climate science community for analysis. PCMDI agreed to take on this considerable challenge, which was destined to be the third phase of CMIP, or CMIP3. PCMDI's role proved to be crucial in CMIP3, the largest international global coupled climate model experiment and multimodel analysis effort ever attempted.

The list of experiments included the following (single realizations were acceptable, but modeling groups were encouraged to run multimember ensembles):

1) Twentieth-century simulation to year 2000 (preferable starting from pre-industrial conditions in the late 1800s) with anthropogenic and natural forcings as modeling groups deemed appropriate;
2) Climate change experiment: Twenty-first-century simulation with SRES B1 (low forcing, i.e., CO_2 concentration about 550 ppm by 2100) from 2000 to 2100;
3) Climate change experiment: Twenty-first-century climate change simulation with SRES A1B (medium forcing, i.e., CO_2 concentration of about 700 ppm by 2100) from 2000 to 2100;
4) Climate change experiment: Twenty-first-century simulation with SRES A2 (high forcing, i.e., CO_2 concentration about 820 ppm by 2100) from 2000 to 2100;
5) Climate change commitment experiment: Fix all concentrations at year 2000 values and run to 2100 ($CO_2 \sim 360$ ppm);
6) Climate change commitment experiment: Fix all concentrations at year 2100 values for B1 and run to 2200 ($CO_2 \sim 550$ ppm);
7) Climate change commitment experiment: Fix all concentrations at year 2100 values for A1B and run to 2200 ($CO_2 \sim 700$ ppm);
8) Idealized forcing and stabilization experiment: 1% yr^{-1} CO_2 increase to doubling at year 70 with corresponding control run, and an additional 150 yr with CO_2 fixed at $2 \times CO_2$;
9) Idealized forcing and stabilization run: 1% yr^{-1} CO_2 increase run to quadrupling with an additional 150 yr with CO_2 fixed at $4 \times CO_2$;
10) 100-yr (minimum) control run with all forcings held constant encompassing same time period as in 1 above;
11) Climate sensitivity experiment: Instantaneously double CO_2 and run to equilibrium with atmosphere coupled to a nondynamic slab ocean [also as input to the Cloud Forcing Model Intercomparison Project (CFMIP)];
12) Extend one A1B and B1 climate change commitment experiment simulation to 2300.

A fundamental part of the earlier phases of CMIP (described above) was the idealized 1% yr^{-1} CO_2 increase experiments, so those were also retained in the CMIP3 list above as standard calibration runs to better intercompare the coupled models' responses. These experiments were also necessary to calculate the transient climate response (TCR), defined as the globally averaged surface air temperature increase at the time of CO_2 doubling in a 1% yr^{-1} compound CO_2 increase experiment, a standard metric to assess the coupled transient response. Equilibrium climate sensitivity, another standard metric for comparing model responses, was also obtained from the atmosphere coupled to the nondynamic slab ocean equilibrium $2 \times CO_2$ experiment.

An extensive list of fields was requested to be supplied to PCMDI by the modeling groups. The volume of model data was so large that, in the international context, conventional online data transfer mechanisms became impractical. Therefore, modeling groups were sent hard disks and asked to copy their model data onto the disks in netCDF format and then mail the disks to PCMDI where the model data were downloaded and cataloged.

To provide an idea of the model outputs that were collected, we summarize here in general terms the types of model variables furnished by the modeling groups. For a full list of fields that were requested with detailed descriptions of the variables, see www-pcmdi.llnl.gov/ipcc/standard_output.html.

High-priority fields are as follows (a few examples of each are given in parentheses; note there were additional low-priority fields requested as well that are not listed here):

- Monthly mean 2D atmosphere or land surface data (e.g., surface temperature, precipitation, sea level pressure, soil moisture);
- Time-independent 2D land surface data (e.g., orography, land area fraction);
- Monthly mean 3D atmosphere data (e.g., air temperature, winds, geopotential heights);
- Monthly mean 1D ocean data (e.g., northward ocean heat transport);
- Monthly mean 2D ocean data (e.g., ocean meridional overturning streamfunction);
- Monthly mean 0D or 2D ocean or sea ice data (e.g., sea surface height, sea level, sea ice fraction, sea ice thickness);

- Time-independent 2D ocean data (e.g., ocean bottom topography);
- Monthly mean 3D ocean data (e.g., temperature, salinity, ocean currents);
- Daily mean 2D atmosphere data (e.g., surface air temperature, precipitation, sea level pressure, winds, surface energy balance components);
- Daily mean 3D atmosphere data (e.g., air temperature, winds);
- Three hourly 2D atmosphere data (e.g., surface air temperature, precipitation, sea level pressure, winds, surface energy balance components);
- Extremes indexes (calculated from daily data, five temperature-related indices, five precipitation-related indices), from Frich et al. (2002, their Table 1).

The modeling groups proceeded to complete as many of the experiments as they could manage during 2004. By early 2005, a total of 16 modeling groups from 11 countries participated with 23 models. Considerable resources (human and computing) were devoted to this project. PCMDI collected and archived more than 30 TB of model data by that time (www-pcmdi. llnl.gov/ipcc/about_ipcc.php). Subsequently, another modeling group has contributed data to CMIP3, so that the WCRP CMIP3 multimodel dataset now consists of 17 modeling groups from 12 countries and 24 models. Figure 1a shows the current breakdown of models and experiments in the WCRP CMIP3 multimodel dataset, and Fig. 1b indicates the ensemble members that were submitted by the groups for each experiment. As shown in Fig. 1, monthly means were generally collected, with some daily data and even some 6-hourly data generated to drive regional models and for other applications.

ORGANIZATION OF THE ANALYSIS PHASE OF CMIP3.

The WGCM Climate Simulation Panel (G. Meehl, chair, C. Covey, T. Delworth, M. Latif, B. McAvaney, J. Mitchell, and R. Stouffer) coordinated the collection of the model data, and then undertook organizing the analysis phase in 2004 when sufficient model data had been archived to allow the initiation of analysis projects. Several announcements were made first by e-mail, and then in generally read publications that would reach the climate science community (e.g., Meehl et al. 2004). Since the schedule would be tight for analyses to be done and submitted for publication in time to be assessed for the AR4, it was decided to hold a workshop in early 2005 where preliminary results from the analyses could be presented. By late 2004

nearly 300 scientists had registered to have access to the multimodel dataset, but it was unclear how many would actually have completed enough work to present results at the workshop.

Meanwhile, to encourage participation of U.S. scientists, the U.S. Climate Variability and Predictability program (CLIVAR) made a significant contribution by coordinating the Coupled Model Evaluation Project (CMEP) that resulted in multiagency funding for 21 analysis projects (www. usclivar.org/CMEP_awards.html).

Results from analyses of the multimodel dataset were presented by 125 scientists from all over the world at the workshop that was convened and organized by U.S. CLIVAR and WGCM and hosted by the International Pacific Research Center (University of Hawaii) on 1–4 March 2005 (http://ipcc-wgl.ucar. edu/meeting/CMSAW/). These results were intended to feed directly into the AR4 process. To be assessed as part of the AR4, it was intended that papers should be submitted to peer-reviewed journals by late spring 2004. Many of the participants at the Hawaii workshop, as well as a number of others, ended up submitting nearly 200 papers for assessment. This was judged to be a considerable success, given the tight time frame and the fact that most scientists performed these analyses without additional funding or resources over and above what they already had in place (the exception being the CMEP investigators). Since then, additional papers have been prepared and submitted, and from those submitted papers over 200 have already appeared in the peer-reviewed literature, with many more either in the review process or in preparation (www-pcmdi.llnl.gov/ipcc/subproject_ publications.php).

EXAMPLES OF RESULTS FROM ANALYSES OF THE WCRP CMIP3 MULTIMODEL DATASET.

Though it is beyond the scope of this short summary article to provide a comprehensive review of all the analyses published to date, we choose here to select a few illustrative examples to provide an idea of the types of analyses that have been performed. Figure 2 shows globally averaged surface air temperature time series from the experiments compiled directly from the archived model data (www-pcmdi.llnl.gov/ipcc/about_ipcc.php). The numbers in the figure indicate how many models completed each phase of the experiments in time to be assessed in the IPCC AR4 (the number of ensemble members for each experiment and model is shown separately in Fig. 1b). The shading is ±one standard deviation of the intermodel variability.

This figure depicts the largest number of AOGCMs that have ever been assembled to simulate twentieth- and twenty-first-century climate and climate change commitment. Results show that the widely quoted observed twentieth-century warming of about 0.6°C (e.g., Trenberth et al. 2007) is well simulated by the
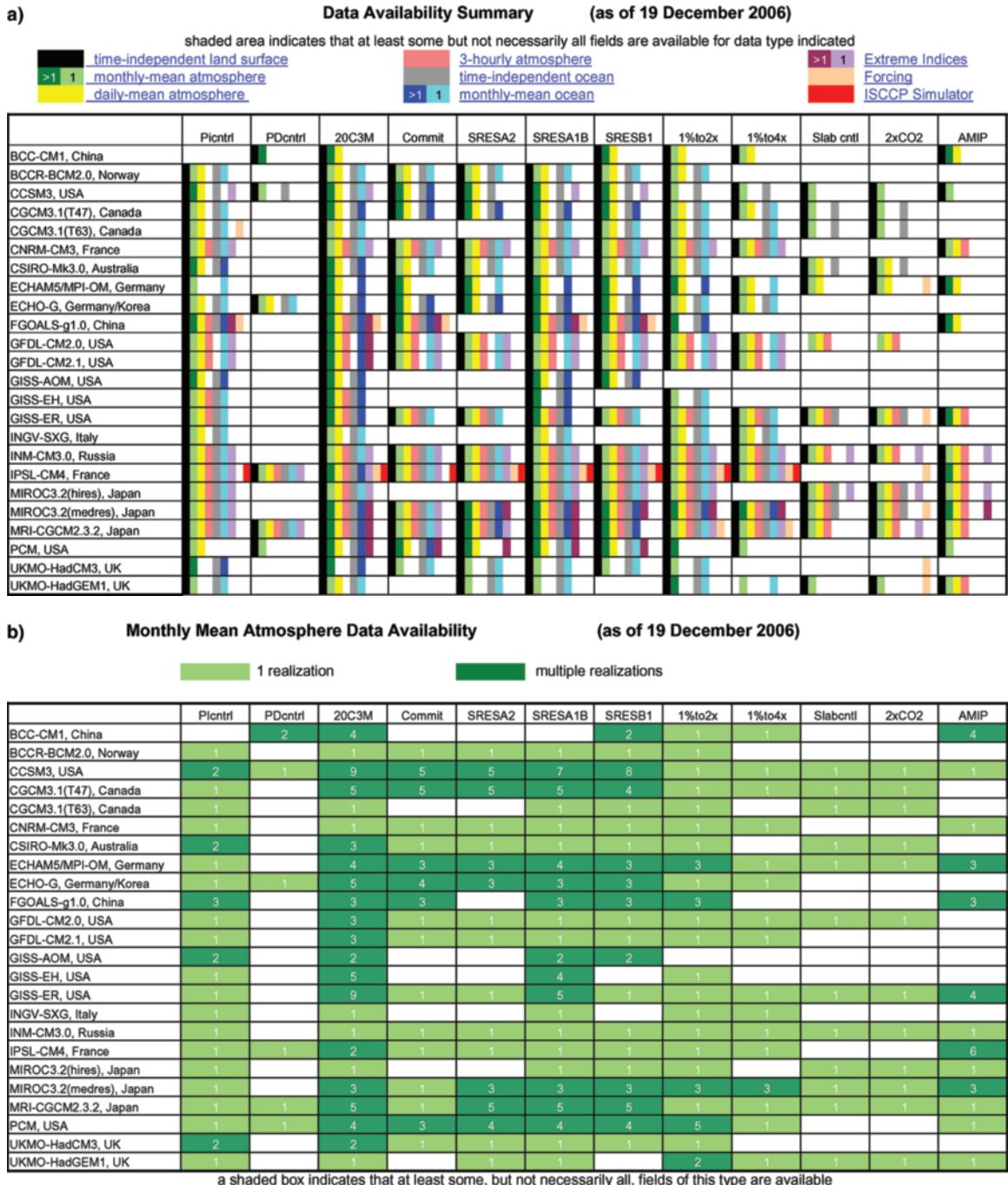
a)　　　　　　　　　**Data Availability Summary**　　　　(as of 19 December 2006)

shaded area indicates that at least some but not necessarily all fields are available for data type indicated

time-independent land surface — 3-hourly atmosphere — Extreme Indices
monthly-mean atmosphere — time-independent ocean — Forcing
daily-mean atmosphere — monthly-mean ocean — ISCCP Simulator

	Picntrl	PDcntrl	20C3M	Commit	SRESA2	SRESA1B	SRESB1	1%to2x	1%to4x	Slab cntl	2xCO2	AMIP
BCC-CM1, China												
BCCR-BCM2.0, Norway												
CCSM3, USA												
CGCM3.1(T47), Canada												
CGCM3.1(T63), Canada												
CNRM-CM3, France												
CSIRO-Mk3.0, Australia												
ECHAM5/MPI-OM, Germany												
ECHO-G, Germany/Korea												
FGOALS-g1.0, China												
GFDL-CM2.0, USA												
GFDL-CM2.1, USA												
GISS-AOM, USA												
GISS-EH, USA												
GISS-ER, USA												
INGV-SXG, Italy												
INM-CM3.0, Russia												
IPSL-CM4, France												
MIROC3.2(hires), Japan												
MIROC3.2(medres), Japan												
MRI-CGCM2.3.2, Japan												
PCM, USA												
UKMO-HadCM3, UK												
UKMO-HadGEM1, UK												

b)　　**Monthly Mean Atmosphere Data Availability**　　　　(as of 19 December 2006)

1 realization　　　　　multiple realizations

	Picntrl	PDcntrl	20C3M	Commit	SRESA2	SRESA1B	SRESB1	1%to2x	1%to4x	Slabcntl	2xCO2	AMIP
BCC-CM1, China		2	4				2					4
BCCR-BCM2.0, Norway	1		1	1	1	1	1	1				
CCSM3, USA	2	1	9	5	5	7	8	1	1	1	1	1
CGCM3.1(T47), Canada	1		5	5	5	5	4	1	1		1	
CGCM3.1(T63), Canada	1		1			1	1	1			1	
CNRM-CM3, France	1		1	1	1	1	1	1	1		1	1
CSIRO-Mk3.0, Australia	2		3		1	1	1	1			1	
ECHAM5/MPI-OM, Germany	1		4	3	3	4	3	3		1	1	3
ECHO-G, Germany/Korea	1		5	4	3	3	3	1				
FGOALS-g1.0, China	3		3	3		3	3	3				3
GFDL-CM2.0, USA	1		3	1	1	1	1	1	1			
GFDL-CM2.1, USA	1		3	1	1	1	1	1	1			
GISS-AOM, USA	2		2			2	2					
GISS-EH, USA	1		5		4		1	1				
GISS-ER, USA	1		9	1	1	5	1	1			1	4
INGV-SXG, Italy	1		1		1	1						
INM-CM3.0, Russia	1		1	1	1	1	1	1		1	1	1
IPSL-CM4, France	1	1	2	1	1	1	1	1	1			6
MIROC3.2(hires), Japan	1		1			1	1	1	1			1
MIROC3.2(medres), Japan	1	1	3	1	3	3	3	3	3	1	1	3
MRI-CGCM2.3.2, Japan	1	1	5	1	5	5	5	1		1	1	1
PCM, USA	1		4	3	4	4	4	5				1
UKMO-HadCM3, UK	2		2	1	1	1	1				1	1
UKMO-HadGEM1, UK	1		1	1	1	1		2	1			1

a shaded box indicates that at least some, but not necessarily all, fields of this type are available

FIG. 1. (a) **Summary of climate model experiments performed with AOGCMs in the multimodel archive. Colored fields indicate that some but not necessarily all variables of the specific data type (separated by climate system component and time interval) have been archived at PCMDI. Where different shadings are given in the legend, the color indicates whether single or multiple ensemble members are available. (b) Number of ensemble members performed for each experiment and each scenario. Details on the scenarios, variables, and models can be found at the PCMDI Web page (www-pcmdi.llnl.gov/ipcc/about_ ipcc.php). Note that some of the ensemble members using the CCSM3 were run on the Earth Simulator in Japan in collaboration with the Central Research Institute of Electric Power Industry (CRIEPI).**
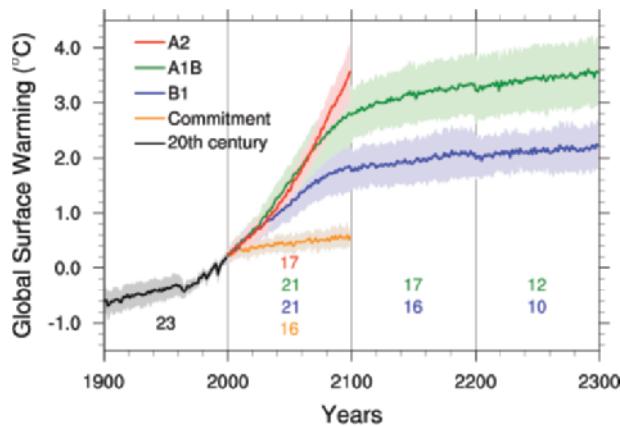
FIG. 2. Multimodel means of surface warming for the twenty-first century for the scenarios A2, A1B, and B1, and corresponding twentieth-century simulations. Values beyond 2100 are for the climate change commitment experiments that stabilized concentrations at year 2100 values for B1 and A1B. Linear trends from the corresponding control runs have been removed from these time series. Lines show the multimodel means, and shading denotes the ± 1 std dev intermodel range. Discontinuities between different periods have no physical meaning due to the fact that the number of models run for a given scenario is different for each period and scenario, as indicated by the numbers given for each phase and scenario in the bottom part of the panel.

models. For the twenty-first century (computed as the difference of mean temperature for years 2090–99 minus 1980–99), the models show an average warming of 1.8°, 2.8°, and 3.4°C for the low (B1), medium (A1B), and high (A2) forcing scenarios, respectively. For the commitment experiments, by 2100 the climate system warms by about an additional 0.6°C after concentrations are stabilized in 2000 while, for the other two commitment experiments, by 2200 there is about another half-degree warming over and above what occurred by 2100 in B1 and A1B, respectively.

The availability of such a large number of models provides considerable opportunity to explore model simulation capability of various aspects of twentieth-century climate (e.g., see publications listed at www.usclivar.org/CMEP_awards.html). One example in Fig. 3 shows the first and second EOFs of Antarctic sea ice concentration from observations (Figs. 3a,b), and also for a number of models' simulations of sea ice concentration. [Note that EOFs depict the principal spatial patterns of variability (see, e.g., Kutzbach 1967)]. Though each model has its own characteristic sea ice variability pattern, all show a dipole with negative values in the Atlantic sector, and positive values in the Pacific sector (Holland and Raphael 2006). This type of quantification of model simulation capability of what we have already observed provides a baseline for the degree of confidence we can place in the models and how they may simulate future changes. In this case, the overall agreement in the basic pattern of variability between the models and the observations builds confidence that sea ice variability in a future warmer climate can be usefully studied.

The CMIP3 multimodel dataset has also been used to help understand climate changes that have already been observed during the twentieth century. For example, model results for the twentieth century

have been analyzed, in concert with additional single forcing datasets from some of the models, to show that the signature from large volcanic eruptions, such as Krakatoa in the late nineteenth century, persist and are manifested by reduced ocean heat content for decades after the event. This offsets, to a certain extent, the positive radiative forcing and associated warming that would otherwise have occurred due to increasing greenhouse gases in the early twentieth century (e.g., Delworth et al. 2005; Gleckler et al. 2006).

Another way that the CMIP3 multimodel dataset has been useful in interpreting observed climate variability and trends over the latter part of the twentieth century is demonstrated in a comparison of different time scales of tropospheric and surface temperature variability from the multimodel simulations of twentieth-century climate to observed quantities from satellites, radiosondes, and surface weather stations (Santer et al. 2005). Figures 4a and 4b show the relationship of variability on the monthly time scale between globally averaged surface temperature (*x* axis) and weighted estimates of tropospheric temperature variability (*y* axis). The colored symbols are results from 49 separate realizations from 19 AOGCMs from the multimodel dataset for twentieth-century climate that included combinations of anthropogenic and natural forcings. The black symbols denote different observed radiosonde and satellite datasets paired with two observed surface temperature datasets. Figures 4c and 4d are the same as Figs. 4a and 4b, but for trends from 1979 to 1999 in the models and observations. Note that in all panels, the observations fall along a regression line relating the model results, with the location of a particular model realization on that regression line depending mostly on simulated El Niño amplitude in the models. The regression line lies above the black line (which has a slope of 1.0), indicating that
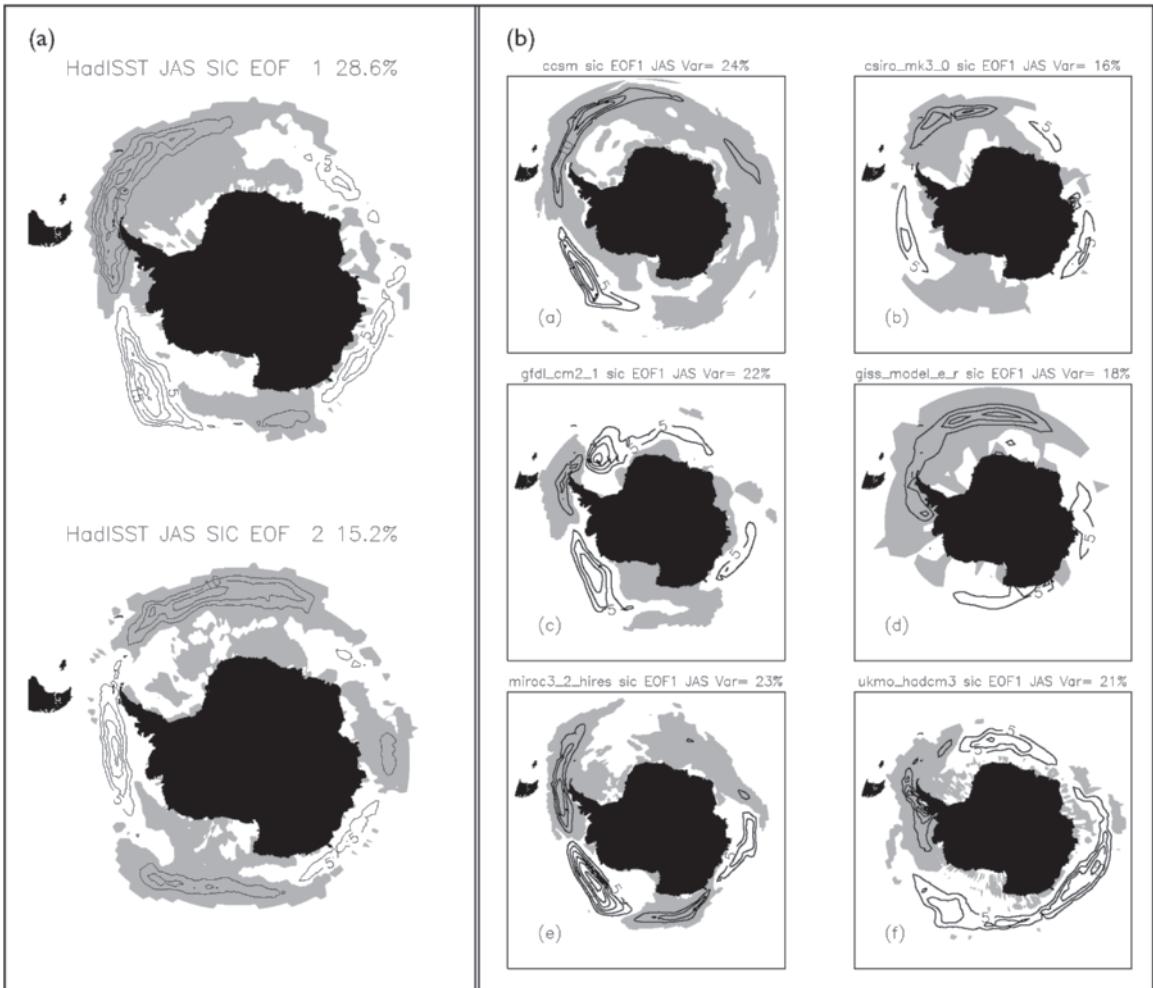
Fig. 3. (a) First two EOFs from observed winter sea ice concentration (1979–99) scaled by the std dev of the corresponding PC time series. Contour interval is 5%, 0 contour omitted, and negative values are shaded. (b) First EOF of winter sea ice concentration from AOGCM simulations of the twentieth century from 1960 to 1999 using linearly detrended data (Holland and Rafael 2006).

there is enhancement of the magnitude of temperature variability in the troposphere compared to the surface in both the models and observations. However, Figs. 4c and 4d show the relationship among trends has less agreement between models and observations. Therefore, either there are different physics operating at monthly and trend time scales in the observations (whereby there can somehow be good agreement on the monthly time scale and less agreement on the trend time scale), or this result points to the difficulties of constructing accurate small trends with disparate observed data with associated discontinuities in observing systems over time.

Regarding changes of future climate a question that is frequently asked is, What will El Niño do in the future? Several analyses of the multimodel dataset have been performed to address that question (e.g., Guilyardi 2006; Meehl et al. 2006; Merryfield 2006), and Fig. 5 summarizes results from one such study by van Oldenborgh et al. (2005). This figure attempts to address the question of what future amplitude of El Niño events could be in a future warmer climate depicted in the multimodel dataset. Figure 5 clearly shows a wide range of possible future behaviors across the various models, agreeing with the other studies cited above that there is no clear indication from the models regarding future changes in El Niño amplitude. This model dependence is the result of several factors, not least of which is that no two observed El Niño events are alike, and that different models capture various aspects of the mechanisms thought to produce El Niño events.

In several of the El Niño studies cited above, the authors attempted to subselect models that more faithfully simulated various metrics that applied to
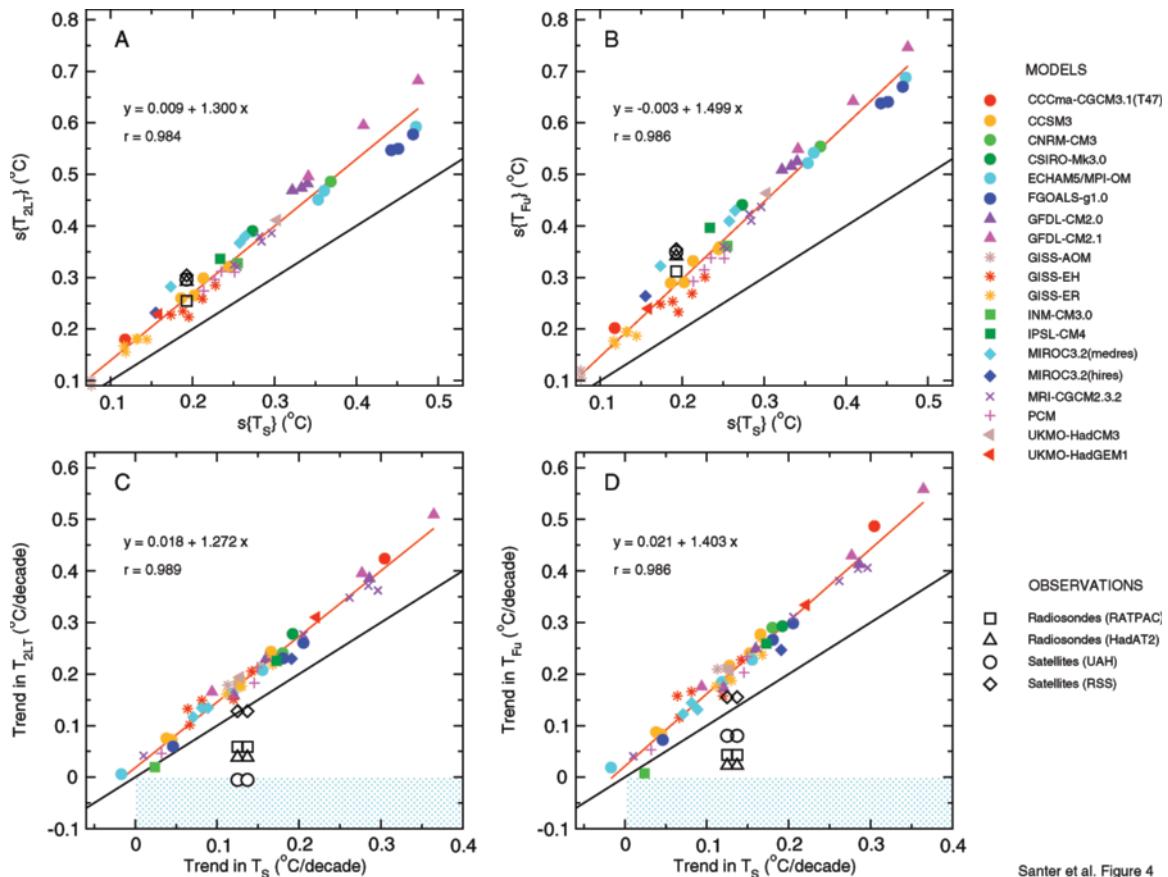
FIG. 4. (a), (b) Information is provided on amplification of the monthly time scale surface temperature variability in two weighted tropospheric temperature products as defined in Santer et al. (2005). (c), (d) Same as in (a), (b), but depicting the relation between decadal time-scale trends at the surface and in the troposphere. The colored symbols in each panel indicate realizations from 49 ensemble members for twentieth-century climate simulations from 19 AOGCMs from the multimodel archive. The fitted regression lines (in red) are based on model data only. The black lines denote a slope of 1.0. Values above the black lines indicate tropospheric enhancement, and values below the black line indicate tropospheric damping of surface temperature changes. Black symbols indicate results from separate radiosonde and satellite MSU data paired with two surface temperature datasets. The blue shading in (c) and (d) defines the region of simultaneous surface warming and tropospheric cooling. Results are for the deep Tropics (20°N to 20°S), and are more fully described in Santer et al. (2005).
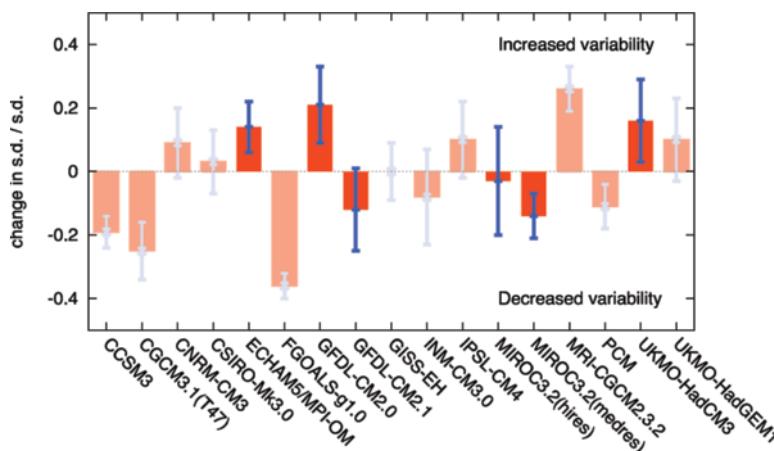
FIG. 5. Relative change in El Niño magnitude (first EOF of detrended monthly SST in the region 10°S–10°N, 120°E–90°W) in the CMIP3 multimodel dataset. The more reliable models, as defined by their ability to simulate several different El Niño metrics in the current climate, are dark red (after van Oldenborgh et al. 2005).
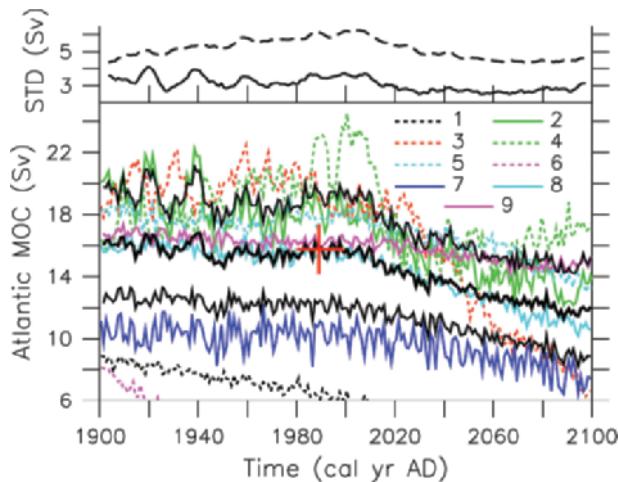
FIG. 6. Evolution of the Atlantic MOC as defined by the maximum overturning at 24°N for the period 1900–2100 using 21 realizations of the response to the A1B emissions scenario from nine AOGCMs. The MOC simulations with a skill score larger than one are solid lines; those from models with a smaller skill score are dashed. The weighted ensemble mean is shown by the thick black curve together with the weighted std dev (thin black lines). Observational estimates of the circulation at 24°N [15.75 ± 1.6 Sv (1 Sv = 10⁶ m³ s⁻¹); Ganachaud and Wunsch 2000; Lumpkin and Speer 2003] at the end of the last century are shown as the red cross centered at year 1989. (top) The weighted (solid) and unweighted (dashed) std devs (from Schmittner et al. 2005).

observed El Niño phenomena. In another variation on that technique, Schmittner et al. (2005) studied possible future changes of the ocean meridional overturning circulation (MOC) in the Atlantic by more heavily weighting models that accurately simulated certain hydrographic properties and observation-based circulation estimates (Fig. 6). Using 28 simulations from 9 different AOGCMs from the multimodel dataset, Schmittner et al. (2005) were able to come up with a best estimate of projected MOC behavior using the weighted model results. Their results indicate a gradual projected reduction in the amplitude of the MOC over the course of the twenty-first century for the A1B emission scenario, finally amounting to a weakening of 25% (±25%) by the year 2100. No model shows a sudden shutdown of the MOC during the twenty-first century. These results agree with an assessment of a larger number of models from the WCRP CMIP3 multimodel dataset in the IPCC AR4 (Meehl et al. 2007).

As noted above, modeling groups were asked to calculate and submit 10 indexes of extreme weather and climate events outlined by Frich et al. (2002).

Five of the indexes related to temperature, and five to precipitation. In all, nine of the modeling groups completed those calculations. Tebaldi et al. (2006) analyzed results from those data, and Fig. 7 shows results from two of the precipitation indices in terms of global averages and geographical changes for the end of the twenty-first century for the A1B scenario from nine models. Precipitation intensity increases almost everywhere (for a given event more precipitation occurs in the future), but dry days (number of days in between precipitation events) also increase in some areas. This seems counterintuitive, but in some regions, particularly where circulation and other climate changes are associated with reduced average precipitation (e.g., Meehl et al. 2005a), there is a longer time period between precipitation events, but when it does rain it rains harder.

Finally, the sheer number of AOGCMs contributing to the WCRP CMIP3 multimodel dataset has allowed some of the first calculations of probabilistic climate change information. For example, using the techniques outlined in Furrer et al. (2007b), Figs. 8a and 8b from Furrer et al. (2007a) show, for 21 models from the multimodel dataset for the A1B scenario, seasonal [December–February (DJF) and June–August (JJA)] values of temperature increases with an 80% chance of occurrence by the end of the twenty-first century. Conversely, Figs. 8c and 8d show contours of probabilities of the occurrence of at least a 2°C warming for the two seasons. The results in Fig. 8 were obtained using a technique employed in Furrer et al. (2007a) wherein probability density functions (PDFs) of temperature change at each grid point are computed from the multimodel dataset. This is done by first calculating the temperature differences from each member of the multimodel ensemble, averaged for A1B for 2080–99 minus 1980–99 for DJF and JJA, and regressing those differences upon basis functions, that is, a series of fields that are chosen as starting points to explain the possible common large-scale patterns of the climate change signal. A statistical model is then formulated through a hierarchical Bayes framework, and a Markov chain Monte Carlo calculation then estimates the true coefficients of the regression and the uncertainty around them, plus estimates of the errors.

Weighting by the relative agreement among the models [such as that used in another technique that produces probabilistic climate change information by region by Tebaldi et al. (2004)] is not assumed in this method. By recombining the coefficients with the basis functions, an estimate is derived of the true
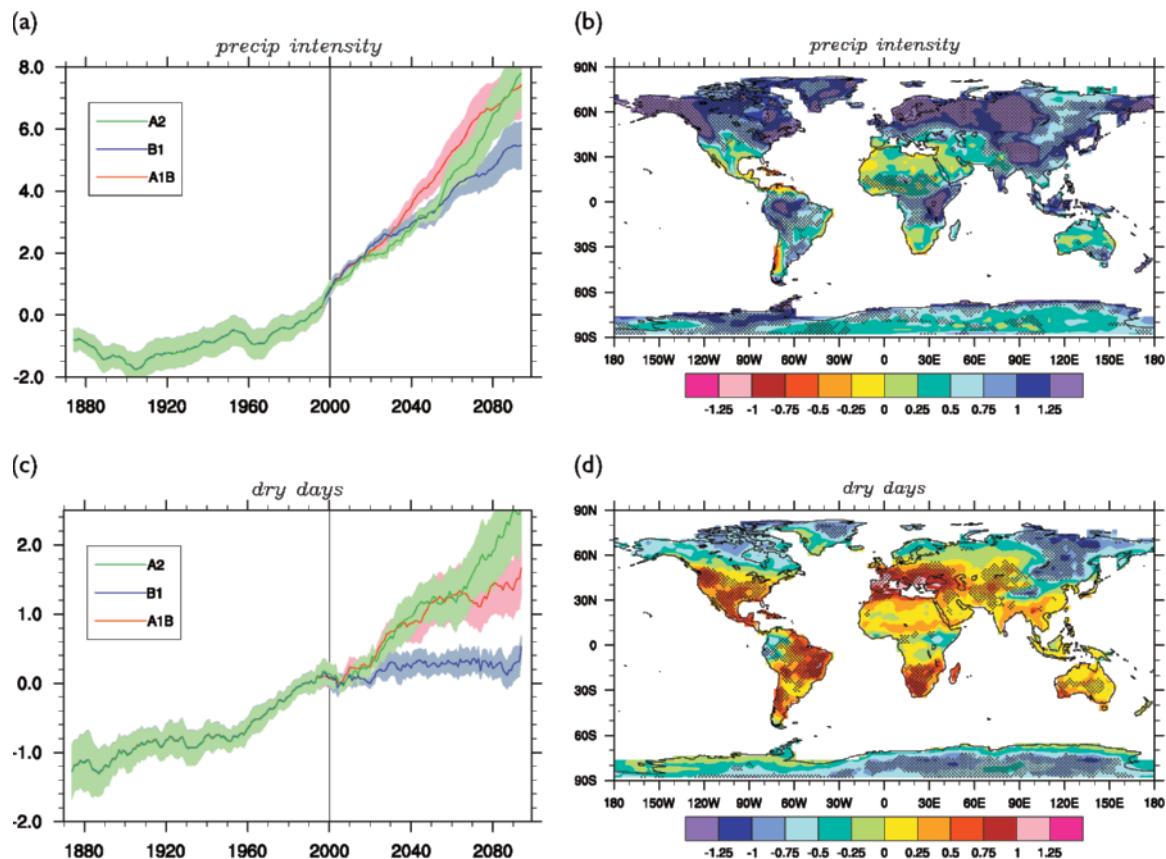
Fɪɢ. 7. Changes in extremes based on multimodel simulations from nine global coupled climate models, from Tebaldi et al. (2006). (a) Globally averaged changes in precipitation intensity (defined as the annual total precipitation divided by the number of wet days) for a low (B1), middle (A1B), and high (A2) forcing scenarios. (b) Changes of spatial patterns of precipitation intensity based on simulations between two 20-yr means (2080–99 minus 1980–99) for the A1B scenario. (c) Globally averaged changes in dry days (defined as the annual maximum number of consecutive dry days). (d) Changes of spatial patterns of dry days based on simulations between two 20-yr means (2080–99 minus 1980–99) for the A1B scenario. Solid lines in (a) and (c) are the 10-yr smoothed multimodel ensemble means; the envelope indicates the ensemble mean standard deviation. Stippling in (b) and (d) denote areas where at least 5 of the 9 models concur in determining that the change is statistically significant. Extremes indices are calculated following Frich et al. (2002) and are shown for land points only. Each model's time series has been centered around its 1980–99 average and normalized (rescaled) by its std dev computed (after detrending) over the period 1960–2099; then the models were aggregated into an ensemble average, both at the global average and at the grid-box level (units are std devs).

climate change field and of the uncertainty around it. Probability density functions of the temperature change are then derived for each grid point over the entire globe, and represent the joint probability of a given warming at each grid point.

This and the other studies shown above are only a few examples of the many more published results from the analyses of the multimodel dataset that can be seen online at www-pcmdi.llnl.gov/ipcc/subproject_publications.php.

CONCLUSIONS. An unprecedented international effort to run a coordinated set of twentieth- and twenty-first-century climate simulations, as well as several climate change commitment experiments, was organized by the WCRP/CLIVAR WGCM for assessment in the IPCC AR4. Model data were collected, archived, and made available to the international climate science community by PCMDI. This is the first time such a large set of AOGCM climate change simulations has been made openly available for analysis. As such, it represents a new era in climate science research whereby researchers and students can obtain permission to access and analyze the AOGCM data. Such an open process has allowed hundreds of scientists from around the world, many students,

a) Highest possible DJF temperature occuring with 80% probability (A1B)

b) Highest possible JJA temperature occurring with 80% probability (A1B)

c) Probability that DJF temperature exceeds 2 degrees C (A1B)

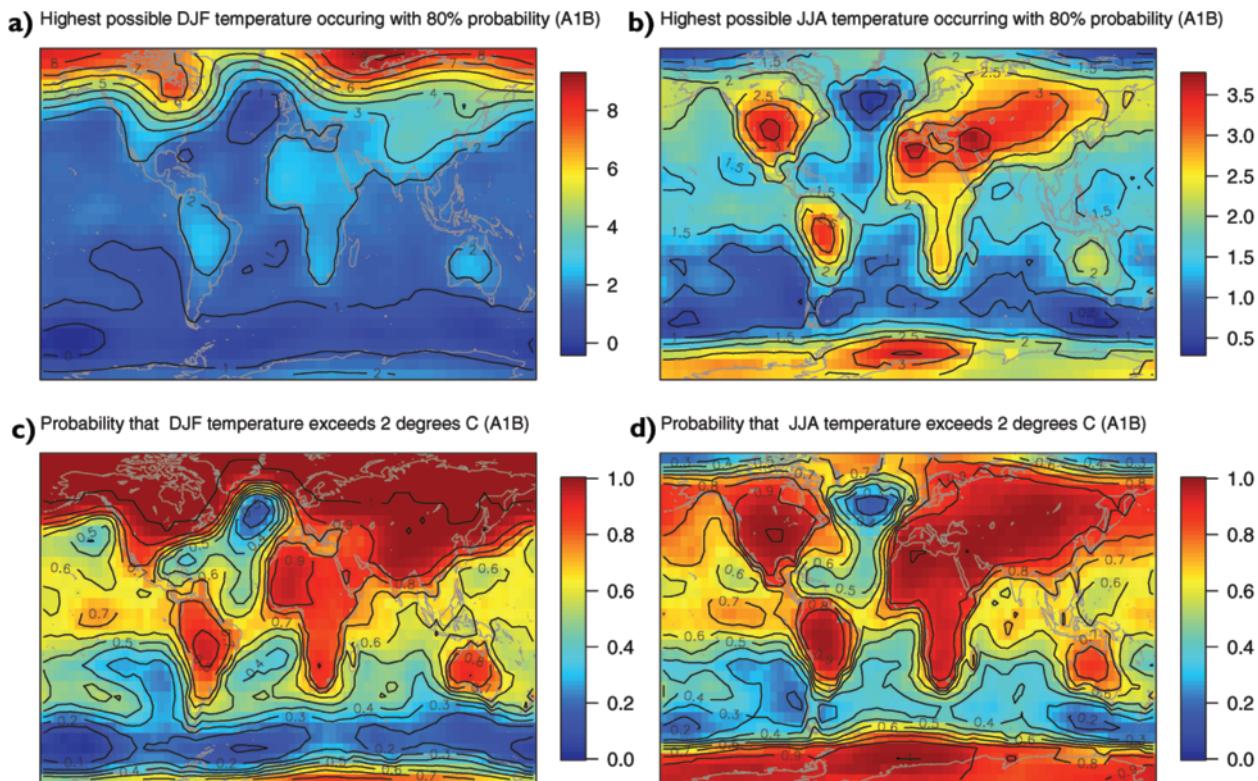**d)** Probability that JJA temperature exceeds 2 degrees C (A1B)

Fig. 8. Probabilistic climate change results from 21 AOGCMs, 2080–99 compared to 1980–99, for the A1B scenario, converted to a common 5° lat–lon grid: (a) DJF and (b) JJA values of temperature increase with an 80% chance of occurrence by the end of the twenty-first century. Also shown are contours of probabilities of the occurrence of at least a 2°C warming for (c) DJF and (d) JJA (Furrer et al. 2007a).

and researchers from developing countries, who had never before had such an opportunity, to analyze the model data and make significant contributions not only to the IPCC AR4, but to human knowledge of the workings of climate variability and climate change. This unique and valuable multimodel dataset will be maintained at PCMDI and overseen by the WGCM Climate Simulation Panel for at least the next several years. It will serve as a resource for climate science that promises to change the way students, developing country scientists, and experienced climate scientists perform analyses and learn about the climate system. For instructions regarding how to obtain access the multimodel dataset, see www-pcmdi.llnl.gov/ipcc/about_ipcc.php.

REFERENCES

Covey, C., K. M. AchutaRao, U. Cubasch, P. Jones, S. J. Lambert, M. E. Mann, T. J. Phillips, and K. E. Taylor, 2003: An overview of results from the Coupled Model Intercomparison Project. *Global Planet. Change,* **37,** 103–133.

Cubasch, U., and Coauthors, 2001: Projections of future climate change. *Climate Change 2001: The Scientific Basis,* J. T. Houghton et al., Eds., Cambridge University Press, 525–582.

Delworth, T. L., V. Ramaswamy, and G. L. Stenchikov, 2005: The impact of aerosols on simulated ocean temperature and heat content in the 20th century.

Geophys. Res. Lett., **32,** L24709, doi:10.1029/ 2005GL024457.

Frich, P., L. V. Alexander, P. Della-Marta, B. Gleason, M. Haylock, A. M. G. Klein Tank, and T. Pearson, 2002: Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Res.,* **19,** 193–212.

Furrer, R., R. Knutti, S. Sain, D. Nychka, and G. A. Meehl, 2007a: Spatial patterns of probabilistic temperature change projections from a multivariate Bayesian analysis of climate model output. *Geophys. Res. Lett.,* **34,** L06711, doi:10.1029/2006GL027754.

——, S. R. Sain, D. Nychka, and G. A. Meehl, 2007b: Multivariate Bayesian analysis of atmosphere–ocean general circulation models. *Environ. Ecol. Stat.,* in press.

Ganachaud, A., and C. Wunsch, 2000; Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data. *Nature,* **408,** 453–457.

Giorgi, F., and Coauthors, 2001: Regional climate information—Evaluation and projections. *Climate Change 2001: The Scientific Basis,* J. T. Houghton et al., Eds., Cambridge University Press, 583–638.

Gleckler, P. J., T. M. L. Wigley, B. D. Santer, J. M. Gregory, K. AchutaRao, and K. E. Taylor, 2006: Volcanoes and climate: Krakatoa's signature persists in the ocean. *Nature,* **439,** 675.

Guilyardi, E., 2006: El Niño–mean state–seasonal cycle interactions in a multi-model ensemble. *Climate Dyn.,* **26,** 329–348.

Holland, M. M., and M. N. Raphael, 2006: Twentieth century simulation of the Southern Hemisphere climate in coupled models. Part II: Sea ice conditions and variability. *Climate Dyn.,* **26,** 229–245.

Kattenberg, A., and Coauthors, 1996: Climate models—Projections of future climate. *Climate Change 1995: The Science of Climate Change,* J. T. Houghton et al., Eds., Cambridge University Press, 285–358.

Kutzbach, J., 1967: Empirical eigenvectors of sea level pressure, surface temperature and precipitation complexes over North America. *J. Appl. Meteor.,* **6,** 791–802.

Lumpkin, R., and K. Speer, 2003: Large-scale vertical and horizontal circulation in the North Atlantic Ocean. *J. Phys. Oceanogr.,* **33,** 1902–1920.

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.

——, ——, ——, ——, and ——, 2000: The Coupled Model Intercomparison Project (CMIP). *Bull. Amer. Meteor. Soc.,* **81,** 313–318.

——, C. Covey, M. Latif, B. McAvaney, J. F. B. Mitchell, and R. Stouffer, 2004: Soliciting participation in climate model analyses leading to IPCC Fourth Assessment Report. *Eos, Trans. Amer. Geophys. Union,* **85,** 274.

——, J. M. Arblaster, and C. Tebaldi, 2005a: Understanding future patterns of precipitation extremes in climate model simulations. *Geophys. Res. Lett.,* **32,** L18719, doi:10.1029/2005GL023680.

——, C. Covey, B. McAvaney, M. Latif, and R. J. Stouffer, 2005b: Overview of the Coupled Model Intercomparison Project. *Bull. Amer. Meteor. Soc.,* **86,** 89–93.

——, H. Teng, and G. W. Branstator, 2006: Future changes of El Nino in two global coupled climate models. *Climate Dyn.,* **26,** 549–566.

——, and Coauthors, 2007: Global climate projections. *Climate Change 2007: The Physical Science Basis,* Cambridge University Press, in press.

Merryfield, W., 2006: Changes to ENSO under CO_2 doubling in the IPCC AR4 coupled climate models. *J. Climate,* **19,** 4009–4027.

Nakicenovic, N., and Coauthors, 2000: *IPCC Special Report on Emissions Scenarios.* Cambridge University Press, 599 pp.

Santer, B. D., and Coauthors, 2005: Amplification of surface temperature trends and variability in the tropical atmosphere. *Science,* **309,** 1551–1556.

Schmittner, A., M. Latif, and B. Schneider, 2005: Model projections of the North Atlantic thermohaline circulation for the 21st century assessed by observations. *Geophys. Res. Lett.,* **32,** L23710, doi:10.1029/ 2005GL024368.

Tebaldi, C., L. O. Mearns, D. Nychka, and R. L. Smith, 2004: Regional probabilities of precipitation change: A Bayesian analysis of multimodel simulations. *Geophys. Res. Lett.,* **31,** L24213, doi:10.1029/ 2004GL021276.

——, J. M. Arblaster, K. Hayhoe, and G. A. Meehl, 2006: Going to the extremes: An intercomparison of model-simulated historical and future changes in extreme events. *Climatic Change,* **79,** 185–211.

Trenberth, K. E., and Coauthors, 2007: Observations: Surface and atmospheric climate change. *Climate Change 2007: The Physical Science Basis,* Cambridge University Press, in press.

van Oldenborgh, G., S. Philip, and M. Collins, 2005: El Niño in a changing climate: A multi-model study. *Ocean Sci.,* **1,** 81–95.