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The fourth session of the JSC/CLIVAR working Group on Coupled Modelling (WGCM)* was kindly hosted by the Scripps Institution of Oceanography, CA, USA, from 9-11 October 2000. The list of participants in the session is given in Appendix A to this report.

The session was opened by the Chairman of WGCM, Dr. L. Bengtsson, at 0915 hours on 9 October. Input to discussions at this session of the WGCM on natural climate variability on multi-annual scales and beyond had been provided by the Workshop on "Decadal Climate Predictability" (organized under the joint auspices of WGCM and the CLIVAR Working Group on Seasonal to Interannual Prediction, WGSIP) that had taken place at the Scripps Institution of Oceanography, 4-6 October. (The WGCM review of the outcome of this workshop is contained in section 3.8).

1. REVIEW OF RELEVANT EVENTS AND DEVELOPMENTS IN MODELLING-RELATED ACTIVITIES IN WCRP

Under this agenda item, WGCM was given information or received reports on discussions and recommendations at the twenty-first session of the Joint Scientific Committee (JSC) for the WCRP (March, 2000), and on work in hand by the JSC/CAS Working Group on Numerical Experimentation (WGNE), the CLIVAR Working Group on Seasonal-to-Interannual Prediction (WGSIP) and the Arctic Climate System Study Numerical Experimentation Group (ACSYS-NEG) as well as an account of the latest results from the GCM-Reality Intercomparison Project in the WCRP project Stratospheric Processes and their Role in Climate (SPARC-GRIPS). WGCM was also provided with an update on the planning of the Co-ordinated Observing Period (CEOP) of the Global Energy and Water Cycle Experiment (GEWEX).

Discussions at the twenty-first session of the JSC

The JSC had expressed its appreciation of the wide-ranging and apposite activities being led by WGCM, in particular the Coupled Model Intercomparison Project, the idealized sensitivity experiments, and the attention being given to the initialization and performance of the ocean component of coupled models. In this last connection, the JSC had stressed the importance of strong liaison between WGCM and the Working Group on Ocean Model Development (a joint WGCM/WOCE group) to ensure that ocean models were not just developed in an "ocean-only" context, but that appropriately designed experiments were organized with coupled models to test the importance of the appropriate representation of the ocean in the overall climate system. On another topic, the JSC pointed out the major advances in techniques for the integration of atmospheric models (e.g., semi-Lagrangian and semi-implicit methods, linear grids, etc.). These techniques had allowed significantly higher resolution to be employed (e.g. in numerical weather prediction) without prohibitive increases in computing requirements. The JSC had encouraged WGCM to examine exploitation of such methods in climate models. On the issue of regional climate modelling, the JSC had noted the reviews carried out and outstanding questions identified by WGCM and WGNE. The JSC had agreed on the establishment of a joint WGCM/WGNE ad hoc panel to summarize the current state-of-the-art in the field of regional climate modelling and to carry out an assessment of potential problems. The intention had been that this might lead to a (WCRP) workshop in 2001 or 2002 aimed at increasing awareness of the community at large to uncertainties in the use of regional climate models.

A particular theme running through the last JSC session had been the importance of developing co-operation and interactions between WCRP and the other global environmental change programmes, in particular the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP). A number of joint projects on major global change issues were being considered, recognizing that an overall study of Earth system science was needed by the three programmes together (and that humankind was also an interactive part of the Earth system). Areas of co-operation being discussed were global change and food systems, the carbon cycle, and water resources. It was also noted that a major Global Change Open Science Conference, would be held in Amsterdam in July 2001. (The organization of the Conference was being led by IGBP, with the involvement of WCRP and IHDP). As well as the main Conference programme, a number of parallel sessions were being arranged including one on the topic of "Coupled Earth System Modelling". The intention was that this would be jointly organized by WGCM, WGNE and the IGBP Global Analysis Interpretation and

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* The JSC/CLIVAR Working Group on Coupled Modelling was reconstituted in 1997 from "CLIVAR NEG-2" (the CLIVAR numerical experimentation group concerned with modelling climate variability on decadal to centennial timescales and predicting the response of the climate system to changes in natural and anthropogenic forcing). As well as the three sessions in its reconstituted form in Paris in 1997, in Melbourne in 1998, and in Hamburg in 1999, the group also met twice as CLIVAR NEG-2 (1995, 1996).

Modelling (GAIM) activity, and would highlight the scientific problems to be faced in developing full Earth system models (e.g. "greening" of general circulation models, introduction of the carbon cycle, coupling atmospheric chemistry and general circulation models, coupling of radiative transfer schemes with dust emission and dynamic vegetation models). Invited speakers would summarise the overall status and indicate directions for future progress, complemented by a series of oral and poster papers. Members of WGCM were invited to consider the contributions that could be made. More generally, the JSC had strongly encouraged expanded levels of co-operation between complementary WCRP and IGBP activities, in particular joint efforts between WGCM and GAIM in modelling the carbon cycle.

In another far-reaching development, the JSC formally adopted the Climate and Cryosphere (CLIC) study as a new component of the WCRP. CLIC would be a broader programme than the existing study of Arctic climate in WCRP (the Arctic Climate System Study, ACSYS) and involve a co-ordinated examination of the role of all components of the cryosphere in the global climate system (as an umbrella for many ongoing individual activities currently undertaken by several bodies separately). The main scientific questions to be treated included: the interactions between the atmosphere, snow/ice and land; land ice and sea level; the interactions between sea ice/oceans and the atmosphere; the role of the cryosphere on the global scale; and the cryosphere as an indicator of climate variability and change. ACSYS would continue for a further few years as an important element of CLIC.

WGNE and the GEWEX modelling and prediction thrust

WGNE is the complementary core modelling group to WGCM in the WCRP with the principal responsibility for the development of atmospheric circulation models for use in climate studies and weather prediction on all timescales. In this capacity, WGNE works in close conjunction with GEWEX on issues of cloud radiation parameterization, studies of land-surface processes and the representation of soil moisture in models.

The extensive scope of WGNE activities is described fully in the recent reports of WGNE sessions. In the area of climate model intercomparisons, the main initiative conducted under WGNE auspices is the Atmospheric Model Intercomparison Project (AMIP), carried out by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) at the US Department of Energy Lawrence Livermore National Laboratory (AMIP is the counterpart to atmospheric models that CMIP is to coupled models, see section 3.1). AMIP is now well into its second phase, involving a standard experiment over an extended period (January 1979-March 1996). Most of the integrations have now been collected by PCMDI. These new sets of model results have stimulated an exciting new range of diagnostic sub-projects and research. Looking to the future, it was foreseen that AMIP would become a "quasi-operational" community exercise in which modelling groups would periodically contribute revised model simulations every few years. The experimental protocol would be updated annually by extending the sea surface temperature/sea-ice boundary conditions to near present and reviewing the standard output list. Drawing particularly on AMIP results, WGNE was organizing a workshop (Melbourne, October 2000) to form an updated view of the status of systematic errors in models and to consider how these errors might be further reduced. Also, in the area of model intercomparisons, a snow model intercomparison project (SNOWMIP) was being organized.

Another topic kept under close review by WGNE was the development of dynamical cores of atmospheric circulation models where, as noted by the JSC (see above), there have been major advances in the speed of basic integration resulting from algorithmic changes. However, whilst such techniques were satisfactory for numerical weather prediction, climate models needed strict conservation (e.g. of energy) over extended periods of integration, and thus care (and perhaps appropriate modification) of schemes were likely to be needed. Other principal activities of WGNE were the validation of ocean-atmosphere and land-atmosphere fluxes as inferred from the routine analyses produced at the main operational centres (sets of fluxes were being assembled on a quasi-operational basis at PCMDI). WGNE also continues to monitor closely progress in atmospheric data assimilation/analysis systems and to keep under review the progress of/plans for the various reanalysis projects.

In collaboration with GEWEX, a vigorous effort aimed at the improvement of land-surface parameterizations in models, and the consistent introduction of "greening" of land surfaces, vegetation changes, soil freezing etc., is being planned. A "Global Land Atmosphere System Study" (GLASS) is being implemented including a new structure of complementary activities:

- local off-line validation of land-surface parameterizations (building on the Project for Intercomparison of Land-surface Processes, PILPS);
- large-scale or global validation (and identification of critical regions);
- issues of heterogeneity and data assimilation;

- impact of land-surfaces and their parameterization on climate (organized and co-ordinated experimentation will be defined).

CLIVAR Working Group on Seasonal to Interannual Prediction (WGSIP)

WGSIP has the responsibility of considering how operational seasonal-to-interannual predictions can be further refined, the improvements that can be made in the skill of probabilistic seasonal forecasts (e.g. by exploiting ensemble predictions and/or multi-model ensembles), examining the dependence of model predictions on the data used for forecast initialization and the way the data are assimilated, and the assessment of relevant observing systems and their effectiveness. These activities are supported by research into relevant modes of climate variability and predictability on seasonal to interannual timescales and seasonal effects interacting with monsoonal flows.

In considering the status of operational seasonal-to-interannual predictions, WGSIP has analysed further the reasons for the limited levels of skill achieved in forecasts of the 1997/1998 El Niño. WGSIP had earlier reached the sobering assessment that models had demonstrated only relatively limited ability in exploiting the predictability of El Niño. Generally, neither the onset nor the amplitude of the event were well predicted and the overall treatment of the evolution (growth, decay) was mixed. WGSIP has subsequently reconfirmed various aspects of its original diagnosis, namely that the specification of the initial ocean conditions was important in determining the quality of the predictions, pointing to the need for the development of improved data assimilation strategies, that shortcomings in the treatment of the annual cycle adversely influenced the predictive skill, and that deficiencies in the treatment of the Pacific/Indian Ocean exchanges deserved greater attention.

A key element of WGSIP work in understanding shortcomings in present models and the basis for making improvements is a series of intercomparison projects. Among these is the intercomparison of ENSO simulations in coupled models (ENSIP), drawing on the data base of simulations assembled in the WGCM Coupled Model Intercomparison Project (CMIP). ENSIP has now been completed and has demonstrated that many models are severely flawed in representing the basic sea surface temperature climatology and annual cycle, and in simulating ENSO realistically in terms of equatorial sea surface temperature anomalies. In the companion study of the variability of the tropical oceans on seasonal and interannual timescales other than ENSO (STOIC), substantial (mainly cool) biases are apparent in sea surface temperature. As in ENSIP, there were generally large differences between the simulated and observed changes in sea surface temperatures and zonal wind stress fields and even the basic annual cycle was not usually well reproduced.

WGCM was concerned at the serious shortcomings being revealed in the performance of coupled models by WGSIP (even in such basic features as the representation of the annual cycle). (On the other hand, the type of work being carried out by WGSIP underlined yet again the importance and utility of CMIP). WGCM was of the firm view that to make progress in seasonal-to-interannual prediction, much more attention and concentration needed to be given to the basic development and systematic improvement of the models being used (rather than the rapid proliferation of centres attempting to make seasonal forecasts!). The results being obtained also pointed to the need to elaborate an appropriate coupled ocean-atmosphere data assimilation approach for initializing seasonal forecasts.

SPARC-GRIPS

The initial intercomparison of basic model simulations of stratospheric climatology (showing a wide spread of skills, but almost all suffering from a cold bias) was reported at the previous session of WGCM, and an account was published in the Bulletin of the American Meteorological Society in May 2000. A number of supporting studies of various aspects of stratospheric simulations (e.g. troposphere-stratosphere connections, travelling waves/tides, tropical oscillations and waves, spectral wave analysis, the treatment of the southern hemisphere vortex) are more or less advanced (with results on travelling waves and tides, and spectral wave analysis expected to be published shortly). Further phases of GRIPS will involve a series of controlled experimentation to examine the realism of parameterizations of various important stratospheric processes (radiation schemes, gravity wave drag, the role of mesospheric drag). Scenario experiments to explore the response of the climate system to perturbations such as volcanic aerosols, solar forcing, ozone changes in the middle atmosphere, are also being planned.

ACSYS/CLIC modelling activities

Following the establishment of CLIC as a WCRP project (see above), the ACSYS Numerical Experimentation Group has become the "ACSYS/CLIC Numerical Experimentation Group". The objectives of the group remain the improvement of the representation of the cryosphere and polar regions in coupled general circulation models by carrying out quantitative evaluations and optimization of the treatment of individual polar- or cryospheric related processes. In practice, this will include continued sea-ice model studies and intercomparisons. A simulation of an annual cycle with one-dimensional atmosphere/sea-ice/ocean (column) models is also being planned. In the development of hydrological modelling in polar regions, an intercomparison of models in treating cold-region water and energy cycles is being jointly organized by ACSYS/CLIC and GEWEX.

GEWEX Co-ordinated Enhanced Observing Period (CEOP)

The GEWEX Co-ordinated Enhanced Observing Period (CEOP) will be a multi-year effort (2001-2003) to assemble common synchronous data sets from the GEWEX regional atmospheric/hydrological experiments (i.e. the GEWEX Continental-scale International Project, GCIP; the MacKenzie River GEWEX Study, MAGS; the Large-scale Biosphere-Atmosphere Experiment in Amazonia, LBA; the Baltic Sea Experiment, BALTEX; the GEWEX Asian Monsoon Experiment, GAME; and the Coupling of the Tropical Atmosphere and Hydrological, CATCH, in preparation in West Africa). CEOP was intended to provide an improved understanding of the role of continental sources or sinks of energy and moisture in forcing or modifying the global atmospheric circulation on seasonal-to-interannual timescales, as well as the effects of anomalies in land-surface conditions. Possible links between anomalies on seasonal, annual and interannual timescales would also be examined. The JSC has asked all WCRP project groups to consider how to take advantage of the opportunity offered by CEOP to study these types of climate features synchronously at a global scale.

2. CLOUD-CLIMATE FORCING AND FEEDBACK

WGCM has for a long time emphasized the importance of an improved understanding of the role of cloud feedback in climate sensitivity, pointing out that the representation of cloud-climate forcing and feedback in models is one of the most uncertain areas in climate simulations and projections of climate change. The GEWEX Radiation Panel is also beginning to consider how to examine this problem. It was therefore very timely that Dr. G. Stephens, Chair of the GEWEX Radiation Panel, participated in the present session of WGCM for a joint discussion by the two groups of the fundamental issues to be faced in considering feedbacks linked with clouds and their representation in models.

In this context, Dr. Stephens recalled that among the primary roles of the GEWEX Radiation Panel was the exploitation of global observations (with a dominant emphasis on remotely-sensed data) in conjunction with modelling. The Panel also aimed to identify gaps in observations, and in understanding of key radiation-cloud interactions and processes and in the representation of these aspects in models. For the cloud-climate problem, it was certainly not adequate to think of feedback in the type of simplified manner generally used up to now. Rather, the full functional dependence of the radiation budget (throughout the atmosphere) on cloud (which in turn depended on the general circulation and temperature, moisture and other variables), on moisture (again, in turn, a function of the general circulation, cloud, temperature etc. and on other atmospheric parameters) had to be considered. In the case of imposed forcing (e.g. increased greenhouse gas concentrations in the atmosphere), this introduced a whole range of feedbacks which affected the climate response including such aspects as the relationship between cloud properties and their key radiative characteristics, the relationship between the atmospheric circulation at large-, meso- and cloud-scales and cloud properties, and many others that have not hitherto been taken into account. In many cases, the relevant observational data have not been collected (nor is it even possible to collect the data required). For instance, in the case of the relationship between clouds and circulation, the most complete description was from numerical weather prediction models and related activities such as forecast verification, data assimilation etc. There was certainly a gap in global observations of clouds in the context of atmospheric circulation. The key to progress lay in a combination of model and observations to establish a (predictive) understanding of the relationship between clouds and the circulation, and in the many other feedbacks/relationships involved. To accomplish this, more interaction between modellers and observational scientists was essential.

WGCM agreed fully on the importance of close co-operation between itself and the GEWEX Radiation Panel in exploring the complex questions involved in cloud-forcing/climate feedback and in the organization of appropriated combined modelling/observational studies. AMIP and CMIP could provide a valuable framework for the type of studies involved. It was proposed that the GEWEX Radiation Panel and WGCM should jointly formulate appropriate AMIP and CMIP projects, consider the type of analysis techniques necessary, and the observational data sets required. Model data sets would have to be collected for certain periods at much higher space- and time-resolution than normally specified in AMIP or CMIP (as well as additional parameters) in order to be able to see clearly gross weather features and the associated cloud systems. At the same time, closer interaction between climate modellers and numerical weather prediction groups in assessing valid cloud statistics and the relationship with other atmospheric variables was needed. Dr. G. Stephens and Dr. J. Mitchell agreed to collaborate in developing these ideas and to designate representatives who could work together in setting up the required AMIP and CMIP projects.

3. WGCM INITIATIVES

3.1 Coupled Model Intercomparison Project (CMIP)

CMIP is one of the most important and long-standing initiatives of WGCM, having been started in 1995. At present, it comprises two components: CMIP1 to collect and document features of global coupled model simulations of present-day climate (control runs); CMIP2, to document features of climate sensitivity experiments with CO_2 increasing 1% per year. CMIP1 and CMIP2 data bases have been established at PCMDI. Dr. J. Meehl (Chairman of the CMIP Panel set up by WGCM to oversee the detailed organization of the project) and Dr. C. Covey (PCMDI) reported on the current status.

Data from the control runs of global coupled models (CMIP1) have been collected from twenty-one modelling groups in eight countries (representing virtually every group in the world with a functioning coupled model), and from transient climate integrations from sixteen groups (all that are expected). Using the PCMDI data bases, ten CMIP1 and fifteen CMIP2 diagnostic subprojects are currently in progress on a wide range of subjects. Four of the CMIP2 projects had begun since the session of WGCM in September 1999, namely: simulation of cryospheric change in coupled models; a study of climate impacts models; evaluation of the uncertainty in the rate of oceanic heat uptake and its contribution to overall uncertainty in climate change projections; and coupling between changes in hydrological and energy budgets. (The other subprojects are listed in the report of the third session of WGCM, WCRP Informal Report No. 1/2000).

As had been agreed at the 1999 session of WGCM, "CMIP2+" had now been initiated aiming to assemble sets of extra data (beyond that collected in CMIP1 and CMIP2) at higher temporal resolution so that additional processes, as simulated in coupled models, especially such aspects as feedback mechanisms (e.g. cloud-climate forcing as discussed in section 2) and ocean mixing could be investigated in more detail. Modelling groups have been duly invited to submit available history files for control runs and 1% transient integrations, but only limited new data were beginning to be received at PCMDI. WGCM strongly encouraged the continuation of "CMIP2+", noting that daily data or data at higher temporal resolution for a certain period would enable for the first time much more detailed studies of characteristics of coupled models (of the same type that have already been performed in AMIP). The CMIP panel would further consider the data sets to be compiled, and advise the research community of the availability of this extended CMIP1/CMIP2 data base.

WGCM reviewed further how the development of CMIP should continue, taking into account remarks made during the process of preparation of the IPCC Third Assessment Report. Work carried out in CMIP, including certain diagnostic subprojects, was an important contribution to various parts of the report. However, the need to continue and refine model intercomparison projects was particularly stressed (with an implied role for WGCM to take the lead role in organizing and overseeing such activities). Requirements highlighted were for an intercomparison of coupled models run under standardized experimental conditions for the twentieth century, co-ordinated well-designed experiments to explore the impacts of resolution (horizontal and vertical), systematic exploration of model uncertainties linked to parameterizations, and an intercomparison of model sensitivities.

WGCM had previously examined the possibility of a third phase of CMIP ("CMIP3") focussed specifically on twentieth and twenty-first century coupled model simulations which would meet the requirements expressed by IPCC. It was seen that the exact approach to be followed was complicated by the numerous scenarios employed and lack of agreement on forcing data sets. Moreover, there was the open question of how such an activity would be linked to that of the IPCC Data Distribution Centre which intended also to archive data from twentieth or twenty-first century runs. A number of general ideas were put forward on how a "CMIP3" might be organized. Firstly, it appeared appropriate that the criteria set by the IPCC Data Distribution should be followed, particularly that only runs with full three-dimensional coupled atmosphere-ocean general circulation models should be considered. It was thought that the period of integration should be from 1850 (if possible from 1700) to the present, with at least three runs per forcing to be undertaken (to permit an ensemble approach to evaluation). For initialization, existing control runs could be employed (although the issue of mixing present-day temperatures with radiative forcing conditions in 1700 would have to be examined). One common run with greenhouse gas forcing only would certainly be useful, but other integrations including other (non-standardized) forcings (e.g., solar, aerosol, volcanisms, changes in land-cover use) should be encouraged. It was agreed that it would be essential for the radiative forcing to be documented, and the forcing data employed to be in the public domain (or made public). Nevertheless, WGCM finally came to the view that, before embarking on a CMIP3, the CMIP2+ data collection should be completed, especially in regard to the archival of daily data, and the organization of appropriate diagnostic sub-projects. Such a complete data set from a coupled model would be the first ever of its kind available for model intercomparison, and would offer unique and exciting opportunities for analysis. This would be of value not only to the climate diagnostics community, but also to ocean modellers (who could take advantage of the entire history tapes of ocean data from the coupled model). Altogether, the further experience would help in setting up a more focussed and relevant CMIP3.

WGCM reiterated its appreciation for the work of the CMIP panel, under the leadership of Dr. Meehl. It was noted that Dr. G. Boer was now stepping down from the CMIP panel, and WGCM expressed sincere gratitude for his outstanding contribution to CMIP. Dr. B. McAvaney was nominated to take the place of Dr. Boer on the CMIP panel. WGCM also acknowledged the essential role of PCMDI in acting as the central archive for CMIP integrations and providing a large range of software facilities in support of the diagnostic subprojects. WGCM emphasized the importance of maintaining the present data base, the basic atlas of CMIP results, including overview figures and various statistical summaries etc. which were distinctive pointers to the level of performance of different models, and also showing whether fundamental characteristics such as ENSO were successfully reproduced. This sort of basic information was directly useful to IPCC. WGCM suggested that modelling groups should be allowed to withdraw earlier integrations and to replace them with more recent results. Looking to the future, it was foreseen that PCMDI would take advantage of technological developments going in the direction of using a distributed archival structure. Nevertheless, PCMDI would still have a key role in acting as a clearing house, a data referral centre, and to hold data subsets from groups not willing or able to offer local access.

3.2 Idealized sensitivity experiments

Drs B. McAvaney and H. Le Treut recalled that, as described at previous sessions of WGCM, intercomparison of results from equilibrium doubled CO_2 experiment (in which the atmosphere is coupled to a simplified slab ocean, thus not involving the complexity of the ocean response) had shown significant differences in inferred cloud forcings and changes in the top-of-the-atmosphere fluxes in different models. This work was now being formally written up and had also fed into the IPCC Third Assessment Report.

There was considerable interest in the community in maintaining this study, and various protocols for continuing to evaluate the inferred feedbacks were being discussed (including a project supported by the European Union). It did appear timely to convene a workshop on this topic to establish generally acceptable experimental plans, and the opportunity to attach such a workshop to an event such as the European Geophysical Society Annual Assembly, an IUGG/IAMAS Assembly, or even the planned GEWEX Conference in Paris in September 2001 would be explored.

Studies of climate sensitivity at the Meteorological Research Institute

Dr. A. Noda noted that two new Japanese coupled ocean-atmosphere general models, that from the Meteorological Research Institute (MRI2) and that from the Centre for Climate System Research and the National Institute for Environmental Studies (CCSR/NIES2) showed respectively the minimum and maximum climate sensitivities in the CMIP2 and SRES* integrations included in the IPCC Third Assessment Report. On the other hand, earlier versions of these models showed intermediate sensitivities. Possible reasons why the models had changed significantly in this respect were examined.

It was firstly recalled that the earlier version of the Meteorological Research Institute coupled model (MRI1) demonstrated a La Niña-like transient response in the Pacific region to increased CO_2 forcing. However, when the atmospheric component of MRI1 was coupled to a mixed-layer ocean, the equilibrium response in the Pacific region was dominated by an El Niño-like signal, and the climate sensitivities shown by the fully coupled and mixed layer versions were different. In contrast, both the coupled and mixed-layer versions of MRI2 showed weak El Niño-like responses, together with (similar) low climate sensitivities. The atmospheric component of MRI2 is a modified form of the model employed operationally by the Japan Meteorological Agency. Differences in cloud parameterization and relevant cloud feedback processes in MRI1 and MRI2 appear to be mainly responsible for the lower climate sensitivity of MRI2.

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* SRES: scenarios proposed in the IPCC Special Report on Emissions Scenarios

In the case of the CCSR/NIES2 model, two main factors are thought to contribute to the enhanced climate sensitivity compared to the earlier model version. One is the choice of radiation parameters for the gas absorption coefficients (although both the new and older values appear realistic compared with line-by-line computations), the other the change in cloud-radiation feedback consequent to modified values for parameters used in the convection and boundary layer representations. Experimentation with mixed layer models suggests that the first factor explains about two-thirds of the enhanced sensitivity, the second about one-third. CMIP2 and SRES integrations are now being carried out with both the earlier and more recent model versions to examine the changes in the simulated transient response.

Dr. Noda continued by presenting global warming patterns and dominant natural variability modes (EOF1 and EOF2) computed from the various model outputs assembled at the IPCC Data Distribution Centre. It was strongly suggested that a more realistic representation of ENSO could contribute to an improved simulation of climate change (cf. work of WGSIP reported in section 1).

WGCM was of the view that the results presented by Dr. Noda underlined the need to continue to investigate the magnitude of various feedbacks and the relative roles of dynamics and thermodynamics. The results further illustrated the value and useful information that could be deduced from mixed-layer or slab ocean models in studying changes in responses produced following model developments.

3.3 Standardized forcing scenarios

The range of forcing data sets (greenhouse gases, aerosols, ozone, solar, volcanic aerosols) that are being used have been reviewed at previous sessions of WGCM. An IPCC Special Report on Emission Scenarios has proposed four modified scenarios based on various assumptions regarding demographic and technological developments. A number of centres have now undertaken runs using the SRES scenarios (e.g. MRI and CCSR/NIES as referred to in section 3.2), as well as continuing runs using other forcing data sets (e.g. as being contributed to CMIP2).

WGCM noted that there remained considerable uncertainties in aerosol forcing. WGCM encouraged modelling centres to conduct runs for greenhouse gas and aerosol forcings separately in order to improve understanding of the latter, and to be able better to scale results from one scenario to another.

3.4 Initialization of coupled models

At this session of WGCM, few new results on the initialization of coupled models were specifically reported. An appropriate initialization is essential for a realistic control integration, and for subsequently being able to assess the signal versus noise ratio in transient climate change experiments. The satisfactory initialization of the ocean component is the key and is a particular scientific challenge, as well as being potentially demanding in terms of computer resources because of the long timescales involved. Various techniques have been tried to accelerate convergence to an initialized equilibrium state, but none have been entirely successful. Moreover, an approach used at one model resolution does not always appear to work for a different model resolution. This issue was further touched on in item 3.5 in the discussion of ocean model development and in item 3.8 in the review of the results of the Workshop on Decadal Climate Predictability where the importance of initialization of coupled models had been raised.

3.5 Ocean model development

Working Group on Ocean Model Development

Following discussion at the WGCM session in Melbourne in October 1998, a joint WGCM/WOCE Working Group on Ocean Model Development had been formally established to give specific attention to a number of questions on the performance of ocean models and to the refinement of the ocean component of coupled models. On behalf of the group, Drs S. Griffies and D. Webb summarized the progress so far.

The group met for the first time in March 2000. The need to document the status of and advances in ocean modelling for climate studies was particularly recognized. Research on methods to improve ocean models, particularly for climate purposes, would be encouraged through workshops and other appropriate activities. Advice to climate modelling centres would then be formulated, underlining what ocean modellers knew was required to reproduce the mean state of the ocean. As a first step in this process and based on the discussions at the first session of the group, an authoritative and comprehensive survey "Developments in Ocean Modelling" had been drafted (with Dr. S. Griffies as lead author, and the other members of the

Working Group as co-authors).* The paper reviewed research developments in primitive equation ocean models which were, or could be, important for the ocean component of realistic global climate models used for simulating or predicting large-scale, low frequency climate variations or changes. The text had been written with an audience of modellers concerned with the ocean component of coupled models in mind, although not necessarily experts in the design and implementation of ocean model algorithms. Aspects to be taken into account and carefully considered in the vertical and horizontal co-ordinate systems and timestepping, in treating barotropic dynamics, in the formulation of the surface mixed layer and bottom topography, in the representation of overflows, in advection of momentum and tracers, in the parameterization of mesoscale eddies and horizontal momentum friction were described.

The final section of the report took up the question of the optimal grid resolution for climate models, and the related issues of whether mesoscale eddies needed to be fully resolved to quantify accurately poleward heat transport, whether it was important to resolve further sub-mesoscale features and even non-hydrostatic processes, what resolution was required to simulate large-scale sea surface temperature patterns, and in how much detail the sills and passages (especially in the North Atlantic and Arctic) should be represented to provide reliable predictions of variations and potential changes in the thermohaline circulation. No answer was given, but Dr. Griffies estimated that a resolution of at least 1/10° was needed to resolve mesoscale eddies and no resolution higher than 1° generally, with 1/4° near the equator, could suffice to give a basically reasonable ocean simulation. However, the use of such relatively coarse resolutions should in any event be compared with a high resolution ocean simulation. It was also pointed out that the use of adaptive grids and/or finite elements should be explored.

WGCM congratulated the Working Group on Ocean Model Development on the excellent summary that had been prepared, and believed it would be an extremely valuable document for the climate modelling community, especially in setting out clearly the objectives to be aimed for. WGCM recognised that more resources were essential to bring ocean models up to the level required, in turn entailing significantly more institutional support in addition to the relatively small mainly academic groups working in this area at present.

Looking to the future the Working Group on Ocean Model Development would meet again in March 2001 to consider the issues in the Working Group Report and the appropriate refinements needed in ocean models. The treatment of the ocean components in coupled ocean-atmosphere simulations as revealed by CMIP1 and CMIP2 results would be reviewed, and generally, more involvement by the ocean modelling community in looking at CMIP1 and CMIP2 integrations would be encouraged. There were already several areas evident where the simulated response of the ocean to climate forcing needed investigation. Also a workshop was being planned in 2001 or 2002 where recommendations for the type of ocean model to be used for climate research would be discussed in the light of the latest available information and results.

High resolution coupled ocean/atmosphere integrations

As noted above, the Working Group on Ocean Model Development had recommended that simulations from relatively coarse ocean models (as normally used in coupled ocean/atmosphere integrations) should be compared with that from a high resolution ocean. WGCM itself at several previous sessions had noted the concerns that relatively coarse resolution ocean models may result in systematic errors in ocean simulations and had strongly encouraged the principal coupled modelling groups to carry out a reasonably long integration with a high resolution coupled model as a means of identifying errors and assessing their significance. However, work on these lines was only proceeding slowly. The Hadley Centre is carrying forward a run with a 1/3° oceanic and 2.5°x 3.75° atmospheric models. This had reached seven years and is being continued. A better representation of heat flow through channels is definitely evident. Plans have been made at NCAR for an integration with a T85 atmosphere and 2/3° resolution ocean. A high resolution experiment was also being considered by the Southampton Oceanography Centre (with a high resolution ocean coupled to the CSIRO atmospheric model).

3.6 Detection and attribution of climate change

Based on material submitted by Dr. G. Hegerl, Dr. J. Mitchell summarized the range of outstanding issues in the quest to detect and attribute climate change. A first significant need is to be able to include estimates of model uncertainties in detection statements (e.g., in the form of the time-space covariance of model error). A first shot at this could be provided by the distribution of mean and deviations of simulations

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* The document has been submitted to "Ocean Modelling" for publication.

from many models forced in an identical manner. This information is more or less available for greenhouse gas forcing, but is also needed for some form of aerosol forcing. A linked question is the assessment of the uncertainty in model simulations of internal climate variability on timescales from annual to multi-decadal which is at present a major gap in detection statements. The CMIP data base could clearly be an important source of data in this respect. Secondly, as already noted in section 3.3, ensembles of runs are needed to identify more clearly the various signals and to separate anthropogenic impacts from natural influences, i.e. greenhouse gas runs only, natural forcing (solar and/or volcanic jointly or separately) only. A third requirement is an overall assessment of how well the twentieth century can be modelled; this would be based on simulations with the best estimates of all forcings (anthropogenic and natural) combined. Ensemble runs for critical periods would be valuable (e.g. for the last decades of the twentieth century when satellite data are available and for the period 1920-1940) to understand better what drove the early twentieth century warming (anthropogenic forcing and internal climate variability, or anthropogenic and natural forcings combined) and to see whether the lapse rate evolution indicated by observations can now be modelled. WGCM recognised that the proposed third phase of CMIP (see section 3.1) could offer the possibility of contributing in an important manner to the detection and attribution issue, but the type of points raised above would need to be taken into account in the planning of a CMIP3.

Other points mentioned were the need to compare model results with observations in a like manner (e.g. use of a data mask to match model coverage with that sampled in observations; comparisons with a range of available reconstructions of hemispheric scale temperature evolution over the last millennium taking into account the limitations and strength of each record; to simulate as closely as possible what is monitored by proxy data). The detection of changes in other more societally relevant variables was also beginning to be explored. Questions were also being raised as to how (present-day) data collection could be improved better to meet the requirements for detection of climate change, and modellers were asked for advice on where more data were needed for detection and sampling climate variability. These issues were especially important in the development and implementation of the Global Climate Observing System Global Surface and Upper Air Networks.

3.7 Palaeoclimatic modelling

Dr. S. Joussaume introduced this item. In regard to the Palaeoclimate Modelling Intercomparison Project (PMIP), results of the experimentation to study the simulation of the climates of the mid-Holocene (6000 BP) and the Last Glacial Maximum (21000 BP) had been fully reviewed at the third PMIP workshop (Canada, October 1999). The full workshop proceedings have been published in the WCRP Report Series (No. 111). (Some of the principal results had been anticipated by Dr. Joussaume at the previous session of WGCM).

The workshop had considered the future of PMIP. There was much interest in the extension of activities in the direction of coupled model simulations and new time intervals. However, the mid-Holocene and Last Glacial Maximum have been the focus of PMIP up to now and it was agreed that these should remain central. In the light of results presented at the workshop, it was proposed that:

(i) for the mid-Holocene, the model-model and model-data comparisons would be extended to include results from coupled atmosphere-ocean model runs now available. The first of such runs have shown the importance of ocean feedback, and sensitivity experiments have indicated that vegetation feedback also needs to be considered. A common coupled ocean-atmosphere-vegetation experiment will be defined.

(ii) for the Last Glacial Maximum, no new standard experiment would be undertaken for the time being. Instead, attention would be given to reconsidering the sea surface temperatures used (the CLIMAP values appear to have been relatively warm). Reliable estimates of sea surface temperature would be essential for future simulations and to validate the ocean models expected to be employed more and more in coupled model simulations of the Last Glacial Maximum in the coming years.

Two other periods of general interest were the early Holocene (10-11000BP) when insolation forcing was strong but ice sheets were still present. The design of a standard (co-ordinated) experiment is being discussed. The inception of the Ice Age at the end of the last interglacial period (115,000 BP) was already being modelled by some groups, but it was judged premature to organize common experimentation as yet. However, a contact list of interested scientists/groups will be established, exchange of information fostered, and a special session dedicated to the studies of this period and the results being obtained would be included in the next PMIP workshop (planned for later in 2001 in Europe).

WGCM expressed appreciation for, and encouragement to the work carried out under PMIP auspices. The simulations of palaeoclimate were an independent test of models and a valuable tool in assessing model performance not otherwise available. WGCM duly urged that continued support should be given to palaeo-modelling and allied palaeo-data studies.

3.8 Atmosphere-ocean predictability on decadal timescales

Dr. M. Latif summarized the main findings and recommendations from the joint WGCM/WGSIP Workshop on Decadal Climate Predictability that had taken place at the Scripps Institution of Oceanography from 4-6 October (the week preceding the WGCM session) (see Appendix B).

WGCM noted that, overall, work and understanding in this area were still fairly rudimentary. There was only tenuous statistical evidence of predictability on decadal timescales, and a limited number of practical or robust results from modelling studies (either simulations or predictions). In considering further activities that could be undertaken, WGCM stressed the need for work and numerical experimentation to explore mechanisms which might underlie decadal predictability (noting that the principal foci of the workshop had been statistical analysis and model simulation of certain specific modes). WGCM suggested that a diagnostic project using the extended CMIP data base (see section 3.1) could be useful in this respect and in understanding time-scale interactions. WGCM, in the light of its own discussions (see section 3.4), was very aware of the difficulty of initializing coupled models (as needed for decadal prediction) and thus did not consider the time yet ripe to take up the "Historical Decadal Forecast Project" suggested by the workshop. Nevertheless, WGCM strongly encouraged work to investigate the many outstanding questions. The importance of developing data assimilation of coupled ocean-atmosphere systems (which would also help in specifying the observational system needed) was particularly stressed. WGCM asked Dr. M. Latif to maintain an overview of activities in this area on its behalf and to report at the next WGCM session on progress that may be made.

4. OTHER ISSUES AND ACTIVITIES

4.1 Carbon-cycle modelling

Co-operation between WGCM and IGBP/GAIM

WGCM has for some time hoped to co-operate with the Global Analysis, Integration and Modelling (GAIM) element of IGBP in an effort to model the observed interannual variations in CO_2 and to assess the relative contributions of the atmosphere, ocean and terrestrial components of the Earth system to these variations. WGCM was pleased to welcome Professor I. Fung (University of California, Berkeley) as representative of GAIM at this session to discuss how the two groups could jointly proceed in this area.

The importance of working together in the development of comprehensive Earth system models was mutually agreed. As a first step, WGCM and GAIM would organize jointly a series of experiments with CO_2 as a prognostic variable. Interested modelling groups would be invited to undertake co-ordinated transient model runs using fully coupled atmosphere-land-ocean-carbon models with specified (fossil fuel) CO_2 emissions for a contemporary period (1800-2000) and for the period 2000-2100 using various emission scenarios. (Other forcings could also be included in terms of equivalent CO_2). The atmospheric CO_2 concentration would be able to evolve freely (depending on the model representation of carbon processes and absorption into or exchanges with ocean/land surfaces). The simulations of the evolution of CO_2 and the climate response would be compared. This project would be in marked contrast to the type of experimentation fostered by WGCM so far where the actual atmospheric carbon dioxide concentration has been specified. It was recognized that some of the predicted changes (both in the simulated model climate and carbon dioxide concentrations could be very large and model dependent, and considerable care would be required in designing the experiments and analysing the results.

Professor I. Fung and Dr. J. Mitchell will jointly lead this activity and work together to define a detailed experimental protocol (Dr. J. Mitchell will also involve Dr. P. Cox from the Hadley Centre). PCMDI agreed to act as a clearing house for assembling the simulations and Dr. C. Covey (PCMDI) was also duly invited to join the planning group, in particular to advise on the list of diagnostics to be collected.

Reports of carbon-cycle integrations

It was noted that several groups represented on WGCM had already carried out integrations incorporating a representation of the carbon cycle. At the Institute Pierre-Simon Laplace, a fully coupled climate/carbon cycle model has been constructed. A pre-industrial (1860) equilibrium was established for the ocean/atmosphere, with the carbon cycle model being set to equilibrium with the corresponding simulated climate. Two runs, one a control, the other with anthropogenic carbon dioxide emissions, were undertaken from 1860 conditions up to 2100. Up to the "present", observed carbon dioxide emissions were used, and the simulated carbon dioxide concentration followed closely that actually seen. An interesting result was an indication of qualitative differences in the feedback associated with changes in the biospheric and oceanic uptake compared to a previous off-line experiment.

At the Hadley Centre, the third version of the coupled ocean-atmosphere model (HadCM3) has been linked with ocean carbon and dynamic global vegetation models. The latter represents the state of the biosphere in terms of soil carbon, and the structure and coverage of five plant functional types within each model grid box. However, the additional computational expense of including an interactive carbon cycle made it necessary to reduce the ocean resolution (to 2.5°x 3.75°), with the consequence that flux adjustments had to be used in the ocean component to counteract climate drift. The complete climate-carbon model was brought to equilibrium with a "pre-industrial" atmospheric carbon dioxide concentration of 290 ppmv and employing an observed land cover data set. The equilibrium condition was stable with negligible net land-atmosphere and ocean-atmosphere carbon fluxes in the long-term mean and no discernible drift in the atmosphere carbon dioxide concentration. The simulated carbon cycle displayed significant interannual variability, driven by model-generated ENSOs (which is consistent with the observational record). Transient simulations were then carried out for the period 1860-2100 using carbon dioxide emissions given by the IPCC IS92a scenario, firstly with fixed vegetation (i.e. a "standard" GCM climate change simulation), secondly with interactive carbon dioxide and dynamic vegetation but no direct impacts of CO_2 on climate (i.e. on "off-line" carbon cycle projection but neglecting climate change), and thirdly a fully coupled climate-carbon cycle simulation. The experiments demonstrated strikingly the potential importance of climate-carbon cycle feedbacks if we are successfully to predict climate change over the next hundred years. For example, the potential conversion of the global terrestrial carbon sink to a source (as seen during the course of the fully coupled climate-carbon integration is critically dependent on the long-term sensitivity of soil respiration to global warming). This sort of question, as well as the magnitude of the other feedbacks in the real Earth system, are still very much a subject of debate.

Dr. Bengtsson referred to the development of dynamical global vegetation model by various institutions (the Potsdam Institute for Climate Impact Research, the Max-Planck-Institute for Biogeochemistry, and Lund University). The realistic representation of vegetation and of the part played in the carbon cycle was crucial since it was believed that 600 G tonnes of carbon dioxide per year passed through plant stomata (compared to an exchange of 250 G tonnes per year between the atmosphere and ocean). An approach from "first principles", building up from bare ground, was being followed. Nine plant functional types had been specified (i.e., tropical broad-leafed evergreen and raingreen, temperate needle-leaved and broad-leaved summergreen, boreal needle-leaved evergreen and summergreen, "cool" grasslands, "warm" grasslands) and four vegetation tissue pools. A "mixed grid cell" parameterization was employed where the different plant types could dynamically compete, taking into account soil texture, temperature, precipitation, solar irradiance, and carbon dioxide. Evapotranspiration, net ecosystem exchange and change in soil moisture were computed. Changes in plant types were determined based on factors such average growth, establishment, soil litter, biogeochemistry and mortality (e.g. competition, general mortality, heat stress, water stress, fire).

4.2 Regional climate modelling

As noted in section 1, the JSC at its twenty-first session in March 2000 had noted the reviews carried out and points made by WGCM and WGNE in respect to regional climate modelling. The JSC had agreed on the establishment of a joint WGCM/WGNE ad hoc panel to summarize the current state-of-the-art in the field of regional climate modelling and to take up the questions that had been raised. These included the technical items noted by WGNE (choice of domain size, scale dependency of model parameterizations, consistency of simulated energy and water budgets in inner and outer models, the care needed in handling the lateral boundary conditions) as well as aspects emphasized by the JSC itself (the limitations imposed by the performance of the global driving model, the predictability/reproducibility of smaller scales simulated in regional climate models). The panel was also asked to consider whether any co-ordinated or focussed experimentation should be organized (e.g. "identical twin" experiments).

The intention had been that the panel might organize a workshop in 2001 or 2002 aimed at increasing the awareness of the community at large to uncertainties in the use of regional climate models. However, in the meantime, a workshop on "Regional climate research: needs and opportunities" had been arranged in the USA (by the US National Science Foundation and Department of Energy) in early April 2001, which would be likely to discuss not only some of the topics to be taken up by the joint WGCM/WGNE panel, but also the sort of ground that might have been covered in a (WCRP) workshop on regional climate modelling. WGCM urged the ad hoc panel to take full advantage of material presented at, and conclusions and recommendations from, the USA workshop. (In fact, at least two members of the ad hoc panel were due to participate in the workshop). WGCM also encouraged the ad hoc panel to proceed as rapidly as reasonably possible with its work which should form a foundation for using appropriate regional climate modelling techniques and building up confidence in the regional climate modelling approach. The panel was reminded that an interim report on progress and the discussions that had taken place should be presented to the JSC at its session in March 2001.

4.3 Requirement for long-term climate integrations

At several points during the session, the problem of identifying specific effects from individual forcings (e.g. see sections 3.3 and 3.6) had been mentioned. At the same time, the difficulty of inferring such effects from the results of model integrations was recognized in view of the high natural variability, the short observational records of forcing, and the fact that the model response to forcing was strongly non-linear. Furthermore, as an adjunct to the PMIP studies (see section 3.7), long control runs of the order of a 1000 years to compare simulated variability with that inferred from available observations and proxy data over the last millennium (e.g. as presented at the joint PAGES/CLIVAR workshop in Venice, November 1999) were expected to be a revealing indicator of model realism and as a possibly effective means of studying the role of external forcing. Only relatively few integrations of this type had so far been undertaken.

WGCM therefore encouraged modelling groups to consider if possible long (control) integrations (i.e. without forcing) for an extended period (e.g. 1000 years). These integrations, which should be initialized with pre-industrial levels of greenhouse gases, would provide a valuable reference and control for CMIP. The runs could also be regarded as a ten-member ensemble of 100 year integrations and provide plentiful sets of initial conditions for initialising other experiments. A firm basis for assessing (model-simulated) internal or natural variability on all time- and space-scales would also be established, and for comparison with proxy data. However, it was noted that the interpretation of the latter is not straightforward and careful consideration was needed of the range of parameters to be collected from the model integrations adequately to describe the simulated low-frequency patterns and to be able to compare with proxy indices. Drs McAvaney, S. Joussaume, and C. Covey were asked to consider these various details. In particular, Dr. Covey would advise on the collection of data/parameters that would be useful from the CMIP perspective, and Dr S. Joussaume would provide the link with palaeo-data (and PMIP) communities and determine their interest in the availability of the collected set of 1000-year integrations.

Looking further ahead, following the assessment of simulated internal variability, a more comprehensive attempt to identify the impact and signature of external forcing might then be attempted. This, however, would involve the painstaking and difficult task of assembling a credible long-term record of appropriate external forcing data.

4.4 IPCC

As noted in section 3.1, the current IPCC assessment had emphasized the importance for future assessments of an intercomparison of coupled models run under standardized experimental conditions for the twentieth century, experiments to explore the impacts of resolution (horizontal and vertical), and systematic examination of model uncertainties linked to parameterizations and of the dependence of climate sensitivity on parameterizations. Attention had also been drawn to the value of continuing palaeoclimatic experimentation, and to increasing climate model resolution in the stratosphere.

WGCM observed that the initiatives being undertaken by itself, and those of WGNE and other groups in WCRP, would go a long way towards meeting the requirements expressed by IPCC. However, much of the work involved was highly complex and time-consuming, e.g. the type of cloud-climate feedback analysis discussed at this session of WGCM in section 2 would be a major project.

WGCM also reiterated that modelling groups were still faced with a daunting array of fundamental problems. However, large amounts of time were currently being spent by very many leading scientists in the repetitive IPCC assessment process and participation in drafting meetings etc. In WGCM's opinion (as has been expressed at previous sessions of the group), this was a matter of concern when so much work was needed in the refinement of climate models themselves. WGCM strongly underlined the view that the intervals between IPCC assessments should be significantly increased.

5. ORGANIZATION OF FUTURE ACTIVITIES

At the kind invitation of Dr. J. Mitchell, the next session of WGCM will be held at the Hadley Centre, in Bracknell, from 17-20 September 2001. Information on arrangements for the session would be sent out in due time.

6. CLOSURE OF SESSION

This would be the last session of WGCM to be chaired by Dr. L. Bengtsson, who would be stepping down from the group on 31 December 2000. At the twenty-first session of the JSC in March 2000, Dr. J. Mitchell had been nominated as Vice-chair of WGCM, as a prelude to his taking up the Chairmanship when the term of Dr. Bengtsson ended.

On behalf of WGCM, Dr. Mitchell expressed deep appreciation to Dr. Bengtsson on his outstanding work in having led WGCM so effectively since 1995, and having established WGCM as such a prominent working group in the field of climate modelling. Dr. Bengtsson had certainly lent his personal authority and inspiration to many of the successful activities and initiatives organized by WGCM. On behalf of the JSC, Dr. P. Lemke also paid tribute to Dr. Bengtsson's excellent contributions to the WCRP in leading WGCM. Moreover, his participation in the work of the JSC in his capacity as Chairman of WGCM had always been very much appreciated. Dr. Lemke relayed the sincere gratitude of the JSC to Dr. Bengtsson.

The fourth session of WGCM was closed at 15.30 hours on 11 October 2000.

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SUMMARY OF JOINT WGCM/WGSIP WORKSHOP ON DECADAL PREDICTABILITY LA JOLLA, CA, USA, 4-6 OCTOBER 2000

The joint WGCM/WGSIP Workshop on Decadal Climate Predictability took place at the Scripps Institution of Oceanography, La Jolla, CA, USA, from 4-6 October 2000. There were over 30 participants from 18 different scientific institutions, groups and organizations. The objective of the workshop was to form an overall sense of the "state of the art" in decadal predictability. Since this area of study is in its infancy, the intent was a true "workshop" which would explore observed and simulated decadal variability, decadal predictability, and such practical attempts to produce decadal forecasts as were available. The Workshop was organized into a series of presentations in these broad areas followed, on the final morning, by three break-out working groups. The groups summarised the status of observations and observed variability, simulations and simulated variability, and prediction/predictability and made recommendations and suggestions for possible future work/activities.

Most presentations on observations and simulations focussed on interdecadal variability in the Pacific and North Atlantic. Several talks highlighted the multi-decadal variability in the Atlantic Ocean. This type of variability has typical time scales of 60-80 years, and it can be described from direct temperature observations and from indirect data for the last millennium. The multi-decadal variability involves an interhemispheric dipole in the Atlantic sea surface temperature, and there is some evidence that it may be predictable several years in advance, based on a perfect-model predictability study made with a coupled ocean-atmosphere general circulation model. Other regions of relatively high "potential" decadal predictability, identified in the control runs of 11 coupled models in the CMIP1 database, are the North Pacific, the tropical Pacific and the Southern Ocean. Decadal predictability of surface temperature over land appears to be very modest in these results.

In sum, the workshop considered long timescale phenomena in the coupled system and the evidence for decadal predictability. There was some indication of predictability, mainly at higher latitudes and associated with long timescales in the ocean, obtained from prognostic perfect model and diagnostic potential predictability studies. The utility and practical achievement of decadal forecasts, nevertheless remains an open question which requires directed attention and active research.

Observations and simulations of decadal variability

Considerable attention was paid to the North Atlantic Oscillation, although no clear consensus emerged as to its preferred timescale. To first order, it appears that the atmosphere forces the sea surface temperature via heat fluxes and Ekman currents. A secondary effect is due to changes in the Atlantic gyre or thermohaline circulations responsible for anomalies. As well as uncertainties in the underlying mechanism for the North Atlantic Oscillation, simulations of response/feedback to the associated sea surface temperature anomalies differed among models.

The understanding of the North Pacific Oscillation (or Interdecadal Pacific Oscillation), is also comparatively rudimentary, although there has recently been progress in modelling decadal changes in the North Pacific. In the tropical Pacific, coupling to mid-latitudes does not appear to explain much of the variance (temperature/salinity anomalies may be the key, but these anomalies are small). The role of the southern hemisphere oceans, if any, is unknown. Decadal variability could also not be clearly separated from global warming which might itself be responsible for some decadal variability. How global warming might interact with "natural" decadal variability is not yet clear.

As a basis for further progress, much longer time series of data and model runs were seen as essential (i.e. from reanalyses, paleoclimatic data, and extended coupled model integrations). The requirement was also expressed for a multi-decadal ocean and/or coupled ocean/atmosphere reanalysis for hypothesis testing, for initialising simulations and decadal forecasts.

Predictability and prediction

Some predictability at decadal timescales of the ocean circulation at higher latitudes (particularly the thermohaline circulation) was inferred from potential predictability studies and perfect model experiments. Associated variations over land might be predictable also, but only explain a small fraction of the total variance. In the tropical Pacific, some weak evidence of decadal predictability was noted. The question of how decadal and interannual variability interact is unanswered. There are large areas where there is yet no firm understanding, namely those concerning the tropical Atlantic dipole, the Interdecadal Pacific Oscillation, and the North Atlantic and the predictability of the North Atlantic Oscillation.

There was some consensus that the thermohaline circulation may be predictable at decadal time scales provided that initial oceanic conditions could be satisfactorily specified. However, the impact of the North Atlantic Oscillation on the export of freshwater from the Arctic remained to be clarified. Improved simulations of overflows and deep (ocean) convection which affect temperature/salinity locally were also needed. The interaction between ENSO variability on decadal timescales and the thermohaline circulation was not well understood. A pioneering attempt at practical decadal forecasting (by the Hadley Centre) is underway but has achieved only modest results to date.

Future directions

It was considered that a vital step in making progress from the current rather elementary position was work on understanding the mechanisms that might underlie predictability (including the study of particular modes). The understanding of the dynamics involved in these mechanisms is limited. Time-scale interactions (e.g. the Interdecadal Pacific Oscillation with ENSO) also needs study.

The possibility of a "Historical Decadal Forecast Project" was raised, which would include efforts toward an improved understanding of mechanisms, use of initial conditions from atmospheric and oceanic reanalyses (based on data from merging all available observations and model simulations), model development (in particular sub-grid scale ocean features such as overflow, convection), and ensemble approaches (forecasts from sequential analyses and from different models, estimates of skill, statistical treatments, probabilistic forecasts). Other areas where work was needed was better international co-ordination of ocean analysis as a basis for initializing decadal forecasts (including quality control of data, obtaining more salinity observations), and the study of the relative roles of sea surface temperature, sea-ice, vegetation cover, and external effects. Another useful step would be to begin to document the potential societal impact of decadal predictions.

The full report of the workshop, including extended abstracts of presentations and summary of main conclusions and recommendations will be produced as a WCRP report (in an appropriate series).