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The fifth session of the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) was kindly hosted by the Hadley Centre for Climate Prediction and Research, the Met Office, Bracknell, Berkshire, UK, from 4-7 February 2002. The list of participants is given in the Appendix to this report.

The session was opened by the Chairman of WGCM, Dr. J. Mitchell, at 0930 hours on 4 February, who welcomed all participants to his home institution. On behalf of the Met Office, Dr. P. Mason, Chief Scientist, added his welcome and expressed satisfaction that the WGCM session was being held in Bracknell. He particularly appreciated the opportunity for interactions between the participants in the session and the scientific staff in the Hadley Centre. He hoped that several staff would contribute to the discussions at the meeting, and all would be ready to offer any assistance to ensure the success of the meeting. On behalf of the WCRP and participants in the session, Professor P. Lemke, Chairman of the Joint Scientific Committee (JSC) for the WCRP, expressed thanks to Drs Mason and Mitchell for their welcome and gratitude to the Hadley Centre for hosting the WGCM meeting.

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

Under this agenda item, WGCM was informed of the main discussions at and recommendations from the twenty-second session of the Joint Scientific Committee (JSC) for the WCRP (March 2001), and the tenth session of the CLIVAR Scientific Steering Group (May 2001). In order to maintain a broad overview of modelling activities in the WCRP in its basic task of building up comprehensive climate models, WGCM also took note of work in hand by the JSC/CAS Working Group on Numerical Experimentation (WGNE) and the GEWEX Modelling and Prediction Panel (GMPP), the CLIVAR Working Group on Seasonal-to-Interannual Prediction (WGSIP), the ACSYS/CliC Numerical Experimentation Group, and modelling-related activities in SPARC.

Twenty-second session of the JSC

The JSC expressed appreciation for the wide-ranging and appropriate activities being undertaken by WGCM, in particular the Coupled Model Intercomparisons Project and the idealized sensitivity experiments now focussing on cloud forcings, as well as emphasizing the importance of the interactions now developing between WGCM and the GEWEX Radiation Panel on this topic. The JSC noted the main conclusions from the Workshop on Decadal Predictability that had been organized by WGCM in October 2000, and confirmed that WGCM should continue to pursue studies of simulations of decadal variability in CMIP. The need to keep the initialization of coupled models under review was also reiterated (see section 3.4). Furthermore, WGCM was invited to comment on the feasibility of, or questions related to, use of new numerical techniques (e.g. linear grids, semi-Lagrangian methods) that might potentially offer advances in the speed of integration of climate models.

WGCM noted the continuing and developing co-operation and interaction between WCRP and the International Geosphere-Biosphere Programme, IGBP, as manifested particularly in the organization of the successful Open Science Conference in Amsterdam, July 2001, and the planning of the three joint projects between WCRP, IGBP and the International Human Dimensions of Global Environmental Change Programme (IHDP) (i.e. concerned with Global Environmental Change and Food Systems, the Global Carbon Cycle, and the Joint Water Project). In this context, the collaboration between WGCM and the Global Analysis, Interpretation and Modelling (GAIM) element of IGBP in carbon-cycle modelling and the plans for a joint WGCM/GAIM meeting were highly important (see section 3.9).

Tenth session of CLIVAR Scientific Steering Group

Dr. A. Villwock relayed the expectation of the CLIVAR Scientific Steering Group that WGCM would oversee and co-ordinate the global modelling activities required by CLIVAR for studying variability on decadal to centennial timescales and for climate prediction. The Scientific Steering Group had specifically called for increased study of how anthropogenic climate change might affect modes of natural climate variability including the seasonal monsoon circulations, ENSO and the North Atlantic Oscillation. Attention was drawn to the plan to hold a major CLIVAR science conference in June 2004 (in the USA). The format and programme of the conference were still under discussion but significant input would be required from WGCM.

JSC/CAS Working Group on Numerical Experimentation (WGNE) and GEWEX Modelling and Prediction Panel (GMPP)

Dr. K. Puri, Chairman of WGNE, recalled that WGNE was 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 worked 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 was described fully in the recent reports of WGNE sessions. In the area of climate model intercomparisons, the main initiative conducted under WGNE auspices was 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 was the counterpart to atmospheric models that CMIP was to coupled models, see section 3.1). AMIP, based on a community standard control experiment simulating the period 1979-1996, was now reaching the end of its second phase. Twenty-three modelling groups had submitted simulations, with most of the data available for a wide range of diagnostic sub-projects. Since AMIP began nearly a decade ago, there had been a general improvement in the simulations both in terms of the "median" model as well as for many models individually. The representation of interannual variability and performance in specific geographical regions, as measured by global climatological statistics also appeared to be more realistic. AMIP had now become a well-defined experimental protocol and extremely well recognized and valuable tool for testing global atmospheric circulation models, with powerful capabilities for handling voluminous model integrations at PCMDI and facilities for the diagnosis and display of results. WGNE was thus strongly encouraging the continuation of AMIP to provide an evaluation of atmospheric models from different groups as they evolved and a gauge of progress in atmospheric modelling, and a focus for advanced diagnostic research. An AMIP workshop was being planned for November 2002 to review the results of the second phase of AMIP and to discuss generally the future of the project.

Other intercomparison activities conducted by WGNE were centred on model-derived estimates of ocean-atmosphere fluxes and precipitation, stratospheric representations in NWP models, and the treatment of snow cover. Another topic kept under close review was developments in the dynamical cores of atmospheric circulation models and numerical approximations. As noted by the JSC (see above), there were potentially major advances in the speed of the basic integration of atmospheric models resulting from algorithmic changes, but issues such as energy conservation, of particular importance in climate models had to be taken into account (see further discussion in section 4.4). The interactions of physical parameterizations with each other and with dynamics also needed to be examined. In this regard, stripped-down versions of atmospheric models with very simplified surface conditions ("aqua-planet" experiments) could be useful, and under WGNE auspices, an "aqua-planet intercomparison project" was being organized by the University of Reading. Another important area of WGNE activity was to keep under review progress in atmospheric data/assimilation systems and in 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., the "Global Land Atmosphere System Study" (GLASS) was underway. This was now being complemented by an initiative aimed at improving the representation of the atmospheric boundary layer in general circulation models.

ACSYS/CliC Numerical Experimentation Group

Dr. H. Cattle from the Met Office, Chair of the ACSYS/CliC Scientific Steering Group, outlined the work being undertaken by the ACSYS/CliC Numerical Experimentation Group. A second phase of the Sea Ice Model Intercomparison Project (SIMIP) had been initiated to compare and assess different sea-ice thermodynamic models (cf. the first phase, an intercomparison of dynamic ice models) and to evaluate the different parameterizations of the processes involved (heat storage, brine pockets, surface energy exchanges). This would provide a basis for guidance to climate modelling groups on the representation of sea-ice thermodynamics. An intercomparison of Arctic regional climate models was also being planned. Furthermore, an Arctic Ocean Model Intercomparison Project (AOMIP) had begun with the objectives of improving understanding of Arctic Ocean processes and their treatment in regional and global climate models. The details of a co-ordinated intercomparison (e.g. forcings) would be worked out at a workshop at the Woods Hole Oceanographic Institute in May 2002. Modelling of the Southern Oceans was being given attention with an initial focus on the behaviour of coupled ice-ocean models in the Weddell Sea. A new initiative being considered was an intercomparison of ice sheet models, building on the earlier European Ice Sheet Modelling Initiative (EISMINT).

The ACSYS/CliC Numerical Experimentation Group looked forward to co-ordination/exchanging views with the Working Group on Ocean Model Development (see section 3.5).

CLIVAR Working Group on Seasonal-to-Interannual Prediction (WGSIP)

Dr. A. Villwock reported on the most recent session of the CLIVAR Working Group on Seasonal-to-Interannual Prediction (WGSIP) held in Budapest, Hungary, November 2001. A number of activities that had been initiated a few years ago had now come to a conclusion including the ENSO Simulation Intercomparison Project (ENSIP) and the Study of Tropical Oceans in coupled Models (STOIC) (results published in Climate Dynamics), and the assessment of the current status of ENSO forecast skill (results published electronically by the International CLIVAR Project Office). As part of the ongoing Seasonal Prediction Model Intercomparison Project, a supporting "historical forecast project" has been organized aiming to investigate the actual forecast skill that could be obtained out to a season ahead using current model-based objective methods. WGSIP was now also giving increasing attention to downscaling and regional climate modelling. In this context, the review of the ad hoc panel on regional climate modelling (that would also be considered at this session of WGCM, see section 4.7) had been welcomed and the recommendations endorsed, including specifically the proposal for a workshop on regional climate modelling. In the future, WGSIP agreed that it should explore the possibilities for a tropical downscaling ("big brother") experiment. On another subject, WGSIP, at the request of the CLIVAR Scientific Steering Group, was formulating guidance on the priorities for real-time and delayed-mode observations for seasonal-to-interannual prediction, as well as for the process studies that were needed. At the WGSIP session, many participants had presented highlights of recent developments and results at their respective centres. It was particularly noted that multi-model ensemble techniques were being increasingly investigated or employed for seasonal prediction and WGSIP thus planned to hold a workshop on this topic in the near future.

Modelling-related activities in SPARC

Professor A. O'Neill (University of Reading, UK) informed WGCM of the continuing development of SPARC activities, noting particularly the co-operation with the IGBP International Global Atmospheric Chemistry (IGAC) project on an atmospheric chemistry-climate initiative. Evidently, WGCM would also have an important role in this. The dynamical coupling of the stratosphere and troposphere was another challenging subject. This coupling was apparently indicated by correlations in time series of the Arctic Oscillation and North Atlantic Oscillation. Some results suggested that, by selecting time series of Arctic Ocean amplitudes after strong stratospheric warmings, there seemed to be downward propagation of anomalies from the stratosphere to the troposphere with the inference that knowledge on the state of Arctic Oscillation in the stratosphere could increase predictive skill in the troposphere. Again, any information that could be garnered from coupled model integrations in this respect would be of interest.

More specifically on modelling-related activities in SPARC, Professor O'Neill reminded WGCM of the intercomparison of model stratospheric simulations (SPARC-GRIPS) that had been underway for a number of years. Major progress had been made in 2000 in collecting and summarising the results of the first phase of GRIPS which included an intercomparison of basic features of model stratospheric simulations. Findings have been published in the Bulletin of the American Meteorological Society and the Journal of Geophysical Research. The past year has been one of consolidation. A number of activities within the first phase remained to be completed (e.g. studies of the treatments of sudden warmings, tropospheric-stratospheric interactions). In the second phase of GRIPS (impacts of different parameterization schemes), tests of radiative codes were underway and this would lead to an investigation of gravity wave parameterizations. Studies of model response to formulations of mesospheric drag have been completed. The third phase of GRIPS would be concerned with explaining the observed variability in the stratosphere taking into account natural variability and the forcing by changes in aerosol loading, in solar radiation, and in atmospheric concentrations of ozone and carbon dioxide). A few groups have begun the experimentation required (some in connection with the European projects "Solar Influence on Climate and the Environment" (SOLICE) and "Stratospheric Processes and their Impacts on Climate and the Environment" (EUROSPICE)).

SPARC was also becoming active in the area of data assimilation to ensure that the advances in techniques in many operational centres were exploited to obtain global quality-controlled, internally consistent data sets of the dynamic and chemical state of the stratosphere (as well as, where possible, the upper troposphere and mesosphere). The data sets would be especially designed to support SPARC-related studies of chemistry-climate interactions, with attention initially being given to making full use of the data becoming available from the ENVISAT and EOS/AURA satellites. The type of effort undertaken would include comparisons of global analysed data sets, and organization of workshops to consider how the methodology of data assimilation in the stratosphere could be refined (e.g. to include new variables such as aerosol loadings).

WGCM recognized that both SPARC-GRIPS and the data assimilation activities had the potential to assist in improving the specification of, and dealing with, stratospheric forcing in coupled model integrations.

2. OUTSTANDING ISSUES IN THE DEVELOPMENT OF COUPLED MODELS

Drawing from the list of uncertainties and priorities listed in the IPCC Third Assessment Report and from the experience of the members of WGCM (representing the main coupled modelling groups), the following items were set down as requiring urgent study and investigation:

- improved methods of quantifying uncertainties in climate projections and scenarios, including development and exploration of ensembles of climate simulations;
- increased understanding of the interaction between climate change and natural climate variability;
- the initialization of coupled models;
- the reduction of persistent systematic errors in cloud simulations, sea surface temperature etc.
- the variations in past climate as a tool in understanding the response to climate forcing factors;
- the reasons for different responses in different models;
- improved knowledge of cloud/climate forcing and the direct/indirect effect of aerosols (including refined methodologies for refining the analysis of feedback processes);
- improved simulation of regional climate and extreme events.

WGCM was directly addressing many of the issues through the specific initiatives being undertaken (see section 3 of this document). In addition, there was at this session of the group, considerable specific discussion of the climate feedback issue as summarized below.

Climate feedback

Despite a decade of intense research on the role of water vapour and clouds in climate change, it was concluded in the IPCC Third Assessment Report that "the sign of net cloud feedback is still a matter of uncertainty, and various models exhibit a large spread". The report recommended that further work was needed to "understand and characterise more completely the dominant processes and feedbacks (e.g., from clouds and sea ice) in the atmosphere".

At the session of WGCM in October 2000, the (then) Chair of the GEWEX Radiation Panel, Dr. G. Stephens participated, and fundamental questions to be faced in considering feedbacks linked with clouds were taken up. It was agreed that close co-operation between WGCM and the GEWEX Radiation Panel was essential, in particular in the organization of appropriate combined/modelling observational studies. At the session of WGCM in February 2002, the new Chairman of the GEWEX Radiation Panel, Dr. W. Rossow, attended and there was further discussion of how progress could be made.

Dr. Rossow emphasized that reviewing current literature on understanding climate feedbacks strongly suggested the need for new approaches to this long-standing problem. In particular, continued use of analysis methods that were conceptually linear was likely to be inadequate given the complex coupling of energy and water cycles in clouds. As a first step, the GEWEX Radiation Panel was proposing the organization of a workshop with the objectives of evaluating current analysis methods for analysing feedbacks and results, identifying the main questions and issues, examining analysis methods from other disciplines and selecting new methods that could be investigated further for application in the climate area. The workshop would set out to specify what needed to be known about climate as a non-linear dynamical system in order to predict the response to changed forcing, and what needed to be known about climate dynamics to understand natural variability, to consider how climate response should be "measured", and how feedbacks might be inferred from observed variability. The type of analysis methods that could be used include multi-variate dynamic statistical composites, diagnosis of energy and water exchanges between the different components of the climate system and within the atmosphere and ocean, and advanced statistical techniques (e.g. neural networks) to point towards multi-variate non-linear relationships and their state dependence.

WGCM welcomed the organization of this workshop planned to be held late in 2002 (or perhaps early 2003) and nominated Drs B. McAvaney and H. LeTreut to serve on the workshop organizing committee. At the same time, WGCM noted and encouraged other work aimed at evaluating cloud feedback such as that described by Dr. C. Senior from the Hadley Centre. This included improved methods of evaluating model clouds against satellite data, and techniques to separate dynamically and non-dynamically forced cloud changes indicating aspects of observed cloud variation which might be useful proxies for cloud feedbacks in a changed climate. In particular, cloud variations were stratified by regional anomalies in sea surface temperature and vertical velocity. By then stratifying cloud response in a climate change simulation according to changes in sea surface temperature anomalies, vertical velocity, cloud characteristics etc., a strong parallel in the cloud response to present day spatio-temporal sea surface temperature variability has been found. Using this technique has also additionally pointed the way to changes in the Hadley Centre physical parameterizations.

A new European project was also being undertaken aimed at reducing uncertainty in cloud feedbacks in which a range of diagnostic comparisons of models with observations was being planned to provide as stringent a test as possible and to highlight deficiencies. Proxy methods for assessing cloud feedback would be developed. The diagnostics could then be used to prioritise model errors in terms of the processes most important for climate change, and a hierarchy of models (coupled, atmospheric, single-column, cloud-resolving) exploited to test the limitations of physical parameterizations.

WGCM itself was continuing its climate sensitivity studies, now being focussed on a systematic intercomparison of cloud feedbacks (see section 3.2).

3. REVIEW OF WGCM INITIATIVES

3.1 Coupled Model Intercomparison Project (CMIP)

It was reiterated that CMIP continued to be one of the most important initiatives of WGCM, and long-standing, having been started in 1995. There were now three components: CMIP1 to collect and document features of global coupled model simulations of present-day climate (control-runs); CMIP2 to document features of control runs and climate sensitivity experiments with CO_2 increasing at 1% per year; CMIP2+, as CMIP2, but many extra fields and data, and monthly means, and some daily data were being collected.

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. The range of extra fields at higher temporal resolution being assembled in CMIP2+ (compared to the limited fields, time-averaged blocks, monthly mean time series in CMIP1 and CMIP2) was enabling in-depth study of many additional aspects of coupled model simulations (e.g. feedback mechanisms, ocean processes, why different models had different responses, higher frequency phenomena).

In CMIP1, data from the control runs of twenty-one global coupled models from nine countries (representing virtually every group in the world with a functioning coupled model) have been collected and archived at PCMDI. About half of these used some form of flux adjustment. In CMIP2, data from climate change experiments with eighteen global coupled models have been assembled (from eight countries). For CMIP2+, data had so far been collected from five models (daily data from four), with at least four further groups preparing data for submission. The organization of these data, especially for CMIP2+, has been a major task for PCMDI. The acquisition of CMIP2+ data has boosted the original volume by two or three orders of magnitude, and it was now approaching 1 Tbyte.

Using these various databases, many diagnostic sub-projects were underway or were being initiated. In the case of CMIP1, there were ten sub-projects (dating from 1997 and 1998), of which six have led to at least one published paper. There was much activity surrounding the CMIP2 database, with twenty-one sub-projects having been initiated and proposals still continuing to be submitted: nine of these have provided material/results for at least one publication. Even though the announcement for CMIP2+ projects was only made in August 2001, thirteen sub-projects have already been proposed, showing the interest of the community in the much greater range of data that was available. Among the topics being taken up were the representation of the Madden-Julian Oscillation and intraseasonal variability in coupled models, the coupling between changes in the hydrological and energy budgets, studies of monsoon predictability, decadal climate variability in climate change scenarios, the trend of El Niño following global warming, air-sea interaction in the tropical Atlantic, and the stationary wave response to climate (some of these are continuations or developments of CMIP2 sub-projects). (A complete list of CMIP diagnostic sub-projects can be consulted at **http://www-pcmdi.llnl.gov/cmip/**). As well as the publications by individual authors of sub-project results referred to above, the IPCC Third Assessment Report drew substantially on several CMIP sub-projects, and included an analysis of CMIP models.

WGCM discussed the further development of CMIP. It was firstly agreed that CMIP1 would now be wound down and no further integrations would be accepted. Nevertheless, the CMIP1 data (although several of the integrations were now fairly old) would remain archived. It was considered that it would be timely to hold another CMIP workshop in late 2003 (probably in conjunction with the WGCM session) (the last workshop was held in 1998). This would appear to be a suitable time to conclude CMIP2 and CMIP2+

(data submission to be completed by October 2002). In the meantime, the ocean community would be strongly encouraged to exploit the CMIP2+ database for assessing the performance of the ocean component of coupled models as the ocean model data become available (see also section 3.5).

Subsequently, a new phase of CMIP, again in the form of a specified standard experiment, would be undertaken. The detailed plans for this next phase (experimental protocol, standard model output data sets to be collected) would be reviewed at the next session of WGCM, but basically another transient experiment with CO_2 increasing at 1% per year was envisaged. The objective would be to collect model simulations by 2004 (which could be also used in the next IPCC assessment, anticipated in the 2005-2006 timeframe). The importance of linking and co-ordinating the new CMIP effort with the Atmospheric Model Intercomparison Project (AMIP) and the Ocean Model Intercomparison Project (OMIP) was stressed, in particular that the atmospheric component of the model used in CMIP should be run in the new phase of AMIP now also being considered (see under "WGNE" in section 2). Additionally, the principal CMIP integration would be supplemented by separate co-ordinated "sensitivity" experiments (e.g. to study the effects of "water hosing", see section 3.8, and the factors affecting the variability of the thermo-haline circulation). The details of these experiments were being worked out and would also be finalized at the next session of WGCM.

3.2 Intercomparison of cloud feedbacks in models

WGCM has undertaken in recent years an initiative entitled "idealized sensitivity experiments" involving intercomparisons of results from equilibrium doubled CO2 experiments, in which the atmosphere was coupled to a slab ocean, thus not involving the complexity of the ocean response. This work has shown significant differences in inferred cloud forcings and changes in top-of-the atmosphere fluxes in different models (and had been drawn upon in the IPCC Third Assessment Report).

The scientific community had expressed considerable interest in continuing this study and various means for diagnosing feedbacks. Consideration was thus given at the recent session of WGCM to a proposal, put forward by Drs B. McAveney and H. LeTreut, for systematic intercomparison of cloud feedbacks in climate models (in addition to the co-operative activities with the GEWEX Radiation Panel outlined in section 2) in the approach to understanding climate feedbacks. The specific study of cloud feedbacks raised various issues, requiring use of the current generation of climate models and cloud resolving models and linking to available observational data. Among the broad questions to be taken up were to examine how well current climate models simulated the distribution and behaviour of clouds, the relationship between feedbacks on different timescales (seasonal and longer), the reasons for the wide range in climate and hydrological sensitivities in models, and the extent to which processes producing feedbacks in cloud resolving models resembled those in climate models.

WGCM duly endorsed the proposal for the intercomparison of cloud feedbacks. This was expected to provide on-going documentation of the strength of cloud feedback represented in models, and an evaluation of the performance of climate models in simulating the aspects of cloud important in cloud feedback. This should be an important contribution to the IPCC call to "characterise more completely the dominant processes in cloud feedback". Two main thrusts were envisaged, the first an investigation of the characteristics of the clouds as simulated in models compared to ISCCP data. This required clouds to be diagnosed in models in a manner that was consistent with ISCCP algorithms. The study of cloud behaviour in different dynamical regimes across a range of climate models as compared to the behaviour of ISCCP clouds in the dynamical regimes determined from reanalyses should serve in categorising the potential for climate models to produce realistic cloud feedbacks. Appropriate links would also be made to AMIP and CMIP.

The second thrust of this initiative would involve two types of systematic model experiments. "Classic" fixed season ±2K sea surface temperature perturbation experiments (i.e. forcing of an atmosphere-only model) were intended to provide historical comparison with the intercomparisons conducted by Cess and collaborators several years ago. Experiments with a slab ocean (with 1 x CO_2 and 2 x CO_2) were now becoming the standard, and the behaviour of model clouds in different dynamical regimes in the "control" climate would be compared with observations in the same manner as in the first thrust of this proposal, as well as being linked to AMIP and CMIP. Additionally, it was planned to establish active collaboration with the GEWEX Cloud System Study to organize a range of "cloud feedback" experiments with cloud resolving models.

Detailed plans for the work and diagnostic studies involved have been drawn up and would be discussed with modelling centres/groups interested in participating.

3.3 Forcing scenarios

Dr. J. Mitchell noted that many centres have undertaken and continued to undertake runs using the emission scenarios proposed by IPCC. The uncertainties in external forcing were one of the major factors limiting confidence in climate projections. The largest uncertainty was in the indirect (aerosol) forcing. Knowledge of variations in the magnitude and phase of solar forcing was also inadequate. Some of the smaller forcings did not cancel regionally.

3.4 Initialization of coupled models

Dr. R. Stouffer introduced this item. There had been no new major breakthrough in this area, and many modelling groups were still undertaking long laborious spin-up integrations, demanding in computer resources because of the lengthy time-scales involved. A technique involving use of air-sea fluxes computed in an adjoint model was being explored at GFDL. Several groups had used an "observed" initial three-dimensional ocean state, in particular that compiled by Levitus. This had the advantage of requiring considerably less computer time, and the initial coupled model state was near to that observed. On the other hand, the ocean initial state might not be in balance (because of deficiencies in data and their analysis and/or since the present climate was changing). Also, when the initial conditions for ocean and atmosphere were not obtained in coupled mode (i.e. by a sufficiently long coupled integration), there was potential for shock when the individual components were brought together.

WGCM agreed to keep this topic under close review: it was foreseen that the problem would gradually be alleviated in time by increases in available computing power and resources.

3.5 Ocean model development

The joint WGCM/WOCE Working Group on Ocean Model Development gave specific attention to a number of questions on the performance of ocean models and to the refinement of the ocean component of coupled models. Dr. D. Webb reported that a main item of discussion at the second session of the group (Santa Fe, NM, March 2001) was the impact of higher resolution in the ocean component of global coupled models. A clear tendency towards resolutions of about 0.5-1.0° was noted, apparently motivated by general recognition of the need for a more realistic representation of topographic features such as passages, equatorial ocean dynamics, and aspects of high latitude water mass formation.

The most significant outcome of the meeting was the decision to launch the pilot phase of an ocean model intercomparison project (OMIP) that should demonstrate the feasibility and value of a co-operative assessment of the performance of global ocean-ice models. Initially, seven groups were expected to participate, with the overall exercise being co-ordinated by NCAR. A common initialization, integration protocol and forcing were agreed, basically following the example of the "mini-OMIP" conducted in Germany by the Alfred Wegener Institute, Bremerhaven and the Max-Planck Institute for Meteorology, Hamburg when comparing the MOM and HOPE models. More confidence was now felt in ocean forcing data sets, and, in particular, forcing from a global flux data set based on refined ECMWF reanalysis products would be used. However, individual groups would also test alternative sets of initial data, integration periods, and forcing air-sea flux data sets. A key element would be investigation of the impact of varying ocean model resolutions. In the pilot phase, the target would be to examine the primary aspects of the large-scale ocean circulation, i.e. fields that could be compared to WOCE climatologies and derived products such as overturning rates and meridional fluxes of heat and freshwater. Moreover, there was the potential for supplementary tracer experiments (e.g. CFC-uptake) to explore the effects of ocean model formulations on the simulation of trace gas distributions. OMIP would additionally offer the possibility of assessing the behaviour of various sea-ice treatments coupled to global ocean models of various resolution, with identical forcing, and the questions involved were being discussed with ACSYS/CliC NEG. WGCM recommended that OMIP should be arranged so as to be complementary with the next phase of CMIP in 2004 (see section 3.1).

The Working Group on Ocean Model Development noted that very few CMIP diagnostic projects were concerned with the characteristics of ocean simulations, and strongly encouraged the initiation of such projects by ocean scientists. The extra availability of data in CMIP2+ should permit a far greater range of revealing projects (see section 3.1).

3.6 Detection and attribution of climate change

Dr. G. Hegerl summarized for WGCM the range of outstanding issues in the quest to detect and attribute climate change. The method generally considered the most rigorous and powerful for this purpose was the multiple regression technique, "optimal fingerprint detection" (as described in the IPCC WG1 Third

Assessment Report, Ch. 12, section 12.4.3). The method required ideally ensembles of simulations of twentieth century climate with individual forcing agents to provide "fingerprints", and very long (multi-centennial or even millenial) control simulations to assess internal climate variability. Several groups have used this approach, with strong indications of anthropogenic influences on surface temperature being found: the results from different groups were consistent and inter-implementation differences small. The technique could also be employed to scale simulations of the twenty-first century based on their simulation of the twentieth (too strong/too weak a signal during the twentieth century could be scaled down/up respectively). Furthermore, key model parameters such as climate sensitivity, ocean heat uptake and the strength of forcings (such as that from sulphate aerosols) could be selected in a manner that yielded best agreement with the observed climate change signals, and parameters that yielded significant disagreement ruled out. Optimal detection methods made this task possible by improving the power of statistical tests.

Uncertainty remained in the model-derived estimates of internal climate variability, which could not be fully validated with observed variability over the required timescales (of several decades to centuries). Reconstructions of temperature variations over the recent centuries from palaeoclimatic data were becoming increasingly important in this context. However, the influence of natural climate forcing on the palaeoclimatic record appeared to be considerable. Thus an essential step in verifying model performance and the simulated internal (or natural) variability would be model integrations over the appropriate period with the appropriate (reconstructed) natural forcing.

Optimal detection methods also tended to be sensitive to the model employed to derive fingerprints. This could be partly alleviated by using fingerprints averaged from several model simulations. Estimates of model error covariance (required for a comprehensive assessment of model uncertainty) depended on the availability of a range of simulations with varying parameters. Another key issue in increasing confidence in climate models was to understand better the different trends in surface and lower tropospheric temperature.

Attention was now turning to identifying signals of anthropogenic climate change in other parameters that were relevant socio-economically such as precipitation, modes of climate variability, or climate extremes. Assessment of changes on a continental scale instead or in addition to global scale would be another means of verifying model simulations in more detail as well as the quality of the fields produced to drive regional or impact models. Such efforts were already starting with promising first results.

3.7 Palaeo-climatic modelling

Dr. S. Joussaume reported that, although the first phase of the Palaeoclimate Modelling Intercomparison Project (PMIP) had been formally completed, a number of groups were producing updated simulations of the climates of the mid-Holocene (6000BP) and the Last Glacial Maximum (21000BP) using the standard forcing (ice sheet limits, atmospheric carbon dioxide, insolation) specified for PMIP experiments. In particular, a number of simulations of the Last Glacial Maximum had now been carried out with coupled ocean-atmosphere models (including those of the Hadley Centre, the Meteorological Research Institute of Japan, and the NCAR/CSM). However, the models still did not generally show cold enough temperatures over western Europe: this appeared to be linked to an inadequate representation of the effect of the feedback associated with vegetation changes.

New impetus should be given to PMIP following the initiation of the European Union project "Model and Observations to Test clImate Feedbacks" (MOTIF). Participating (European) modelling groups would undertake PMIP-like integrations with coupled ocean-atmosphere, and coupled ocean-atmosphere-vegetation models for 6000BP and 21000BP. The future plans for PMIP itself would be discussed at a workshop in July 2002, and it was likely that experimentation with coupled ocean-atmosphere-vegetation models for 6000BP and 21000BP would be proposed. Other time periods were also of interest, namely the early-Holocene (11000BP) and the inception of the Ice Age at the end of the last interglacial.

3.8 Coupled ocean-atmosphere variability and predictability on decadal timescales

WGCM had wide-ranging discussions on this topic following up the interest expressed by the JSC and the CLIVAR Scientific Steering Group. Firstly, note was taken of the views the CLIVAR Atlantic Implementation Panel (relayed to the WGCM by Dr. R. Sutton from the Hadley Centre) on the need for a better understanding of the role of the Atlantic thermohaline circulation (or meridional overturning circulation) in climate variability and change and, in particular, in tropical Atlantic variability. The Panel had suggested that modelling work could aid improved understanding, and provide guidance for framing observational programmes seeking to study and monitor the meridional overturning circulation. Among outstanding questions were the magnitude and space-time structure of the meridional overturning circulation, the upper ocean and sea surface response to variability and change of this circulation and, in turn, the climate response, and the predictability of these changes and their impact. Detailed analyses of the behaviour (natural variability, greenhouse gas response, climate impacts) as simulated would be valuable. In addition, co-ordinated experiments (e.g. designed to show the sensitivity to perturbed initial conditions and/or surface fluxes) could be helpful in elucidating the physical processes and mechanisms involved.

Secondly, Dr. T. Delworth reported that decadal climate variability had been the subject of a workshop in January 2001 in Hawaii. The findings agreed well with those from the Workshop on Decadal Predictability, organized by WGCM in October 2000, namely that there was some slender evidence for limited predictability in the oceans at decadal timescales, but little over continental regions. Oceanic heat content changes demonstrated long-term trends and decadal variability. Climate models were being used to interpret multi-century proxy records, complemented by studies on the dynamics of simulated variability. An AGU Chapman Conference on the North Atlantic Oscillation in November 2000 had produced suggestions of the potential role of the tropics in affecting decadal and longer-term swings in the North Atlantic Oscillation index. Long reconstructions of the North Atlantic Oscillation Index had been presented, and temporal shifts in the North Atlantic Oscillation noted. The question of the predictability of swings on seasonal and longer time scales had been raised, as well as the relationship between NAO dynamics and the stratosphere (as already referred to in the presentation on SPARC, see section 2).

WGCM agreed that the main challenges and priorities in decadal to multi-decadal variability and predictability were to augment the observational record better to define the characteristics of the variability, to diagnose the mechanisms of simulated variability, to investigate further predictability at these time scales and, particularly, whether there might be any predictability over continents, and to try and assess the interaction between decadal variability and anthropogenic climate change. More specifically, questions that needed to be answered were the extent of air-sea coupling in decadal variability, the relative roles of the tropics and extra-tropics, the role of high latitudes, space-time structure of decadal variability (to be deduced from observations), and the parts played by vegetation and external forcings. With regard to decadal predictability, open issues were the contribution from internal predictability, the predictability of changes at decadal time scales in the statistics of interannual variability, and the definition of an appropriate initial state and initialisation.

The main WGCM contribution to progress in this area would be through CMIP2+, in which much more ocean data were available (see section 3.1). WGCM urged interested groups to organize appropriate diagnostic sub-projects aimed at such questions as detailed analyses and comparisons of the magnitude and space-time structure of the meridional overturning circulation (as simulated in coupled models) and other aspects as referred to above. WGCM would also examine the possibility or organizing co-ordinated "sensitivity" experiments to improve understanding of some of the processes involved. These might include changes in initial conditions, perturbations in salinities, and/or perturbed surface experiments (partial coupling). These would be undertaken as a complement to the next principal CMIP integration (as referred to in section 3.1), and details of the experimental protocol were being worked out. Regarding the use of model studies as a guide to observational programmes, WGCM advised caution. However, this could become a more valid approach in the future as model resolutions increased and ocean simulations improved.

3.9 Carbon-cycle modelling

In the developing co-operation between WGCM and the Global Analysis, Integration (GAIM) component of the IGBP in the task of developing comprehensive Earth system models, Dr. P. Friedlingstein (Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS), participated in the session on behalf of GAIM. The planning of the joint WGCM/GAIM "Coupled Carbon Cycle Climate Model Intercomparison Project" (C4MIP) was carefully considered. This would basically be organized on the same lines as the other main WCRP model intercomparison projects, CMIP and AMIP, with standard co-ordinated experimentation being proposed. In the first phase, interested groups were being invited to undertake a historical land-atmosphere experiment with global models having full coupling between radiation, biogeochemical cycles and carbon dioxide with specified sea surface temperature forcing, carbon dioxide emissions, and land-use change. Key diagnostics would include the model-predicted carbon dioxide fluxes and concentrations. The detailed experimental protocol was being defined and a workshop bringing together representatives of interested groups would be organized in the coming months.

Dr. R. Betts described the work being undertaken at the Hadley Centre in developing coupled climate-carbon cycle modelling, particularly designed to study the role of biospheric feedbacks in climate change. The third version of the coupled ocean-atmosphere model (HadCM3) (but at the lower resolution of 3.75°x 2.5° and a flux-adjusted ocean) carried CO_2 as an atmospheric tracer and was linked with an ocean carbon model (HadOCC) and a dynamic global vegetation model (TRIFFID). HadOCC included freely evolving (dissolved) carbon dioxide and alkalinity and a biological pump (a nutrient-phytoplanktonzooplankton-detritus ecosystem model). TRIFFID represented 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, the vegetation distribution and leaf area determining land-surface characteristics.

WGCM noted the comparative results from the experiments at the Hadley Centre using the model outline above and at the Institute Pierre Simon Laplace (IPSL). Both used historical carbon dioxide emissions (from burning fossil fuels and deforestation) for the period 1860-1995, but with slightly different emission scenarios for the period 1995-2000 (Hadley Centre: IPCC IS92A; IPSL: IPCC SRES-A2). Sinks were different because of contrasting treatment of the terrestrial biosphere [the IPSL model did not include dynamic vegetation]. Nevertheless, there was agreement in the experiments that the climate-carbon cycle was positive, mainly as a consequence of the negative climate impact on the biosphere, the feedback being much larger in the Hadley Centre model. Key uncertainties in the results were, over land, the vegetation and soil response to changing atmospheric concentrations of carbon dioxide and warming/drying, and over the ocean, the geochemical uptake (e.g. by the Southern Ocean circulation).

Further steps will be taken in bringing together the hitherto largely separate work of WGCM and GAIM in the required development of Earth system models. In particular, it was planned that the next session of the two groups would be held jointly (Victoria, BC, Canada, October 2002) and that a joint workshop on Earth system modelling could be organized (possibly in April 2003 in conjunction with the European Geophysical Society Annual Assembly).

4. OTHER ISSUES AND ACTIVITIES

4.1 Proposal for initiation of a major WCRP project on prediction and predictability in the WCRP

The Chairman of WGCM, Dr. J. Mitchell, informed the group of the proposal that would be considered by the JSC for the formation of a major WCRP project on prediction and predictability. In general terms, WGCM agreed that it was in the interests of WCRP to be seen to be encouraging work that would lead to development of the practical side of climate prediction on a variety of timescales from seasonal to centennial. It appeared to WGCM that this suggestion could best be accommodated by suitably modifying the role of the existing Working Group on Seasonal-to-Interannual Prediction (WGSIP). However, it was stressed that this should not mean WGCM would be concerned only with the issue of anthropogenic climate change. WGCM dealt fundamentally with the development of coupled ocean-atmosphere models (although it is recognised that much of the development has been motivated by the need to make projections of anthropogenic climate change). In this regard, WGCM considered the full climate system, interacting with all the WCRP core projects as well as WGNE and WGSIP as appropriate. As noted above, strong co-operation was also developing with IGBP/GAIM (including planning of a joint WGCM/GAIM workshop on Earth system modelling). WGCM additionally noted that, as changes in the frequency and intensity of extreme events were potentially one of the most important manifestations of climate change, it must continue to assess and work on improving understanding of natural climate variability on all time scales. The views of WGCM would be relayed to the session of the JSC*.

4.2 Simulations of climate of the twentieth century

WGCM again reviewed the issue of trying to organize standardized simulations of the climate of the twentieth century. Such integrations were plainly of much interest and have been or were being carried out by many centres. However, numerous forcing scenarios were being employed and there was no general agreement on forcing data sets. (In many cases, the forcing was not accurately known especially for indirect forcing). The situation was becoming more complicated as centres introduced their own model carbon and sulphur cycles.

WGCM believed it would be difficult to regiment these integrations, but, nonetheless, considered it important to assemble the twentieth century runs that had been made, together with a detailed specification of the forcings that had been used. Such a database would be valuable for detection and attribution studies and for model validation. Simulations with one specific forcing only would be of particular interest, as would

* At the JSC session, it was agreed that a new visible WCRP-wide banner on "predictability" should be considered, with the aim of major steps forward in climate prediction over the past two decades: this should be a total activity involving all projects, beneficial to society and to sustainable development. A task force was set up to develop ideas and proposals for implementation to report to the next session of the JSC in March 2003. All projects groups were requested to provide views to the task force by 31 July 2002.

runs with other forcings such as that linked to land use change. PCMDI expressed its willingness to act as the centre for collecting the data, and to offer its extensive software in support of diagnostic sub-projects drawing on the database. A detailed list of model output to be archived from twentieth century climate simulations together with a complementary list of forcing fields and the form in which they should be collected would be compiled.

Care would be taken not to duplicate work already undertaken in this area by others, notably the IPCC Data Distribution Centre which was also archiving data from twentieth or twenty-first century coupled model simulations. However, the forcing and response data held by the IPCC Data Distribution Centre were not likely to be extensive enough for the type of in-depth studies in which WGCM would be interested (see also section 4.6 below on the role of IPCC Data Distribution Centre).

4.3 Long-term climate integrations

WGCM reiterated its encouragement to modelling groups to consider if possible long (control) integrations for an extended period (e.g. 1000 years). These integrations, which should use pre-industrial forcing, would provide a valuable reference and control for CMIP and the 6000 year BP PMIP simulations, as well as a good basis for assessing (model-simulated) internal or natural variability. Comparisons with proxy data would be possible. However, interpretation of the latter was not straightforward and careful consideration needed to be given to the range of parameters to be collected from the model integrations to describe the simulated low-frequency patterns adequately and to be able to compare with proxy indices.

WGCM stressed that when such runs are made, as with the climate of the twentieth century simulations, the forcing used should be carefully archived along with the model results.

4.4 Use of advanced numerical techniques in climate model simulations

As noted in section 2, the JSC, at its twenty-second session, invited WGCM to comment on the feasibility of/questions related to the use of numerical techniques (e.g. linear grids, semi-Lagrangian techniques) that have been developed for use in NWP and which potentially may also offer advances in integration speeds in climate modelling applications.

An introduction to the WGCM discussion of this item was provided by Dr. T. Davies from the Met Office who reviewed the range of issues that had been considered in developing the Met Office "New Dynamics" i.e., the coupling between dynamics and physics, conservation properties, reduced noise (with less dependence on artificial diffusion), more accurate advection, suitable for mesoscale to climate scales. The main features of the scheme being implemented (which would be included in future versions of Hadley Centre models) were: non-spectral; semi-Lagrangian advection; semi-implicit time-scheme; Charney-Phillips staggering in the vertical; a C-grid in the vertical; and a hybrid terrain-following co-ordinate in the vertical.

Among the points made by WGCM were that, firstly, the use of semi-Lagrangian schemes did not offer a similar gain in integration speed in climate models as compared to NWP because of the considerably coarser resolution of the former. Climate models depended fundamentally on a satisfactory treatment of the physics, and it was known that problems could arise if too long a timestep was used. Secondly, conservation, particularly of energy, was of the utmost importance in the integration of climate models. Schemes with non-linear intrinsic diffusion could lose energy at unacceptably high rate (as could also explicit diffusion schemes). Thirdly, potential gains in efficiency in integrating the dynamical core were relatively small when weighted against the importance of the number of levels, and greater complexity of the physics in climate models compared to the dynamics. Nevertheless, the issue was not being ignored by the climate modelling community, and techniques such as semi-Lagrangian, semi-implicit timestepping, and staggered grids were beginning to find their way into climate models especially when they have been well tested in operational models and have demonstrated the required properties (as for example, at the Hadley Centre where the next version of the model will include the "new dynamics" developed for the Met Office NWP model outlined above).

4.5 Developments in data formats and handling climate model data sets

Long runs with coupled models generated extremely large volumes of data. As well as working with basic modelling problems, the climate research community has also to consider formats for the efficient handling and exchange of these large volumes of data, and how the data should be managed.

In respect to the former topic, Dr. J. Gregory from the Hadley Centre explained that a number of centres (including the Hadley Centre, NCAR, PCMDI) have developed the "NetCDF/CF" format for climate data, aimed to achieve easier data exchange, definition of climate meta data, and to serve as a possible archive format. The NetCDF format itself, developed by Unidata, has been commonly used for some time, and was freely available and portable. NetCDF files were binary and machine-independent, utilities existed for translation from binary to plain data, and a library was available to read and write NetCDF files, with interfaces in many programming languages. The files contained variables, dimensions and attributions, and NetCDF conventions defined how to use these: the format was highly suitable for a self-describing logical data format. The NetCDF/CF convention was intended for use with atmospheric, surface and oceanographic climate and forecast data and was particularly designed with model-generated data in mind. NetCDF/CF extended the Co-operative Ocean/Atmosphere Research Data Service (COARDS) (the NOAA/university co-operative for sharing and distributing global atmospheric and oceanographic data sets) by establishing standard names for identification of variables, offering facilities such as specification of boundary co-ordinates, grids other than latitude-longitude, and indications of statistical reduction, and a number of other features. PCMDI has adopted NetCDF/CF and it was also being used by the European infrastructure project "Programme for Integrated Earth System Modelling" (PRISM) (this had the objective of developing a flexible model structure with interchangeable model components with standard interfaces and a universal coupler).

WGCM recognised the important potential value of NetCDF/CF as an exchange format between centres involved in climate research, especially the feature of including/specifying climate meta data. However, it was pointed out that, in the data processing industry, new standards were rapidly being defined (in particular "W3C"). WGCM encouraged contact with the W3C standards group to explore inclusion of NetCDF/CF and agreed to review the situation at its next session.

Following a presentation by Dr. R. Stouffer, WGCM also discussed the issue of centralized versus distributed data sets. In the case of the former, data were held at one central location/institution (PCMDI was an excellent example of such a centre), with the advantages of being able to obtain all data from one site and assured data quality. However, this meant the data handling fell on one group which may be faced with having to deal with very large data volumes: also the data were separated from the providers. In contrast, a distributed data system was internet-based, and data and services were provided by individual institutions using a common framework (e.g. the NOAA Operational Archive and Distribution System, which allowed access to model data via the Internet, and users to perform simple analyses without moving raw data). There was a close tie between the data providers and users, easy automation of tasks (downloading data, mapping, etc.), and the data management load was also distributed. There could, however, be weaknesses in the overall data consistency and data quality between different stations.

WGCM agreed that distributed data techniques clearly appeared to be the way of the future, but there was a need for oversight, co-ordination in areas such as definition of standards, formats, types, the exchangeability of data, a reference system to indicate the availability of data, and user help. WGCM agreed to keep this issue under review jointly with PCMDI.

4.6 IPCC Data Distribution Centre

WGCM noted that the IPCC Data Distribution Centre (DDC) (at the Max-Planck Institute in Hamburg) collected results of SRES forced climate experiments which were then available for use by the climate impacts community and groups in developing countries. Although guidelines have been set down for sets of results submitted to the DDC, WGCM had some concern that there was not the same scientific discrimination as for the CMIP database which included results from more closely defined experiments. Some members of WGCM also felt that the label "IPCC" attached to the DDC gave the wrong impression, and that IPCC was steering research rather than assessing. The issue of the connection with the climate impacts community was also raised, and whether it would be better that a direct relationship with WCRP/WGCM was fostered. The suggestion was therefore made that WCRP and/or WGCM should be more closely associated with the DDC, or possibly that PCMDI could take over the role of the DDC under WCRP/WGCM auspices. However, the DDC did hold a lot of data (population growth figures, emission scenarios etc.) which are far outside the current remit of WCRP and have political overtones. It was agreed that comments should be sought from the JSC on this issue*.

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* The JSC at its session in March 2002 considered that the DDC and WGCM/PCMDI (CMIP-type) data bases needed to be maintained separately in view of their different roles and purposes: in particular, the latter should be designed as a resource for the scientific modelling community in the search to understand why different models gave different results, had different climate sensitivities etc. Nevertheless, WGCM should maintain full awareness of DDC activities, with interaction/co-operation as necessary.

4.7 Regional climate modelling

Following the reviews carried out by WGNE and WGCM in respect to regional climate modelling at their respective 1999 sessions, the JSC established a joint WGNE/WGCM 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. WGCM took note of the main points in the advanced draft of the report: "Atmospheric regional climate models: a multiple purpose tool" prepared by the panel (R. Laprise, University of Québec, Montréal; Canada: convener; R. Jones, Hadley Centre, UK; B. Kirtman, COLA, USA; H. von Storch, GKSS Research Centre, Germany; W. Wergen, Deutscher Wetterdienst, Germany).

There was no doubt that dynamical atmospheric RCMs have matured over the past decade and now allowed (and were used in) a very wide spectrum of applications. At horizontal scales of 300km and larger, simulations were consistent with the nesting (driving) data. At fine spatial and temporal scales, the RCM-simulated patterns of important surface variables, such as precipitation and winds, often had demonstrable skill. However, grid spacing was currently often constrained by computing resources to typically about 50km, which limited the amount of detail available at the finest scales. Future increases in computer power and applications of multiple nesting techniques would be likely to allow increases in resolution to grid spacing of order of 1km (this would require the use of fully non-hydrostatic models and scale-dependent parameterisations).

It was recognised that RCMs had deficiencies and improvements were required. The sensitivity of RCM-simulated results to computational domain size, to the jump in resolution between the nesting data and the RCM, to errors or deficiencies of nesting data, and to nesting techniques, needed further investigation. Moreover, the added value provided by regional modelling should be assessed relative to simpler statistical post-processing of coarse-grid data. An assessment of the performance of an RCM required climate data on much finer spatial and temporal scales than traditionally used for validating global models. In some regions such data were available but not necessarily easily accessible, and appropriate gridded analyses have not been prepared. Where such data were not available, methods of validation other than comparison with standard climatological variables ought to be developed or applied. The performance of different RCMs should be compared both in their simulation of current climate and in their use as a dynamical downscaling tool to provide high-resolution climate-change information. This was necessary both to guide future developments in regional climate modelling and to contribute to the assessment of uncertainty in regional climate simulations and projections.

The Panel reiterated that the final quality of the results from a nested RCM depended on the realism of the large scales simulated by the driving general circulation model. The reduction of errors, systematic or otherwise, in general circulation models must therefore remain a priority for climate modellers.

The various recommendations made by the Panel included the following points:

(i) Obviously, all numerical models suffered from various defects and were a reduced image of a considerably more complex reality. In this sense, all models should be made more realistic in very many different ways, but the process of improving models should be guided by the needs of the specific applications.

(ii) An international RCM workshop should be organised bringing together, not only RCM modellers, but also global climate modellers, diagnosticians and dynamicists, users of RCM results, research managers and funding agencies, under the theme "the added value of regional climate model simulations in many applications". The Panel suggested holding the workshop during 2003 in the Southern Hemisphere, possibly in Buenos Aires, Argentina, where there was growing community of scientists who could contribute to the essential local arrangements.

(iii) The assessment of RCM climate simulations continued to be hampered by the lack of high-resolution observed gridded climate data over many regions of the globe. Regional re-analysis projects using observations from national archives should be encouraged.

(iv) Long, multi-decadal RCM simulations nested within an ocean-atmosphere model and forced by observed SST could be made to assess RCM skill in reproducing fine-scale features associated with large-scale year-to-year anomalies. This would constitute a "Regional (climate) Model Intercomparison Project", RMIP, analogous to AMIP, for global circulation models. The recently-completed European project MERCURE has delivered such simulations for the European region using three RCMs and could act as a model for such an exercise.

(v) When intended for climate-change projections, the RCM should be validated in different climate regimes in order to establish their general applicability. It would be valuable to organize a co-ordinated international modelling effort to nest a number of global model-simulated data sets over a few regions. This would be a major undertaking requiring strong international support and convincing funding agencies of the importance of such a project. The new European project "Prediction of Regional scenarios and Uncertainty for Defining European Climate-change risks and Effects" (PRUDENCE) which would compare simulations and climate change over Europe from several general circulation models and RCMs could be an important component in such a project.

WGCM welcomed the report of the panel and expressed appreciation to Dr. R. Laprise and his group for their work and the wide-ranging review of regional climate modelling that had been produced (Dr. R. Jones from the Hadley Centre, member of the panel, participated in the WGCM session in person). Agreement was expressed with several of the points made by WGNE in its review of the report at its session in October 2001 (e.g., the risk of "blind application" of a regional climate model, the importance of checking conservation properties, the need to test regional climate model physics different "climates"/geographical regions). WGCM particularly reiterated the importance of assessing the added value provided by a regional climate model simulation compared with a statistical down-scaling approach. WGCM concurred with the proposal for an international "Regional (climate) Model Intercomparison Project", RMIP, and for an international regional climate modelling workshop. WGCM advised that a regional climate model intercomparison should include tests with reanalyses as boundary conditions to verify the ability of these models to simulate the climate in various climatological regions*.

5. NEW DEVELOPMENTS IN OR PLANS FOR GLOBAL COUPLED MODELLING

5.1 Reports from modelling groups

Max-Planck Institute for Meteorology (M. Latif)

A new coupled ocean-atmosphere-sea ice model that did not employ flux adjustments has been developed at the Max-Planck Institute for Meteorology. The atmospheric component was ECHAM5 at resolution T42, the ocean C-HOPE with variable resolution and a Hibler-type dynamic/thermodynamic sea-ice model. The coupled system exhibited only a small drift in a 200-year control integration. The new model would be used in various applications, including the study of palaeoclimatic variations, present day variability, anthropogenic climate change, and El Niño and decadal predictability, as well as serving as the nucleus of the Hamburg Earth System Model.

National Center for Atmospheric Research (G. Meehl)

A substantial reorganization and development of NCAR coupled modelling has been undertaken with the existing CSM1 (built for a vector computer, NCAR ocean model, simplified sea-ice dynamics and thermodynamics) and PCM1 (built for parallel systems, parallel ocean program code, sea-ice model from the Naval Postgraduate School) being merged into the "Community Climate System Model", CCSM (or CCSM1). The structure and model components were being carefully considered with advice on the different aspects being provided by a series of especially established working groups. An interim, transitional model has been constructed, but full merging would occur when the new atmospheric component and flux coupler (linking the atmosphere with the land, ocean, and sea-ice models) were available. The new atmospheric component would include an updated water vapour treatment in the longwave radiation computation, a generalized cloud overlap and prognostic cloud water schemes, a modified convective mass flux parameterization, and a

* The report of the regional climate modelling panel was also reviewed by the JSC at its session in March 2002, together with the comments made by WGCM and WGNE. The JSC considered that WCRP (through WGCM and WGNE) should keep this subject under review both to monitor progress and to ensure that all new users of "off-the-shelf" RCMs were aware of the potential pitfalls. The WGNE/WGCM panel was thus expected to continue work in this area, and, in particular, to take up the organization of an international RCM workshop in the next 1-2 years to consider the use of RCMs in various applications, and to plan, as far as feasible, a co-ordinated assessment of RCM skill in reproducing fine-scale regional features that might be associated with large-scale year-to-year anomalies. The panel was expected to prepare a slightly updated/revised version taking account of the comments that had been made, which could then be produced as a WCRP technical document (as well as an appropriately edited version perhaps being prepared for publication in something like the Bulletin of the American Meteorological Society).

topographic filter. The "standard" resolution would be T42L26, but an alternative version of T85L26 would be used for testing, and T31L26 for palaeo-climatic runs. The ocean model would be based on the parallel ocean program code (specifically designed to run efficiently on massively parallel machines), the north pole would be "displaced" into Greenland (thus no filtering of the Arctic Ocean simulation), the horizontal resolution would be higher (averaging less than 1°, with 0.5° in the equatorial tropics, with the Bering Strait now open) and the number of the levels in the vertical would be increased to 40. Other features were an anisotropic horizontal viscosity, the Gent-McWilliams eddy parameterization, the "K-profile" treatment of vertical mixing, river run-off directly into the ocean or marginal seas, and a much more accurate equation of state for sea-water. The land model included improved surface flux parameterizations, multi-layer soil water and temperatures explicitly tracking frozen and unfrozen water, a multi-layer snow model allowing for compaction and refreezing, a refined run-off parameterization distinguishing upland hill slopes and lowland saturated areas, and river routeing with a _° grid-cell based representation of river flow for determining the freshwater flux to the ocean. The sea-ice component comprised a dynamic/thermodynamic model with a surface snow layer and, in particular, a sub-gridscale ice thickness distribution using five categories of ice with different surface properties, thickness and ice/ocean and ice/atmosphere exchange. Also incorporated were mechanical redistribution of ice as a result of ridging/rafting, and ice strength based on energetics. In an initial control run to 250 years (starting from Levitus conditions, no flux adjustment), moving forward at about 4 years per day, no great improvement in the systematic error in sea surface temperatures seen in earlier model versions was as yet apparent. A series of other runs was being planned, including a mixed-layer equilibrium experiment, a 1% pa CO_2-increase CMIP integration, and an ensemble of twentieth century simulations with greenhouse gas, aerosol, solar and volcanic forcings. A simulation with a horizontal resolution of T85 for the twentieth and twenty-first centuries would also be carried out.

In the meantime, various experiments were still being conducted with the CSM and PCM models (e.g. simulations with black carbon distributions and an ensemble with volcanic and solar forcing using PCM1), and CSM and PCM simulations were still being carefully analyzed. Other experimentation in prospect was related to the impacts of energy use on the climate system, an interactive carbon cycle, time- and space-varying twentieth-century sulphur dioxide emissions, and analysis of simulated weather and climate extremes.

Meteorological Research Institute of Japan (A. Noda)

It was recalled that two models from Japan (that from the Meteorological Institute, MRI-CGCM 2.0, and that from the Centre for Climate System Research and the National Institute for Environmental Studies (CCSR/NIES 2a) showed respectively the minimum and maximum climate sensitivities in the IPCC Third Assessment Report, although the differences in the simulated patterns of the response were not significant. The reasons for the contrast had been examined.

It was found that the low climate sensitivity of the MRI model was linked to insufficient tuning of clouds with respect to the observed meridional energy balance and a larger heat uptake in the ocean mixed layer. On repeating the run with a revised version, a larger climate sensitivity (similar to that shown by NCAR models) was seen, together with a change in the spectral distribution of interannual to decadal sea surface temperature variability. This suggested the important role of the cloud-related meridional energy balance and radiative feedbacks in determining the climate sensitivity, and, interestingly, a possible relationship between interannual/decadal variability and climate sensitivity.

On the other hand, elements contributing to the large climate sensitivity of the CCSR/NIES model appeared to be an updated absorption line table in the radiation scheme and a tuning of the clouds giving less cloud water in stratiform types and more in cumulus. On repeating the scenario run with the old absorption line table, the magnitude of the warming obtained was reduced. Nevertheless, CCSR and NIES believed their scenario runs were in the range of uncertainty especially since the updated radiation scheme was apparently improved compared to a line-by-line calculation. To assist in clarifying the outstanding questions, an intercomparison of clear-sky radiation codes and an updated assessment of cloud-radiative fedbacks was proposed (the work of WGCM as outlined in sections 2 and 3.1 should certainly help in the latter respect).

Geophysical Fluid Dynamics Laboratory (T. Delworth)

Current studies with the existing R15 and R30 coupled models at GFDL naturally included the response of the climate system to natural and anthropogenic forcing. A particular finding of interest was that the observed increasing trend in the frequency of major floods appeared to be consistent with (GFDL) climate simulations. In respect to decadal variability, three ensembles, each of eight members, have been prepared using the R30 coupled model. Significant predictability was found in the high latitude North Atlantic sea surface temperature, salinity and thermohaline circulation - but this did not translate into predictability in the atmospheric circulation. Looking to the future, the CRAY T90 was being replaced with an SGI Origin 3800 and, in parallel, the development of the next generation of the global coupled model was being planned. All model components would conform to a "Flexible Modelling System", aimed at flexibility and portability in model development and use. The atmospheric component would be completely new, with substantial changes in the physics and increase of the vertical resolution (but only modest enhancement of the horizontal resolution). The target resolution was 2°x 2.5° (grid-point model), 18-25 levels. Two versions were being developed: "AM2" with a new radiation package, land-surface model, convection, cloud-parameterization and the Mellor-Yamada boundary layer scheme; "AM3" including additionally orographic and non-orographic wave drag, and an enhanced stratosphere (25 levels). The ocean model, particularly designed to cater for decadal-centennial timescales, would incorporate a suite of improvements in ocean physical processes (e.g. explicit free surface, vertical mixing, representation of the bottom topography by partial cells, Gent-McWilliams eddy mixing) and numerics (including use of a tri-polar grid). The target resolution was 2° in the extra-tropics, 2/3° within 12° of the equator, and 50 levels in the vertical (22 in the upper 220m). A higher resolution model would be used for ENSO forecasting. The sea-ice model employed full dynamics with a viscous-plastic ice rheology, three-level thermodynamics (two ice, one snow) with penetrating solar radiation and brine pockets, and categories of ice-thickness to be able to represent the sub-grid scale distribution. The land-surface treatment was conceptually similar to the earlier Manabe bucket model but enhanced by non-water stressed stomatal resistance, vegetation and soil-dependent surface parameters, soil sensible heat storage, a ground water storage reservoir, and a river routeing. Additions planned later were interactive vegetation and a biogeochemical model. Currently, the atmospheric model development was well under way and the ocean model was being assembled/tested (the land-surface and sea-ice components were relatively mature). The full new version of the coupled model should be available later in 2002.

Bureau of Meteorology Research Centre and CSIRO (B. McAvaney)

At BMRC, a new version of the coupled model had been implemented (atmospheric component T47L17, a version of the BMRC unified atmospheric model; ocean, MOM2, with the addition of throughflow and the parameterization of the strong tidal mixing in the Indonesian area, meridional resolution 0.5° within 9° of the equator, 1.5° near the poles, 25 levels in the vertical of which 12 in the top 185m). An OASIS coupler was used with no flux adjustment. The model had been developed primarily for seasonal prediction, but an evaluation for its application to climate change experimentation was in progress. In prediction mode, forecasts for NINO3 sea surface temperature were cooler than observed (bias of about 1°), but the seasonal variation was good. For the NINO4 area also, the model forecasts were consistently cool compared to observations.

Dr. McAvaney reported additionally on the work on coupled modelling at CSIRO Atmospheric Research, Aspendale, Victoria. The CSIRO "Mark 3" model consisted of an atmospheric component of resolution T63L18, the Met Office convective parameterization, and an advanced cloud liquid water scheme. The ocean component was built round the GFDL MOM code (version 2.2) with a resolution of 0.9°x 1.8° and 31 levels, a Richardson mixing scheme, and third order advection. A dynamical sea-ice model was also included. For a scenario integration of 220 years, the "Mark 3" model indicated a much reduced warming compared to "Mark 2", although the response patterns were similar. The inference drawn was that the feedback associated with clouds and the snow albedo were weaker in the more recent model.

Hadley Centre (J. Mitchell, M. Roberts)

Dr. J. Mitchell gave a general overview of Haldey Centre plans. As noted in section 4.4, the atmospheric component of the next version of the Hadley Centre model would be based on the Met Office "new dynamics" core with semi-Lagrangian advection and a semi-implicit timestep. The envisaged resolution of the new atmospheric component was 1.25 x 1.875°, with 48 levels in the vertical (a 38-level version also existed). The ocean model would be 1°x 1° but with enhanced resolution in the tropics. It was intended inter alia, to prepare ensembles of scenario runs, and undertake work to understand the thermohaline circulation and decadal prediction (the developments in coupled carbon cycle modelling were described in section 3.9).

Dr. M. Roberts presented another version of the Hadley Centre climate model with an eddy-permitting ocean (HadCEM) to study the impact of higher ocean resolution on climate simulations. HadCEM was derived from the HadCM3 coupled model (with the identical atmospheric model 3.75°x 2.5°, 19 levels) but had increased ocean resolution (1/3°x 1/3°, 40 levels compared to 1.25°x 1.25°, 20 levels in HadCM3). "Tiling" boundary codes ensured flux conservation between the non-contiguous atmospheric and oceanic grids. A seventy-year spin-up and eighty-year control integrations have been completed and an idealised climate change run was under way. In the spin-up and control runs, the global mean climate was stable over the period, but some of the mean errors were much the same as in the original HadCM3. Nevertheless, the higher resolution improved many aspects of the ocean circulation such as Indonesian throughflow, dense overflows and the equatorial circulation. There were indirect subtle effects on the mean climate simulated with notably some improvement in land temperatures as a consequence of improved sea surface temperatures. Still finer resolution (perhaps 1/10°) would appear to be needed to represent the North Atlantic current satisfactorily. Another general conclusion was that enhanced atmospheric resolution was also necessary to achieve the full potential improvements in the simulations.

5.2 Other climate-related modelling activities

The "Earth Simulator" project

Dr. A. Noda gave an update on the Earth Simulator Project in Japan. This was part of the ambitious and far-reaching initiative co-ordinated by the Japanese Science and Technology Agency to promote integrated research and development in the climate and environmental area. There were three components: the Frontier Research Programme for Global Change to study climate processes, the Frontier Observational Research System for Global Change to build up supporting observational programmes, and the development of the Earth Simulator to simulate and predict the Earth system. The core of the Earth simulator was a massively parallel system with computing nodes (vector-type multi-processors) tightly connected by sharing main memory. Assuming an efficiency of 12.5%, a peak performance of 40 TFlops was expected (640 processor nodes each with 8 processing elements with a peak performance of 8 GFlops i.e. 64 Gflops at each node) with an effective performance of 5Tflops making it the most powerful computing facility in the world. The total main memory was 10 Tbytes (shared memory per node of 16 Gbytes). The "Earth Simulator" site has been established in Yokohama (the Yokohama Institute for Earth Sciences), and the initial activity was planned to begin in March 2002. A particular target would be to complete a highly advanced global warming prediction for the next IPCC assessment (probably 2006). Arrangements for overseas scientists to use the facility were expected to be made through a special project (the Human-Nature-Earth-Symbiosis Project) set up by the Japanese Ministry of Education, Culture, Sports, Science and Technology.

Developments in the USA

Dr. W.L. Gates observed that policy shifts were under way which could significantly affect the organization of climate modelling activities in the USA. Essentially more emphasis would be given to producing practical results required to help formulate national USA policies in the climate area. Changes could be expected in both the support given by NSF (to NCAR) and by NOAA (to GFDL) with the objective of achieving closer co-ordination in climate modelling in the USA than in the past (as had been recommended by the USA National Academy of Science). In particular, it was foreseen that there would be a focussed national modelling development effort on one hand, and a focussed national effort in preparing scenarios/simulations on the other. A project to produce a common infrastructure for weather and climate modelling was also under consideration (the "Earth System Modelling Framework"). The principal institutions involved were NCEP, NASA/DAO, NASA/NSIPP, NCAR, MIT and GFDL). NCAR would lead the principal development of the framework, GFDL its application to coupled climate models, and NCEP and NASA/DAO the data assimilation aspects.

ACACIA Regional Climate-data Access System (ARCAS)

Dr. C. Hakkarinen (Electric Power Research Institute, EPRI) gave a demonstration of the ACACIA Regional Climate-data Access Systemn (ARCAS), (ACACIA - A consortium for the Appliction of Climate Impact Assessments - sponsored by EPRI). ARCAS was installed at NCAR and was designed to meet the needs of individuals and institutions requiring selected climate data (but who were non-specialists in data analysis) from often very large climate data sets, perhaps distributed among different centres in different formats. ARCAS was an interactive data visualization and extraction web-system based on the "Live Access Server" software developed by NOAA/PMEL. Users defined a query by selecting specific variables over a region of interest and time range, the server processed the query, and generated output in the desired format. Distributed data could be presented as a unified virtual data base. Facilities offered included data visualization, background reference material (meta-data), comparison of variables from distributed locations, unification of access to multiple types of data in a single interface, and derived products. The initial version of ARCAS permitted to access to various climate change simulations with the NCAR CSM and PCM models (see section 5.1) (business as usual, stabilization scenario, historical). A new version was under development which would offer a number of enhancements (e.g., user-specified windows, improved choice of image titles, labels, grids, ability to display multiple images simultaneously). ARCAS was available for testing at **http://dataserver.ucar.edu/arcas** and all participants in the WGCM session and others were encouraged to try the system. Comments and suggestions regarding further development of ARCAS would be very much welcomed.

6. ORGANIZATION OF FUTURE ACTIVITIES

At the kind invitation of Dr. F. Zwiers of the Canadian Centre for Climate Modelling and Analysis of the Meteorological Service of Canada, the next session of WGCM would be held in Victoria, BC, Canada, during the week beginning 7 October 2002. As noted in section 3.9, the session would overlap in part with that of GAIM, allowing joint discussions of key issues. Information on arrangements for the session would be sent in due time.

7. CLOSURE OF THE SESSION

There was a unanimous expression of gratitude to Dr. J. Mitchell and to the Hadley Centre for having kindly hosted this session of WGCM, the excellent arrangements made, and the facilities and hospitality offered. Appreciation was also voiced for the valuable support and assistance offered by Ms Livingston and other staff from the Hadley Centre. The contributions to the session made by several scientists from the Hadley Centre had also been very much appreciated.

The fifth session of WGCM was closed at 12.00 hours on 7 February 2002.

APPENDIX

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