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The sixteenth session of the CAS/JSC Working Group on Numerical Experimentation (WGNE) was kindly hosted by the Bureau of Meteorology Research Centre, Melbourne, Australia, from 23-27 October 2000. The session was held jointly with the fourth meeting of the GEWEX Modelling and Prediction Panel (GMPP). The list of participants in the (joint) session is given in Appendix A. The session followed the Workshop on Model Systematic Errors, also hosted by the Bureau of Meteorology Research Centre in Melbourne, the previous week, 16-20 October. The workshop (jointly organized by BMRC and WGNE) provided an excellent prelude to the WGNE session (see section 3.1 for consideration of the results of the workshop).

The session was opened at 0905 hours on 23 October with warm greetings from the Chairman of WGNE, Dr. K. Puri. He expressed particular pleasure at hosting WGNE at his home institution and of having the opportunity to entertain so many friends and colleagues in Melbourne. Dr. Puri particularly welcomed Dr. V. Kattsov (Voeikov Main Geophysical Observatory, St. Petersburg, Russia) who was attending WGNE for the first time as a new member of the group.

Dr. M. Manton, Chief Scientist of the Bureau of Meteorology Research Centre, speaking on his own behalf and on behalf of the Director of Meteorology, Dr. J. Zillman (also President of WMO and Permanent Representative of Australia with WMO), was also very pleased to welcome WGNE to Melbourne. He referred to the unique and special role of WGNE, cosponsored by the Joint Scientific Committee (JSC) for the WCRP and the WMO Commission for Atmospheric Sciences (CAS), in supporting the development of atmospheric models used in climate simulations and NWP. He particularly noted the increasing scope and specialization of NWP products and their application, and the growing expectations of warnings of extreme events. Meteorological services were increasingly criticized if such events were not well predicted and advance warnings not issued. Here WGNE had an important role in investigating how the accuracy of forecasts depended on the models employed. In this context, the workshop on model systematic errors the previous week had been valuable in demonstrating the reduction in errors in recent years. In a related vein, the assessment of regional climate modelling being undertaken in WCRP, in which WGNE was playing a significant role, was also timely and important. Dr. Manton mentioned areas of development and progress in the work of the Bureau of Meteorology. Recently an air quality prediction for Sydney and Melbourne had been introduced (see section 5.4). The National Climate Centre (at the Bureau) was continuing to extend its activities. Also, at the Bureau of Meteorology Research Centre, operational ENSO forecasts were now prepared. In collaboration with the Commonwealth Scientific and Industrial Research Organization, a fully coupled ocean-atmosphere model had been developed for long-term climate simulations and climate change projections. Dr. Manton concluded by wishing all participants a productive and enjoyable stay in Melbourne.

1. ROLE OF WGNE IN SUPPORT OF WCRP AND CAS

As noted by Dr. Manton, WGNE, as a joint working group of the JSC and CAS, has the basic responsibility of fostering the development of atmospheric models for use in weather prediction and climate studies on all space and timescales. In the WCRP, WGNE, with the WCRP Working Group on Coupled Modelling, lies at the core of the climate modelling effort. There is evidently a need for close contact and co-ordination between WGNE and WGCM and, to this end, the Chairman of WGNE participates in an ex officio capacity in WGCM sessions. WGNE also works in close conjunction with the WCRP Global Energy and Water Cycle Experiment (GEWEX) in the development of atmospheric model parameterizations, and, in this respect, WGNE sessions are held jointly with those of the "GEWEX Modelling and Prediction Panel" (GMPP).

With regard to the WGNE role in support of CAS, the increasing collaboration with the developing World Weather Research Programme (WWRP) is of particular importance, notably the involvement in the planning of The Hemispheric Observing System Research and Predictability Experiment (THORPEX) (see section 5.1). It was noted that CAS was also expecting WGNE input to a request from the President of WMO for the preparation of a policy statement on the basis for and limitations of forecasting, indicating the limits of predictability and what useful information forecasts could be expected to provide.

Beyond this, the close relationship that exists between WGNE and operational (NWP) centres is crucial to WGNE activities, and it is the work of these centres that provides the major impetus for the refinement of atmospheric models. As usual, this WGNE session included reviews of progress at operational centres in all aspects of NWP including data assimilation, numerics, physical parameterizations, ensemble predictions, seasonal prediction, and verification of precipitation and tropical cyclone track forecasts (see sections 4 and 5). WGNE also follows progress in various relevant national initiatives such as the Frontier Research Programme for Global Change in Japan (see section 3.11).

In organizing the work of the session, the discussion of the GEWEX Modelling and Prediction thrust (encompassing the issues of cloud/radiation parameterization, studies of land-surface processes and soil moisture, a proposal for an atmospheric boundary layer study, and planning for the GEWEX Co-ordinated Enhanced Observing Period, CEOP) was considered as constituting the GMPP session, and was moderated by Dr. D. Randall, Chair of the GMPP (see section 2 of this report). The studies and comparisons of features of atmospheric model simulations (see section 3), data assimilation and analyses (see section 4), and numerical weather prediction (see section 5) were considered formally as part of the WGNE session.

2. THE GEWEX MODELLING AND PREDICTION THRUST

2.1 The GEWEX Cloud System Study (GCSS)

Dr. D. Randall, Chair of GMPP (and the GCSS Science Panel), reviewed progress in GCSS, one of the main activities supporting refinement of model cloud parameterizations in GEWEX. GCSS is aiming to achieve a better understanding of the coupled physical processes at work within different types of cloud systems, the overall emphasis being on determining the effects of clouds acting as systems rather than as individual clouds or the role of individual cloud processes. In GCSS, five different cloud types are now being specifically studied: boundary layer; cirrus; extra-tropical layer clouds; precipitating convectively driven cloud systems; polar clouds. Five sub-working groups have been set up to deal with each of these cloud types and, in each area, a series of case studies drawing on observations from various field programmes is being conducted to evaluate the simulations of cloud-resolving or cloud-system models and the treatment of the relevant processes. Single-column models are also valuable tools particularly in making connections between general circulation models and data collected in the field, thereby facilitating observationally based evaluations of new parameterizations in isolation from the large-scale dynamics. Ultimately, cloud parameterizations must, of course, be tested in full climate simulations or in numerical weather prediction models and the organization of such activity is being considered. Attention is now turning increasingly to parameterization development, especially by reviewing specific new treatments and their performance in single-column or cloud system models. Full details of the scientific issues being addressed in GCSS and the studies carried out or underway are described in the recent version of the GCSS Science and Implementation Plan (**http://www.gewex.com/gcss_sciplan.pdf**). A general GCSS meeting is being planned for 2002 bringing together all the scientists working on the various different cloud types and experts from the (large-scale) atmospheric modelling communities.

More detailed reports on specific recent GCSS activities were given by Dr. B. Ryan (Division of Atmospheric Research, Commonwealth Scientific and Industrial Research Organization, Mordialloc, Victoria, Australia) on a joint workshop in UK in July 2000 between GCSS Working Groups 2 (Cirrus clouds) and 3 (Extra-tropical layer clouds) reviewing recent case studies, and by Dr. S. Krueger (University of Utah) summarizing findings from case studies organized by GCSS Working Group 4 (Precipitating convective cloud systems).

Joint Working Group 2/Working Group 3 workshop

It emerged clearly from the joint GCSS Working Group 2/Working Group 3 workshop that the expertise in the two working groups is complementary, and there is much to be gained by mutual interaction. There were also good interactions with the (larger-scale) climate modelling and NWP communities. As noted above, the focus for Working Group 2 is cirrus clouds and that of Working Group 3 layer (or frontal) clouds - but cirrus formation is obviously also an important part of frontal systems. Somewhat different approaches have been used, that of Working Group 2 employing cloud parameterizations based on "bin microphysics" looking explicitly at particle size distributions (in contrast to representations based on bulk microphysics where particle size distribution is implicitly or explicitly parameterized). Only idealized or very simple cases have been studied. Working Group 3 draws on experience in bulk microphysics and in exploiting observations and models on various scales, with complex cases chosen from major field campaigns such as the Fronts and Atlantic Storm Track Experiment (FASTEX). There have been attempts to generalize the conclusions from such case studies using satellite cloud climatologies. It was agreed that both working groups should try and find a suitable case study from the ARM CART site, providing an opportunity to exercise the groups' different skills in the same situation.

Results were reported from the Working Group 2 idealized cirrus model intercomparison. There appear to be (previously unreported) difficulties in the representation of ice-water precipitation. Bin and bulk microphysical schemes tended to fall into two separate patterns, the former showing more ice water, more energetic clouds and smaller ice crystal fall-speed compared to the latter, and a growing cloud top compared to a static cloud top. A cirrus parcel model comparison has also been carried out investigating the problem of nucleation and microphysical development in cirrus. Models using homogeneous nucleation showed qualitative agreement, but models with heterogeneous nucleation were divergent. There is no doubt of the importance of ice nucleation, but no agreed formulation of this process. Other outstanding questions are the number of types of ice crystals that should be represented in models (at least large and small), the vertical resolution needed to be able to treat thin layers, the role of radiation and lapse rate in cirrus formation (and possibly that of gravity waves), and whether the formation of synoptic (cold) cirrus is different from the (warm) cirrus detrained from convective systems.

The outcome from the Working Group 3 FASTEX case (intercomparison and sensitivity experiments) was also noted. It was encouraging that all participating models simulated the warm frontal band and basic cloud head that was observed between 15-20°W and 56-58°N, but there were differences in cloud top height. Some models had a clearer separation between the cloud head and warm frontal band than others. There was a suggestion of systematic differences between models with a single ice species and those with multiple species. The sensitivity experiments were designed to explore such aspects as the effects of ice-fall speed, deposition/sublimation rates, and sub-grid scale variations in cloud schemes. In particular, it was found that the specification of the fall speed could have an impact on the cyclone energetics and significantly affect the ice and water contents of the warm frontal band, and that, with a higher fall speed, the cloud top temperature was reduced.

Working Group 4

The main tool used in Working Group 4 studies of precipitating convective cloud systems is a cloud resolving model (i.e. capable of resolving cloud- and meso-scale circulations in two- or three-dimensions). Among issues that are being taken up are the occurrence (frequency and intensity) of deep convection, the production of upper tropospheric stratiform clouds, and parameterized versus resolved motions as horizontal resolution increases (already a consideration for mesoscale NWP models and will be in the future for global NWP and general circulation models). The two most recent case studies are the assessment of the ability of cloud resolving models to simulate, firstly, the large-scale properties of deep convective cloud systems over the tropical oceans (based on episodes of deep convection observed in TOGA-COARE) and, secondly, the large-scale properties of deep continental convective cloud systems (using observations collected at the ARM Great Plains experimental site during June and July 1997). From the first study, results confirm that the bulk characteristics of deep convection over the tropical ocean are determined (in a diagnostic sense) by the large-scale thermodynamic advection, and that cloud resolving models are helpful in forming this diagnosis. The differences in the simulated macrophysical cloud properties in the various cloud-resolving models appeared to be primarily due to differences in parameterizations of microphysics. With regard to the simulation of continental deep convective clouds by cloud resolving models, there are consistently smaller biases in time-averaged temperature and water vapour fields than shown by single column models using traditional forcing methods. Time-averaged cloud fraction profiles are also in reasonable agreement with cloud radar observations, but the onset of convection and precipitation tends to be delayed relative to observations. Concerning the simulation by cloud resolving models of the mass flux profiles of deep convective cloud systems, results appear to be robust, and updraft and downdraft statistics compare well to available observations (e.g. from aircraft during GATE and from ARM).

2.2 Land-surface processes

Global Land-Atmosphere System Study (GLASS)

Dr. J. Polcher introduced this item and reviewed the progress being made in the planning and implementation of the Global Land Atmosphere System Study (GLASS), which aims to encourage the development of a new generation of land-surface schemes for incorporation into general circulation models in support of weather and climate prediction on all time scales. New schemes will, in particular, include biophysical processes and the evolution of vegetation, and give increased importance to the horizontal complexity of the surface. Up to now land surface scheme validation and intercomparison projects such as the Project for Intercomparison of Land-surface Schemes (PILPS) (see also below) and the Global Soil Wetness Project (GSWP) have made major contributions in assessing the performance of land-surface schemes. These are being supplemented by new experimentation specifically designed to address issues of sub-grid scale variability of the surface, and the feedbacks between the changing land surface and the atmospheric circulation (e.g. co-ordinated experiments to explore the sensitivity to different approaches to soil moisture modelling in climate change predictions.

To facilitate the range of testing, validating and intercomparison of land-surface schemes required at a wide range of scales, GLASS is being formally structured round four main scientific thrusts:

- Local-scale/off-line intercomparisons: this will essentially be a continuation of PILPS activities, in particular phase 2 projects. Activities to test how CO_2 flux is represented in current land-surface schemes will also be undertaken (see also below);

- Global-scale/off-line intercomparisons: again this will build on the existing GSWP, using ISLSCP-II data to drive off-line simulations of soil moisture and its interannual variability over a ten-year period. (A preparatory step will be run with an updated version of ISLSCP-I data). Questions that will be particularly taken up are the sensitivity of land-surface schemes to errors in the forcing data, how well schemes can be validated at a global scale with remotely-sensed data, how closely the drying cycles in different schemes compare, and whether schemes operate in similar soil moisture stress ranges;

- Local-scale/coupled intercomparisons: the plan here is to employ a (common) simplified single column model and extend PILPS-type experiments by including coupling with the atmosphere. ARM/CART data will be used as a basis for the experimentation and intercomparisons. A "parameter estimation" procedure should ensure that the same effective values are used for key parameters. This work should help in clarifying the feedbacks between land-surface schemes and the planetary boundary layer, the effect of surface heterogeneities on the planetary boundary layer, and whether the behaviour of land-surface schemes is different in off-line mode to when coupled with the planetary boundary layer;

- Global scale/coupled intercomparisons: the work in this thrust will aim to assess the role of land surface processes in determining climate sensitivity to anthropogenic forcing, and in climate variability and predictability. The first step being taken is to explore the impact of improved specification of land-surface conditions on short-range forecasts, in particular such aspects as the geographical distribution of the strength of the land-atmosphere feedback, its inter-model variation, and the part played in the predictability of the hydrological cycle.

These scientific thrusts are complemented by work to set up an infrastructure to facilitate GLASS intercomparisons and to help the community involved to move towards standard methods for coupling land-surface schemes to atmospheric models. Standards for data transfer are being specified, the continued availability of data from past experiments ensured, and software for modelling and analysis of land-surface processes distributed. The full GLASS implementation plan contains more details of the activities foreseen (**http://hydro.iis.u-tokyo.ac.jp/GLASS**).

Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS)

Dr. A. Henderson-Sellers reviewed the range of continuing activities in PILPS (as a component of GLASS). New intercomparisons (i.e. off-line local simulations) are being organized using data sets available over the Torne basin in Sweden, and a mature forest site at Valdai, Russia. This work will allow an evaluation of the treatment of cold-season processes in land-surface schemes. Separately, high quality data from a South Ontario field campaign are also being used for this purpose. Moreover, experimentation is being planned in PILPS to assess the newly-developed capability of land-surface schemes to simulate CO_2 fluxes. An analysis of model simulations of land surface climates in AMIP-II is also proceeding, but has been limited by uncertainties in global climatological reference data sets. It is generally being found that the latent heat flux is underestimated especially in humid climates, and that deep soil moisture is poorly handled. More details may be found on the PILPS home page at **http://cic.mq.edu.au/pilps-rice/**.

2.3 Proposed atmospheric boundary-layer study

A lead into this item was given by Dr. M. Miller who stressed that a major continuing problem in the performance of coupled models was the large-scale systematic errors in surface net energy fluxes over the oceans, especially in the tropics and sub-tropics. A dominant cause of these errors often appears to be excessive latent heat flux in trade wind areas and excessive downward shortwave fluxes in regions of marine stratus/stratocumulus cover. At ECMWF, verification against ocean buoy data indicated that forecast near-surface specific humidities were too low, resulting in enhanced evaporation . Furthermore, comparison of boundary layer depth as estimated by lidar measurements from the space shuttle with the average model-simulated planetary boundary layer pointed to the latter being too deep (by about 100-200m). This is probably linked to the dry bias consequent to the entrainment of too much dry air through the top of the planetary boundary layer because of an unsatisfactory representation of cloud/inversion interactions. Dr. Miller also demonstrated that the well-known problems in models with marine stratus might involve cloud/radiation interaction as well as errors in maintaining or dispersing the cloud cover.

Dr. D. Randall then introduced a proposal for an atmospheric boundary layer study to be undertaken within GEWEX (under the auspices of the GMPP). As noted above, the parameterization of the planetary boundary layer was becoming of heightened importance as the development of coupled atmosphere-ocean-land surface models continued. The physical processes involved were often not as well understood as appeared at first sight, manifested by, for example, the difficulties in simulating marine stratus clouds, in representing shallow cumuli and their radiative effect, in quantifying surface fluxes in light wind conditions, and in predicting the depth of the planetary boundary layer and the effects of entrainment. Outstanding issues included the interactions of the planetary boundary layer with moist convection and with the land surface, the simulation of the diurnal cycle over tropical continents, and the behaviour of the planetary boundary layer over topography. The main goal of the proposed GEWEX atmospheric boundary layer study would thus have the overall goal of improving the representation of the atmospheric boundary layer in models, based on advancing understanding of the relevant physical processes involved. It was intended that the study would provide a framework, similar to those set out for GCSS and GLASS, in which scientists working on boundary layer research issues at different scales would interact.

GMPP and WGNE fully recognized and endorsed the need for activities in this area. However, it was recalled that, following the TOGA-COARE Conference in 1998, recommendations had been made for the continued study of coupled ocean-atmosphere boundary layer phenomena. It would be important that a GEWEX initiative on the boundary layer should be conducted in collaboration with the group that had been involved in TOGA-COARE and perhaps jointly with CLIVAR. Any group established to follow up the review prepared by the JSC/SCOR Working Group on Air-Sea Fluxes (see section 3.5) would also need to be consulted in the development of this work. The proposal to establish such an atmospheric boundary layer project in GEWEX would be discussed at the GEWEX Scientific Steering Group at its session in January 2001, and then considered by the Joint Scientific Committee for the WCRP in March 2001.

2.4 Co-ordinated Enhanced Observing Period

Dr. R. Stewart reviewed the planning and preparations for the GEWEX Co-ordinated Enhanced Observing Period (CEOP). A full description of the status of CEOP can be found at **http://www.msc-smc.ec.gc.ca/GEWEX/GHP/ceop.html**. It was seen that CEOP was shaping up to be an important activity which should provide a wealth of data to enable further extensive testing of atmospheric model parameterizations. The basic objective was to collect common data sets synchronously from all the regional GEWEX hydrological-atmospheric studies for a period from 2001 to 2003. (The regional studies being undertaken, aiming to characterize energy and water budgets on the scale of continents, include the USA Continental-scale International Project, GCIP; the Baltic Sea Experiment, BALTEX; the GEWEX Asian Monsoon Experiment, GAME; the MacKenzie River GEWEX Study, MAGS; the Large-scale Biosphere-Atmosphere Experiment in Amazonia, LBA. Progress is also being made in the organization of an investigation of the Coupling of the Tropical Atmosphere and Hydrological Cycle, CATCH, in the Sahel region of West Africa with the objective of improving predictions of the impact of climate variability on water resources management). The overall objective of CEOP was to explore the impact of soil moisture in the climate system on a global scale and to improve the understanding of several fundamental land surface/atmospheric interactions. There are many aspects of interest to the modelling community, in particular the experience to be gained in using standard, special and new observational information, assessment of the capabilities of global and regional models to simulate and predict key continental-scale features of water and energy cycles, the opportunity for global validation of products, and regional intercomparisons and model transferability over the globe. Regional and global model evaluations would also be supported by special test experiments over the La Plata River basin and the Canadian prairies. Moreover, CEOP offered the opportunity of diagnosing how well improved assimilated model products characterize water and energy budgets over land, and how the land is interacting with the atmosphere. Conversely, CEOP needed expertise in global and regional modelling and in organizing model intercomparisons.

WGNE and GMPP gave strong encouragement to CEOP, and urged modelling centres to consider how to take advantage of the opportunities provided and what experimentation/research/validation could be carried out, and, for example, to assess whether model systematic errors might be affected in any way. Attention was drawn to the possibility of organizing appropriate budget diagnostic studies in the framework of AMIP. The importance of as much as possible of the data collected in CEOP being available in real-time so that rapid feedback could be provided from operational centres was stressed. On the practical side, WGNE asked that information on CEOP and the range of data planned to be collected should be more widely advertised, together with regular updates on progress in implementation. More specifically, noting the role foreseen for national weather services in carrying out special supporting operations and/or providing additional data, it was pointed out that an official request should be made to these services as soon as possible.

3. STUDIES AND COMPARISONS OF FEATURES OF ATMOSPHERIC MODEL SIMULATIONS

3.1 Review of model systematic errors

A highlight of WGNE activities in the past year was the Workshop on Model Systematic Errors, 16-20 October 2000 (jointly organized by BMRC and WGNE as the Twelfth Annual BMRC Workshop), in conjunction with the session of WGNE in Melbourne. The workshop was attended by representatives of virtually all the world's active modelling groups, and an extensive range of papers were presented orally or in poster form during the course of the week. A summary of the main findings and conclusions is attached as Appendix B. The abstracts of presentations given at the workshop have been compiled as BMRC Research Report No. 80.

As pointed out in the summary of findings and conclusions, the workshop revealed what has been achieved in recent years, what has been learned and where difficulties remained. Most notable was the marked decrease in errors, especially in short- and medium-range weather forecasts. However, there may be merely a delay in onset, since errors, with the same sort of signature, still appeared with increasing magnitude at around ten days or so. What has undoubtedly helped is a general improvement in understanding of the nature of model errors, allied with practical advances such as the finer model resolutions that can now be employed in the vertical and horizontal. There has also been much progress in the representations of physical processes, in particular radiative transfer and cloud/radiation interaction, deep convection, and surface and boundary layer behaviour. The major steps forward in data assimilation (in particular use of variational methods) and in model initialization will also have contributed significantly to a reduced error growth in the early stages of predictions. However, the workshop did not point to any one single "breakthrough", but rather incremental advances resulting from detailed work and study of individual aspects of models one by one.

WGNE expressed profound appreciation to BMRC for the effort and support in organizing this important workshop which was regarded by all who participated as having been very successful, helpful and productive with many useful interactions and discussions.

3.2 General model intercomparisons

As well as promoting the organization of periodic events such as the Workshop on Model Systematic Errors mentioned above, the key element in the ongoing WGNE quest to identify errors in atmospheric models, their causes, and how they may be eliminated or reduced, is a series of model intercomparison exercises. These encompass a number of fairly general wide-ranging intercomparisons as outlined in this section, as well as more specific efforts, e.g., evaluation of snow models as employed in atmospheric circulation models (see section 3.6), or assessment of predictions of stratospheric activity (see section 3.8).

Atmospheric Model Intercomparison Project

The most important and far-reaching of the WGNE-sponsored intercomparisons is the Atmospheric Model Intercomparison Project (AMIP), conducted by the Programme for Climate Model Diagnosis and Intercomparison (PCMDI) at the Lawrence Livermore National Laboratory, USA, with the support of the US Department of Energy. Drs P. Gleckler and K. Taylor reviewed the status and progress in AMIP, which is now well into its second phase (AMIP-II). Like the first, this calls for a community standard control experiment (January 1979-March 1996) in conjunction with careful specific analyses of various aspects of the simulations. The atmospheric concentration of CO_2, sea surface temperature and sea-ice distributions, solar constant and relevant orbital parameters to be used have been specified. Recommendations have also been made for a zonal monthly ozone climatology, land-sea mask and topography, concentrations of greenhouse gases such as methane, nitrous oxide (if considered separately), and a background monthly aerosol climatology. Nineteen modelling groups have now submitted AMIP-II simulations to PCMDI and at least another five have expressed their intentions to do so soon. WGNE suggested that a time limit should now be set for collecting simulations.

Over the past few years, PCMDI has taken several strides forward in handling the voluminous AMIP-II data sets. An automatic system has been put in place to organize the simulations, perform extensive quality control, document problems, and make the data accessible (via FTP) to interested users. The status of the AMIP data base and model integrations is posted nightly on the AMIP home page (**http://www-pcmdi.llnl.gov/amip**). These facilities are essential to the substantial range of diagnostics studies that have been organized, and half of the AMIP-II simulations are now available to the groups carrying out these studies (with the remainder expected to be on line in 2001). These diagnostic projects are a key component of AMIP. Based on AMIP-I experience, the specification and procedures for acceptance of these projects has been improved. Currently, research is in progress in over thirty (approved) sub-projects (the full list may be found on the AMIP home page). One aspect which WGNE discussed was what might constitute an adequate model resolution for climate studies (this question had also come up at the Workshop on Model Systematic Errors). Furthermore, resolution was clearly important in the treatment and prediction of extreme weather events which is another subject of increasing attention. WGNE suggested that these issues could be tackled through an AMIP sub-project on resolution and asked the AMIP panel to consider how this might be organized (the WGNE-appointed AMIP panel oversees details of AMIP implementation).

PCMDI itself also prepares a number of basic diagnostics, including a "quick-look" set of diagrams and statistics. Among these, plots of zonal means of every AMIP-II variable, tailored for every model and complemented by observational and reanalysis products, have been placed on the AMIP home page. Climatological maps will be made public in 2001. More specialized "Taylor diagrams" and plots are also being constructed for each simulation. In addition, PCMDI routinely compiles the standard WGNE set of diagnostics of mean climate (see section 3.3) and variability statistics will be added as WGNE proposals in this respect develop. These basic statistics are indicating some degree of improvement in the AMIP-II simulations compared to AMIP-I. Nevertheless, overall the mean or median of all the simulations seems to be superior in many respects.

The AMIP panel was expected to meet early in 2001 to solidify plans for the continuation of AMIP. It was foreseen that AMIP would become a "quasi-operational" community exercise in which modelling groups would periodically contribute revised model simulations (e.g., every two or three years). The experimental protocol will be updated annually by extending the sea surface temperature/sea-ice boundary conditions to near present and reviewing the standard output list. Consideration will also be given to the organization of a second international AMIP conference, probably later in 2002 (the first international AMIP Conference was held in May 1995). By that time, comprehensive results from the AMIP-II diagnostic sub-projects should be available.

The most recent information on AMIP, including the status of AMIP-II and results of the diagnostic sub-projects may be accessed via the AMIP home page (address as above).

"Transpose" AMIP

Dr. D. Williamson described the further consideration being given to the development of a "transpose" AMIP. He recalled various means that could be used to examine parameterization errors in atmospheric circulation models, including, of course, the approach of AMIP itself in which time averages from long climate simulations were analyzed. This did suffer from the drawbacks that cause and effect were often difficult to separate, the parameterizations might be operating in unrealistic or erroneous states, and that errors in the parameterization might be balanced by other model errors. The technique of nudging model states towards reanalyses restrained the model circulation so that the behaviour of the parameterizations might not be typical. One particular method that did appear to hold promise was the analysis of an evolution of ensemble of forecasts and to examine how parameterizations behaved before the predicted state diverged too far from the truth. The concept of such an approach being developed was that climate models might be run in NWP mode, and the evolution of the forecast and of various variables examined - this is being termed a "transpose" AMIP. More specifically, predicted variables would be compared with values from reanalyses over regions where these variables were known to be correct from comparison with observations (i.e. data rich areas over the US and/or Europe) in forecasts of only a few days during which the state may be considered "correct". The intention was very much to try and learn why there are model errors, rather than just what the errors were.

WGNE recognized that the initialization and spin up of the forecasts were likely to be critical aspects of whether useful results could be obtained, especially in trying to assess model treatments of cloud and radiation. Nevertheless, a pilot project was being undertaken at NCAR with the CCM using initial data provided by ECMWF (which then had to be interpolated to the CCM grid).

International Climate of the Twentieth Century Project

The objective of the International Climate of the Twentieth Century Project, developed under the leadership of the Center for Ocean-Land Atmosphere Studies and the UK Meteorological Office Hadley Centre for Climate Prediction and Research, was to assess the extent to which climate variations over the past 130 years can be simulated by atmospheric general circulation models given the observed sea surface temperature fields and sea-ice distributions and other relevant forcings such as land-surface conditions, greenhouse gas concentrations and aerosol loadings. The initial experimentation being undertaken involved carrying out (four-member) ensembles of integrations with the observed sea surface temperature and sea ice as the lower boundary conditions (the HadISST 1.1 analyses provided by the Hadley Centre). However, data availability and reliability prior to 1949 was a limiting factor in specifying all the required forcing fields. A small common set of diagnostic quantities was being saved from all integrations to facilitate comparison and quantitative analysis. The project was complementary to other internationally co-ordinated numerical experimentation projects, notably AMIP, and the general guidelines are similar to these activities. Fifteen groups are participating. Results from the initial set of experiments are expected to be reviewed at an international workshop at the Center for Ocean-Land Atmosphere studies in September 2001.

3.3 Standard climate model diagnostics

Dr. D. Williamson reviewed the widening interest in and use of the WGNE "standard diagnostics" and extensions to the list being considered. As well as being the basis for the "quick-look" diagnostics for AMIP simulations computed by PCMDI (see section 3.2) (where the formal definitions can be viewed), the WGNE diagnostics were being employed at NCAR in comparing atmospheric model components to be used in future versions of the Community Climate System Model. Examples from models would be available on the web at **http://www.cgd.ucar.edu/csm/working_groups/Atmosphere** after the model algorithms have been frozen. The scripts for the WGNE diagnostics allowing comparison of two model simulations, or one simulation against that of a community Climate Model could also be freely accessed at **http://www.cgd.ucar.edu/csm/support/Diag/wgne.shtml**.

It was noted that several proposals had been made for extensions to the diagnostics at the Systematic Error workshop in the week preceding the WGNE session (see section 3.1). These would be taken into account in updating the list of WGNE diagnostics. As discussed at the 1999 WGNE session, it was planned to include additional parameters to describe the representation of modes of climate variability such as ENSO, the Madden-Julian Oscillation, intraseasonal variability, and phenomena such as monsoons and blocking, as well as the simulated frequency of occurrence of extreme events (hurricanes, floods, droughts etc.) and appropriate harmonics to show the diurnal cycle. The revised list including specific examples would be circulated to WGNE (as well as more generally in the scientific community) for comments/additions before finalization.

3.4 Studies of model dynamical cores and numerical algorithms

With the advent of massively parallel processing and distributed computer architectures, the development of refined numerical algorithms to extract the best performance possible from the machines available at modelling centres is receiving much attention. In this area, effective collaboration has been established between modelling and computer science centres.

Eighth Workshop on the Solution of Partial Differential Equations in Spherical Geometry

A comprehensive view of activities was provided by the Eighth Workshop on the Solution of Partial Differential Equations in Spherical Geometry, San Francisco, 30 November-3 December 1999. New numerical algorithms are being constructed for integration of the primitive atmospheric equations, and algorithms employed in other areas of fluid dynamics are being adapted to the atmospheric equations. The set of shallow water equations is a particularly good test bed since they encompass the essential computational difficulties of full atmospheric modelling. New techniques being examined in this manner include cell-integrated semi-Lagrangian transport schemes and Osher's scheme (a higher order finite volume scheme of the upwind type) applied on a reduced grid (stereographic in polar regions). Triangular or icosahedral grids are also being used with such schemes as Lagrange-Galerkin finite elements (solving the equations in Cartesian space), third and fourth order three-dimensional Cartesian methods, polynomial reconstructions (originally developed for unstructured grids and thus applicable to variable meshes), and genuinely multi-dimensional accurate and non-oscillatory upwind techniques (also on unstructured grids). Furthermore, attention has been directed to cubed sphere or gnomonic mappings which include high resolution finite-volume shock-capturing methods with limiters to the second order, and control-volume-based finite element schemes. New quasi-uniform meshes have been developed such as Fibonacci grids which have structures resembling the seeds on a sunflower or the scales on a pineapple. Theoretical work has provided the basis for the definition or near optimal interpolation points on the sphere although appropriate approximation methods have not as yet been elaborated.

Test cases

A few of the newer methods have been applied to three-dimensional baroclinic models with promising results. However, in this respect, although the shallow water test suite has been useful, there is now a need for (simple) tests of the various schemes for a baroclinic system before they are introduced into complete models when complex feedbacks obscure the effects of the changes. Tests have been devised including the treatment of a breaking Rossby wave on the polar vortex as an initial value problem, and of a growing baroclinically unstable wave. These are both deterministic tests, but without analytic solutions and high resolution reference computation is required. Furthermore, an assessment of the long-term characteristics of new methods is being attempted based on the "age-of-air" concept in the stratosphere. This requires a Lagrangian particle code to separate the effect on the age of the air by the dynamics as represented in the new schemes (and hence the advection of air), and that of the transport approximations themselves when used with that dynamical representation. The test being considered involves an extension upward into the stratosphere of the idealized Held-Suarez forcing (used to drive model dynamical cores in test mode), but, so far, the resulting atmosphere has been too sluggish to produce realistic ages.

Aqua-planet experiments

There is also a requirement to test the interactions of physics parameterisations with each other and with the dynamics. Stripped down versions of atmospheric models with very simplified surface conditions, in particular "aqua-planet" experiments with a basic sea surface temperature distribution, offer a useful vehicle in this regard, and their value in understanding the performance and effects of different representations of physical processes in individual models has been clearly demonstrated. For example, a suite of experiments has been run with the Hadley Centre atmospheric model (version HadAM3) to investigate sensitivity to an idealized set of four different zonal hemispherically symmetric sea surface temperatures, and how the organization of tropical convection and the tendency for rain to occur on or off the equator were affected. Further tests were run with an off-equatorial sea surface temperature maximum and zonally asymmetric sea surface temperature anomalies. Similar experimentation has also been carried out at NCAR (with CCM3).

WGNE recognized that such "aqua-planet" experiments could have wide application in evaluating interactions of various processes in models, and encouraged individual groups to carry out these types of tests (especially using the idealized sets of sea surface temperature distributions referred to above). An intercomparison of the various results obtained would clearly be of considerable interest and the possibility of assembling results at one centre should be explored. WGNE agreed to keep the studies in this area under review.

3.5 Model-derived estimates of ocean-atmosphere fluxes and precipitation

Progress is now being made in the implementation of the updated WGNE evaluation and intercomparison of global surface flux products (over ocean and land) from the operational analyses of a number of the main NWP centres (the "SURFA" project), this being organized on behalf of WGNE by Dr. P. Gleckler (PCMDI) whose interests lie particularly in the study of air-sea fluxes, and Dr. J. Polcher (Laboratoire de Météorologie Dynamique) whose interests lie in the study of land-surface fluxes. As well as the increasing concern in NWP centres with improving the treatment of surface fluxes, this activity responds to the request of the joint JSC/SCOR Working Group on Air-Sea Fluxes for a WGNE initiative to collect and intercompare flux products inferred from operational analyses. Furthermore, the GCOS/GOOS/WCRP Ocean Observations Panel for Climate has underlined the requirement for high quality surface flux products that would have to be provided from routine operational analyses to meet its objective of implementing the ocean observing systems and assembling the data sets for the purposes of climate studies. The Global Ocean Data Assimilation Experiment (GODAE), aiming to provide a practical demonstration of real-time global ocean data assimilation as a basis for complete synoptic descriptions of the ocean circulation at high spatial and temporal resolution, also has requirements for high quality global real-time products. Moreover, the study of land-surface fluxes is of growing importance in the context of the new Global Land Atmosphere System Study (GLASS) (as referred to in section 2.2).

In the initial pilot study that has now begun, eleven operational NWP centres have been invited to submit full global fields of various surface products at twelve-hour intervals (accumulated fluxes for predictions from 00-12, 12-24, 24-36 and 36-48 hours) to PCMDI. Advantage is being taken of AMIP experience in setting the standards, formats, and procedures for assembling SURFA data sets and developing software for diagnostics and studies of the products received. Documentation of the models and operational assimilation/analysis systems will also be built up. The goals of the project are to provide the participating NWP centres with routine (i.e. yearly) evaluation of their surface fluxes and how they may change as a result of modifications of assimilation and forecast models, to offer a basis for co-operation between NWP centres and relevant observational programmes in comparing surface fluxes, and to stimulate detailed comparisons with high quality direct measurements. If the pilot study proves to be sufficiently useful and succeeds in involving the various communities concerned with surface fluxes, it is intended that SURFA should evolve into a long-term exercise collecting data in near-real time. In this latter regard, strong interest is being shown in SURFA by GODAE and GCOS.

Workshop on Intercomparison and Validation of Ocean-Atmosphere Fields

WGNE noted that a major workshop on the intercomparison and validation of ocean-atmosphere fields was being organized by WGASF in Washington, DC in May 2001. The workshop would bring together the different scientific communities interested in air-sea fluxes, and, as a first step, review the substantial and authoritative WGASF assessment of the state of the art in regard to air-sea flux determination. (The WGASF assessment is available at **http://www.soc.soton.ac.uk/JRD/MET/WGASF** and has been published in the WCRP report series, WCRP-112, Intercomparison and Validation of Ocean-Atmosphere Energy Flux Fields). Feedback from the community as a whole would be collected and the conclusions and opinions of WGASF would be commented on and debated as appropriate. The latest developments in obtaining flux and flux-related parameters from in situ and remotely-sensed data, and from model output fields would also be presented, as well as studies of uncertainties inherent in various fields. Additionally, although primarily concerned with global-scale flux climatologies, the evolution of flux parameterizations, and ideas for field experiments and collection of high quality flux data would be discussed. Most importantly, the Workshop would, like the earlier WCRP Workshop on Air-Sea Flux Fields in 1995, promote further inter-disciplinary consultations, and encourage feedback and dialogue between the producers and users of surface fluxes and related data. This would be a basis for agreeing on an effective and balanced strategy and the internationally co-ordinated initiatives needed to make progress in studying, determining more accurately, and making appropriate use of air-sea fluxes. The workshop has been successful in attracting wide interest in the scientific community and well over a hundred abstracts have been submitted. The opportunity would be taken to advertise the "SURFA" project. Information on the workshop can be found at **http://www.soc.soton.ac.uk/JRD/MET/WGASF/ workshop**.

The Global Ocean Data Assimilation Experiment (GODAE)

Dr. N. Smith (Bureau of Meteorology Research Centre) outlined the progress in planning the Global Ocean Data Assimilation Experiment (GODAE), an ambitious oceanographic project that could be regarded as the equivalent in the ocean of the (atmospheric) First GARP Global Experiment (FGGE). The principal aim of GODAE was to introduce a new era for oceanography and to bring ocean forecasting to the fore. An activity such as GODAE has now become feasible with the development and maturity of remote sensing and in situ observing systems capable of supplying global real-time oceanographic observations at the same time as steady advances in scientific knowledge and in the ability to model the global ocean and to assimilate data. GODAE is intended to meet the user demand for global ocean products for a variety of applications, including scientific research, and to provide a convincing demonstration of the advantages that would be obtained from a future routine permanent and well-supported ocean observing system. More specifically, the objectives of GODAE are to apply state-of-the-art ocean models and assimilation methods to produce short-range open-ocean forecasts, the boundary conditions to extend the predictability of coastal and regional subsystems, and initial conditions for climate forecast models. Also, the global ocean analyses provided would enable an improved understanding of the oceans and refined assessments of the predictability of ocean variability as well as offering a foundation for the design of an effective global ocean observing system. For observational data, GODAE would depend on both polar orbiting and geostationary satellites and, in particular, accurate and high resolution altimetry and high resolution surface winds. In situ data would be obtained from tropical buoy arrays, ships-of-opportunity, and the ARGO project in which a global array of profiling floats would be deployed. Globally consistent fields of upper ocean temperature, salinity and velocity would be generated through the multi-variate synthesis of satellite and in situ data using eddy-resolving global ocean models with as many as fifty levels in the vertical and advanced physics.

WGNE was excited by the opportunities offered by GODAE and recognized the importance of appropriate liaison and dialogue in view of the interest to operational NWP centres.

3.6 Snow Models Intercomparison Project (SNOWMIP)

Dr. P. Bougeault reported on the planning of SNOWMIP, being undertaken under WGNE auspices by Météo-France (Centre National de Recherches Météorologiques, Centre d'Etudes de la Neige, CNRM/CEN) and aimed at evaluating the different types of snow models that have been developed for applications ranging from climate modelling, snow stability and avalanche forecasting. The basic approach to be followed would be point validations of the simulated evolution of the snow mantle. An atmospheric forcing would be supplied (as well as heat flux from the soil for those models which do not include a coupling with the underlying ground surface). Figures to be collected include bulk properties and fluxes every hour for all models and internal characteristics of the snow mantle every three hours. Various sensitivity studies would also be undertaken. Data sets from sites in various parts of the world would be used (e.g. from Col de Porte in the French Alps where excellent radiative and precipitation measurements are available; from Sleepers River in the Appalachians; Goose Bay, Canada). Over twenty groups have expressed interest in participating in the exercise. Data sets were expected to have been distributed by the end of 2000, with results to be submitted by the end of March 2001. A workshop was being planned in conjunction with IAMAS Assembly in Innsbruck, Austria, 2001, to review the results. More information is available on the web site **http://www.cnrm.meteo.fr/snowmip/**.

WGNE welcomed the progress now being made in this project, noting also its relevance to GLASS (see section 2.2). WGNE urged that the appropriate liaison be established between SNOWMIP and GLASS.

Other relevant work in this area is an intercomparison of snow depth analyses at the Canadian Meteorological Centre (CMC), Deutscher Wetterdienst (DWD) and the Japan Meteorological Agency (JMA) (undertaken by the Japan Meteorological Agency in response to a request from the WCRP/GCOS Atmospheric Observation Panel for Climate). One factor contributing to the differences seen is the wide variation of input observations of snow depth (from SYNOPs) (e.g. DWD and JMA did not use any SYNOP data from the USA). Additionally, significant discrepancies can be seen in the analysed fields, particularly in data-sparse areas pointing to possible shortcomings in snow analysis methods (which are still somewhat rudimentary). Progress in this area will depend on an enhanced exchange of observations of snow depth, as well as a careful evaluation of model predictions of snow-related fields.

3.7 Orographic representation in models

Dr. P. Bougeault presented a range of problems and recent developments in the representation of orography in models. There remain a variety of questions in respect to treating roughness and gravity wave effects, the use of envelope or silhouette approaches, and whether a specific lift parameterization may be needed. Significant research effort is being directed to these and related issues. In particular, there is continuing investigation of co-ordinate systems adapted to capturing orographic effects. For several dynamical problems, it appears that the conservation of the maximum height may be more important than conservation of mountain volume. Although the treatment of planetary waves was improved by such techniques as "valley-filling", envelope orography and silhouette techniques, there were consequently problems with data assimilation. Thus, the general trend has been to go back to a mean orographic representation in recent years, complemented by an inclusion of a low-level (gravity-wave) drag. With regard to roughness effects, the "effective roughness" concept, with horizontal scales ranging from a few meters to a few kilometers, is in wide use. Various results have indicated that benefits can be achieved with increased roughness values (for example, in the second COMPARE case study carried out in 1995 and 1996, increased roughness gave better results than envelope orography at least for meso-scale models). The appropriate momentum flux profile induced by gravity wave drag continues to be a subject of discussion. Recent refinements (which are essentially a mixture of complex theories and empiricism) have included taking into account the effects of blocked flow, of high drag states, of trapped lee waves, and of critical levels in the presence of shear. Among a number of outstanding problems are how the planetary boundary layer and clouds may affect gravity wave drag, the relevance of high drag states, and the behaviour of schemes in the stratosphere (this last aspect is being studied in SPARC-GRIPS). Another topic attracting renewed attention is that of lift forces. Clearly, orography is responsible for a lift force acting on the flow: it has recently been suggested that this may have a large impact on the planetary waves in an atmospheric circulation model (in contrast to the drag which mainly influences the zonal wind). In this case, a specific parameterization of lifting effects may be needed in some models (in addition to a lift forcing proportional to the mountain volume).

In summary, it was noted one model may include several complex schemes to take account of various orographic effects, often interacting in a complicated manner. It appeared that a simpler unified approach was required, in particular to avoid double-counting effects. Momentum budget studies, detailed comparison with observations and studies with very fine-scale models would all certainly serve a useful purpose, but available relevant observational data sets are limited. It was also proposed that the question of orographic representation in models could be treated by a further COMPARE case study, perhaps again exploiting the unique data sets collected in the Franco-Spanish Pyrénées Experiment (PYREX) a few years ago.

3.8 Model stratospheric intercomparisons

Comparison of deterministic predictions of stratospheric activity

The initial intercomparison of deterministic predictions of stratospheric activity at lead times of a few days for a period in October 1994 undertaken by WGNE has now been concluded, since the results collected were becoming relatively old. However, in the past two or three years, WGNE was well aware that there has been growing interest in the representation of and prediction in the stratosphere and several major global operational centres have significantly increased the vertical extent and resolution of their models and associated data assimilation and predictions in the stratosphere and into the mesosphere (50-60km). This development is linked to need to make optimum use of data from new operational satellites such as NOAA-15 and NOAA-16, and AMSU/HIRS radiance measurements. WGNE thus strongly endorsed a new activity aimed at carrying out quantitative intercomparisons of stratospheric analyses in terms of mean fields and biases and variances, and of model predictive skill in the stratosphere. BMRC (Dr. G. Roff) expressed willingness to lead these further studies on behalf of WGNE and, in collaboration with interested data centres, will arrange the assembly of required data sets, lay down common diagnosis and verification procedures, and identify a period for study.

SPARC-GRIPS

The activities of WGNE in studying stratospheric predictions are complemented by the intercomparison of stratospheric climate simulations being organized by the WCRP study of Stratospheric Processes and their Role in Climate (SPARC) (known as the GCM Reality Intercomparison Project for SPARC, GRIPS). Over the past two or three years, GRIPS has been growing both in the number of research groups involved and the range of tasks being tackled. The first phase of GRIPS was focussed on a simple intercomparison of model stratospheric simulations, and as reported in past years, a wide range of skills is apparent. Detailed accounts of findings from the first phase of GRIPS have now been or are being published (as Pawson et al, Bulletin American Meteorological Society, 2000; Koshyk et al, Journal of Geophysical Research, 2000; and Amodei et al, to appear in Annales Geophysicae). New data from various modelling groups continue to be collected, with analysis now being focussed on mechanisms that may be involved in causing stratospheric variability (e.g. wave or diabatic forcing). Specific experimentation may also be organized designed to explore the sensitivity of the stratospheric circulation to various forcing mechanisms and their interaction.

The second phase of GRIPS is now underway, including an extended validation of models and carrying out controlled experiments to test parameterization schemes, including particularly investigation of radiative codes in use, of model responses to the formulation of mesospheric drag, and of gravity wave parameterization. Models have been shown to be very sensitive to the radiation code employed, and this is clearly a major factor affecting the convergence of different model simulations.

Progress has also been made in setting out the objectives and plans for the third phase of GRIPS. The main goal is to try to explain the observed variability in the stratosphere in the period 1979-1999, taking into account natural variability and known forcing mechanisms (changes in aerosol loading, solar variations, changes in atmospheric concentrations of ozone and carbon dioxide). As a further step, experiments will be run with imposed climate change scenarios from 2000 to 2020 (using the best possible predictions of trace gas concentrations).

3.9 Modelling large-scale atmospheric transport

A series of workshops to assess the ability of atmospheric models to simulate the global distribution of inert or chemically interacting matter has been organized under WGNE auspices. The planning of a further workshop aimed at assessing how models treat and resolve the size distribution of multiple aerosol types by examining the results of a standard comparative simulation is only moving ahead slowly. The Brookhaven National Laboratory of the US Department of Energy has agreed to act as the focal point for the work, to specify the observational data required, and to evaluate the model results obtained.

3.10 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. 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, and 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).

WGNE noted that the work of the group had so far proceeded by exchange of e-mails, with discussion mainly centred on how to proceed with the assessment of regional models, their utility and application and how to structure the report. 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 WGNE/WGCM panel, but also the sort of ground that might have been covered in a (WCRP) workshop on regional climate modelling. The ad hoc panel was expected to take advantage of the USA workshop and the material presented there in its work, as well as using it as an opportunity for face-to-face discussions (several members of the panel were due to participate in the workshop).

Regarding the scientific questions that it had raised, WGNE observed that many of these had been addressed in the paper by Giorgi and Mearns (JGR, 1999). This had emphasized the need for "customization" of a regional model for its domain of operation. Whilst this could be advantageous, there was uncertainty as to whether the same performance could be expected in a changed climate. Overall, WGNE reiterated its concern at the proliferation and use of regional models without due scientific consideration.

Test of the down-scaling ability of one-way regional climate models

In regard to possible experimentation to show the validity of the regional climate modelling approach (in particular the one-way nesting strategy) as referred to at previous sessions of WGNE (and above), a report was given of work undertaken at the University of Quebec by B. Denis and R. Laprise. Because the validation of a regional climate model is severely limited by the lack of high-resolution detailed climatologies, a "perfect-prognosis" approach was adopted, called the "Big Brother Experiment". This consisted, firstly, of establishing a reference climate using a large-domain high-resolution regional climate model simulation (the "big brother"), which was then degraded by removing scales shorter than 750km that are unresolved in the atmospheric models normally used in climate simulations. The degraded fields were then used to drive a nested regional climate model integrated at the original high resolution except that it is embedded in the big brother domain. The climate statistics were then compared to those of the big brother simulation over the same area. Differences should thus be attributable to errors associated with the down-scaling, not to model errors or observational limitations. Using the Canadian regional climate model of Caya and Laprise at 45km resolution, big brother and nested simulations were carried out for a period of one month (in winter) for a domain over the east coast of North America. The results indicated that the mesoscale features in the big brother experiment were successfully reproduced in the regional climate model domain when driven by the degraded fields from the big brother experiment. The inference was that, at least for the winter month tested, the nesting approach appeared to be reliable. Future experiments using this big-brother framework will be aimed at studying the sensitivity to the resolution jump and to the frequency with which the lateral boundary conditions are updated.

Regional climate modelling at NCEP

Dr. G. White described co-operation between NCEP and COLA in running seasonal forecast experiments with the COLA R40 global atmospheric model coupled with an 80km version of the NCEP/"ETA" regional model over North America. Forecasts of precipitation over the USA in the summer were seen to be substantially improved compared to the forecasts directly from the COLA model, although the flow patterns appeared basically to be very similar in both models. It is not clear whether the improvements result from the increased horizontal resolution and better resolved orography in the ETA model, or whether this model's parameterization was more appropriately "tuned" to the climatological conditions in the USA in the summer.

Recent results from regional climate simulations at Iowa State University

A report was relayed to WGNE on recently completed 25-member ensemble regional climate simulations carried out at Iowa State University examining the variability of precipitation caused by changing the parameterization of deep convection, this being relevant to questions raised by WGNE on the sensitivity of regional climate model results to details of the parameterization of moist processes. In the Iowa State University work, it appeared that the convective parameterization had little effect on the area-mean cumulative precipitation over a region, but a marked influence on the spatial distribution of the precipitation. This was taken as implying that the average precipitation over the regional domain was controlled mainly by the large-scale moisture flux from the lateral boundaries, while the model physics served to redistribute the precipitation within the domain.

3.11 Other climate-related modelling initiatives

WGNE noted with interest reports of important developments in climate modelling activities in Japan and the USA.

Japan

Dr. T. Tsuyuki gave an update on the "Frontier Research Programme for Global Change" in Japan, an ambitious and far-reaching initiative co-ordinated by the Japanese Science and Technology Agency. An extensive range of studies in the fields of climate variations, the hydrological cycle, global warming, atmospheric composition, and ecosystem change was envisaged centred round strong modelling (the "Earth simulator") and supporting observational programmes. A large number of research scientists have now been recruited. A key element is also the computer development required, involving 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 is expected (640 processor nodes each with 8 processing elements with a peak performance of 8 GFlops i.e. 64 Gflops at each node). The total main memory is 10 T bytes (shared memory per node of 16 G bytes).

USA

As reported at the past two sessions of WGNE, steps were being taken in the USA towards a unified weather prediction and climate simulation framework and, more generally, to increase the involvement of the broader US research community in advancing US global modelling activities. An ad hoc US "modelling infrastructure" working group had been set up to guide this effort, but this group was now becoming less important as activities that had been instigated gathered momentum. In regard to setting up a "common modelling infrastructure", NCAR was planning to lead the development of an Earth system model framework, comprising reusable collections of code. This was being proposed as one of a number of scientific "Grand Challenge" investigations solicited by the USA Office of Earth Science and Office of Space Science intended to increase the computing interoperability and performance in a range of earth, space, life and microgravity science applications. The feasibility of exchanging model dynamical cores was also being explored and this had now become a component of the US Department of Energy's Accelerated Climate Prediction Initiative (ACPI), of which one objective (the "Avant Garde Project") is to develop a modular, portable climate system model. Concerning data standards, the aim is to achieve agreement on standard data attributes (i.e. information describing what the data are and how they are stored, including grid information). Climate and forecast metadata conventions for NetCDF were also being discussed.

As a complement to the foregoing, a "Weather Research and Forecast" (WRF) modelling system was being planned as a step in the process of developing an advanced mesoscale forecast and assimilation system and as a means of promoting closer ties between research and operational groups. This effort was bringing together NCEP, the NCAR Mesoscale and Microscale Meteorology Division, the NOAA Forecast Systems Laboratory and the Oklahoma University Center for Analysis and Prediction of Storms. Additional collaborators included the US Air Force Weather Agency, GFDL, NASA/GSFC Atmospheric Sciences Division, the NOAA National Severe Storms Laboratory, the NRL Marine Meteorology Division, the Atmospheric Modelling Division of the US Environmental Protection Agency, and a number of university groups. Development teams looking at numerics and software, data assimilation, analysis and validation, operational implementation, and community involvement have been established.

4. DATA ASSIMILATION AND ANALYSIS

4.1 Reanalysis projects

At ECMWF, the ambitious and comprehensive 40-year reanalysis project (ERA-40) has received support from the European Commission for a three-year period. Several years of preparatory work have now culminated in the first year of experimental production (September 1986-August 1987) using a 60-level T159 forecast model coupled with an ocean wave model. Using this as a spin-up, production of a first stream 1987-2001 had begun (but with a slightly updated version of the model to overcome problems noted with the phase of the S2-tide). A much wider selection of data sources is being used for ERA-40 than the earlier fifteen-year reanalysis project (ERA-15). This includes a full set of TOVS raw radiances beginning in October 1978 with the original TIROS-N observations. With regard to conventional data, a merged set bringing together many sources (NCEP/NCAR, COADS, US Navy, Canadian and Russian snow observations, Australian Antarctic information, data from the University of Wisconsin and the British Antarctic Survey), as well as the ECMWF operational data base, has been assembled. A surprisingly large amount of extra data is available (in particular a significant increase in the number of radiosonde and pilot wind soundings from NCEP). Radiosonde biases have been calculated since 1957. Special attention has been paid to the assimilation of the satellite radiance data, with the operational system being modified to include raw radiances from the HIRS and SSU instruments that have flown (with the MSU instruments) on TOVS satellites since 1978. More generally, there has been significant technical development of the assimilation system to meet the needs of ERA-40 and many of the deficiencies noted in ERA-15 have been rectified (e.g. the time continuity of the analyses, wind speed over the oceans, the Hadley circulation (with a double ITCZ over the Pacific now being produced), stratospheric humidity (now evolving realistically), annual cycle in tropical stratospheric winds).

The original NCEP/NCAR reanalysis from 1948 is continuing to be carried forward to the present in a quasi-operational manner (two days after data time) and has now been extended to a total period of nearly 53 years. The ready accessibility of the reanalysis either electronically or on CD-ROM has encouraged its wide exploitation in many parts of the world (e.g. the majority of papers at the recent conference on Southern Hemisphere Meteorology made use of the NCEP/NCAR reanalysis). As noted above, NCEP co-operated with ECMWF in producing a merged data set of conventional data holdings, in which it was found that NCEP had significantly more data than ECMWF. It is hoped that this merged data set of conventional observations can be used for all future reanalyses. Regarding further reanalysis activities, a joint NCEP/DOE reanalysis (NCEP-2) for the period 1979-1999 has now been completed (available electronically). This was based on an updated forecast model and data assimilation with corrections for many of the problems seen in the original NCEP/NCAR reanalysis, and also provided improved diagnostic outputs. The possibility of extending the second reanalysis backwards pre-1979 is being explored. A regional reanalysis over the USA is also being prepared for the period 1979-2003 (and will then continue on in quasi-real time), using a 32km resolution, 45-layer model. Particular features will be assimilation of precipitation (using a nudging technique) and fixed and evolving bias corrections to radiances. Streams of input information will include SSM/I ocean surface wind speed and total column precipitable water, surface land observations, three-hourly US air force nephanalyses, cloud-top pressures (from HIRS), snow-depth analyses, reanalysed sea surface temperature, and hurricane position, depth and radius of maximum wind. The expectation is that the regional reanalysis will offer a superior product for the North American sub-continent taking advantage of the intrinsic ability of regional models to offer more detailed results for domains of interest than global models, as well as exploiting the boundary conditions provided by the existing global reanalysis to drive a regional system.

WGNE noted with interest that the Japan Meteorological Agency was also studying the feasibility of undertaking a reanalysis project, with particular emphasis being given to the behaviour of the Asian monsoon and tropical cyclones.

4.2 Observing system and observation impact studies

WGNE was informed of activities by a number of groups at the international level to assess the potential effect of changes in observing systems. In particular, the WMO/CBS Expert Team on Observation Data Requirements and Redesign of the Global Observing System has instituted a rolling review of user requirements combined with an objective critical assessment of the capabilities of observing systems. A "statement of guidance" aimed principally at influencing the design of future satellite programmes is being prepared. The WMO/CBS Expert Team to Evaluate the Impact of Changes in the Global Observing System on the Global Data Processing System has carried out a study of the impact of the loss of Russian Federation RAOBs on NWP skill in the northern hemisphere. However, the variability of scores/verification statistics is too great for this approach to give any conclusive results: parallel observing system experiments were needed. The second CGC/WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction was held in France in March 2000. Compared to the previous meeting of the group in 1997, more attention was given to the impact of satellite data on NWP, to the use of targetted observations, and to experiments with more advanced data assimilation methods. A summary of the main conclusions is being prepared which will be considered by the appropriate WMO working groups and/or expert teams and then by CBS itself. This should lay the foundation for further impact studies (e.g. observing system experiments) to provide guidance for the redesign of the Global Observing System.

4.3 Developments in data assimilation/analysis systems at operational centres

A number of participants in the session gave information on the latest developments in the implementation of data assimilation/analysis systems at their centres, and on related work and activities.

UK Met Office

Dr. A. Lorenc reviewed changes introduced into the Met Office global 3DVAR assimilation in May 2000, namely:

(i) use of observed rather than retrieved TOVS/ATOVS radiances;
(ii) a revised background error covariance model;
(iii) use of the first-guess field at the correct observational time.

A significant advance in forecast scores had resulted, the second change above giving the largest contribution, and the third leading to improvements in important cases of rapid developments. Item (i) was the correction of an error introduced when direct use of radiances replaced 1DVAR retrievals in 1999. The impact of the correction was much less than the original change. Also, the experience with the meso-scale limited area system had provided a basis for improved 3DVAR covariances as well as to many small refinements in using data during the year. Further changes to exploit better particular observations were planned for early 2001. The assimilation has additionally been helped by improvements in various model parameterizations. Other developments are the conversion of the (separate) stratospheric assimilation system to 3DVAR, and to modifying the assimilation suites to use the "New Dynamics" version of the Met Office Unified Model.

NCEP

Dr. G. White highlighted a number of the main enhancements in global data assimilation at NCEP over the past year. In July 2000, the tropical cyclone initialization procedure was changed so as to relocate storms to positions provided by the Tropical Prediction Center, leading to significant benefits in forecasting cyclone tracks. In October 2000, an improved ozone analysis and forecast were introduced, upgrades made to the way rawindsonde data were used, and a higher resolution orography brought in. At the end of 2000, it was expected that GOES-10 radiances, NOAA-15 AMSU-B data, and precipitation from SSM/I and TRMM would be assimilated, as well as NOAA-16 AMSU A/B and HIRS data if available. Refined data selection and quality control algorithms would also be implemented. By the middle of 2001, it was planned to include a prognostic cloud water/ice scheme and related improvements to the radiation scheme in the assimilation model, and cumulus momentum mixing which should have the effect of reducing false forecasts of tropical storms.

For longer-range predictions and climate forecasts, the importance of modelling and appropriately initialising the land surface and the oceans as well as the atmosphere is being increasingly realised. NCEP has duly developed a land data assimilation system (largely for North America) and an ocean data assimilation system (employed for initialising the ocean component in coupled ocean-atmosphere seasonal forecasts). The former is based on a land surface model elaborated jointly by NCEP, Oregon State University, the US Air Force, and the US National Weather Service Office of Hydrology. The model comprises four soil layers, and explicit physical treatments of the vegetation canopy and snow pack, and can be coupled to an atmospheric model or run in stand-alone mode. In coupled mode, the precipitation and insolation forcing from the atmospheric model can have significant drifts, but the assimilation of precipitation being implemented in the regional reanalysis (see section 4.1) and in the operational "ETA" model next year, could well reduce the drifts. (In the stand-alone mode, precipitation and insolation come directly from observations).

For the ocean data assimilation, measurements are available from the Tropical Atmosphere Ocean (TAO) moored buoy array, the XBT network, surface drifters and island tide gauges as well as satellite-observed sea surface temperature and altimetric data, and ARGO temperature profiles. A 3DVAR system is employed (now being modified for use with the global GFDL MOM-3 model that is being adopted as the ocean component of the NCEP coupled model). For the analysis of sea surface temperature, a new (2DVAR) technique is being developed, as is inference of salinity variations from altimetric data.

In the mesoscale atmospheric data assimilation system, satellite radiances have been included since September 2000, with plans to make use of precipitation from April 2001, and WSR-88D radial velocities in June 2001. An improved 3DVAR system with adaptive anisotropic error fields and assimilation of cloud observations is expected to be introduced in late 2001.

In the field of observing system studies, an experiment is being planned at NCEP to investigate whether loss of RAOB data in the Russian Federation may have affected the quality of NCEP analyses and forecasts. A preliminary examination of the verification scores of operational forecasts from several centres had not given any conclusive result. NCEP and the NOAA Forecast System Laboratory had also jointly organized a North American Observing System experiment to assess possible redundancy between radio-sonde data and the profiles of temperature and wind produced automatically during the climb and descent of commercial aircraft (MDCRs). It was concluded that radiosonde ascents could not be fully replaced by the present MDCR profiles. In another initiative, observing system simulation experiments to study the impact of lidar wind observations from satellites were now underway at NCEP.

Dr. White finally noted that a joint NASA/NOAA Center for Satellite Data Assimilation had been proposed with the goals of: developing a common NASA/NOAA model and data assimilation infrastructure for application to satellite data assimilation projects; developing a community-based forward radiative transfer model for assimilation of satellite data; accelerating development of techniques and algorithms for current satellite data, including GOES and QuikSCAT winds, GOES sounding data, GOES and POES data over land, and DMSP sounding data; and preparing for advanced new satellite instruments (such as AIRS, SSM/IS, GPS, GIFTS, IASI, CrIS).

Meteorological Service of Canada

Dr. B. Dugas summarized the main developments in data assimilation at the Meteorological Service of Canada. A new version of the 3DVAR scheme on η-levels had been implemented including the capability of assimilating TOVS radiances (Level 1d) and ACARS. Analysis increments were also defined directly on model levels. The advantages of the new system were an improved vertical resolution, particularly in the boundary-layer, a better framework for the assimilation of surface data, and refinements to the background-error covariance model. Attention was being given to assimilating additional types of observations or other information including conventional data (surface information, radiosondes at 43 significant levels), raw radiances (TOVS/ATOVS, Level 1b), total precipitable water (SSM/I), surface winds (ERS-2, SSM/I), data from AIRS and IASI. At the same time, work was going ahead in the development of 4DVAR assimilation (in a massively parallel environment) with an implementation target of 2003.

JMA

Dr. T. Tsuyuki outlined the recent changes in the JMA operational data assimilation system and those foreseen. As from January 2000, NESDIS ATOVS/BUFR data were being assimilated in the global and regional analyses. In March 2000, an analysis of global snow depth using SYNOP data was implemented, as well as a 1DVAR system for ATOVS radiance data in the global analysis. Also, a mesoscale analysis (one-hour cycle of a 3D optimum and physical interpretation scheme) had been undertaken on an experimental basis. Looking to the future, it was planned to replace the computer system (with an SR 8000) and to make a major upgrade of the whole NWP system (see also section 5.4), including introduction of 3DVAR for the global analysis in late 2001 and a 4DVAR scheme for the mesoscale analysis in early 2002. For the latter, an incremental approach would be followed with an outer loop model of resolution 10km (161x289) L40 and an inner loop model of 20km (181x145) L40.

Météo-France

Dr. P. Bougeault pointed to two important milestones passed in June 2000 in the Météo-France assimilation system. The first was the assimilation of ATOVS radiances, the second the replacement of the intermittent 3DVAR scheme by a 4DVAR continuous assimilation. The new system utilized similar observation screening and quality control as had the 3DVAR scheme, but with hourly time-windows, and a multi-incremental version of minimization. An original simplified physics is employed and the digital filter initialisation algorithm has been replaced by a specific J_c term in the cost function.

ECMWF

Dr. M. Miller reported on the main sets of changes in the operational suite at ECMWF during the past year. In October 1999, a new method for deriving background errors statistics, the use of 10m marine wind-speed retrievals from SSM/I radiances, a revised bias correction of MSU and AMSU-A radiance data, and a corrected use of sonde and SYNOP humidity observations were all implemented. Extensive pre-operational tests of these changes (together with the model modifications made at the same time, (see section 5.4) demonstrated considerable improvements in the quality of the summer 1999 forecasts, and the winter 1999-2000 medium-range forecasts had the lowest ever rms geopotential errors (although this is believed in part to be a result of interannual variability). A second set of changes in April 2000 (better suppression of humidity increments in the stratosphere; revised SSM/I quality control, bias correction, thinning and use of second satellite; use of coastal ship and buoy winds in the extratropical southern hemisphere; relaxed quality control of dropsondes; minor modifications to the wave model and analysis) were not as far-reaching and thus only had a modest impact on performance. In June 2000, revised observation and background error variances, a revised snow analysis, and the use of more TOVS/ATOVS data (HIRS-12, AMSU-14, less constraint on AMSU-8; more off-nadir data) were implemented.

Further operational changes are being prepared to improve the implementation of 4DVAR, notably to gain full benefit when using a longer 4DVAR time-window. A problem in twelve-hourly cycling seems to stem from the difference in resolution between the models used in the incremental inner and outer loops. The situation is improved when higher resolution inner loops are used, so decreasing the discrepancy with the main forecast model. In this respect, the recent development of the adjoint of the semi-Lagrangian scheme offers a good opportunity to reduce the differences in resolution. Several potential enhancements to the 4DVAR background error term are also being assessed. Versions of a revision to the balance operator have been tested which use a transformation to potential vorticity and geostrophic departure (instead of vorticity and unbalanced divergence as currently) with the objective of making better use of temperature data.

A further aspect of work in this area is the testing of a reduced-rank Kalman filter. Such a filter system does alter the 4DVAR analysis increments along the unstable manifold, meaning that growing analysis errors are correctly identified, but the analysis does not appear to be systematically improved along these directions. Preliminary results also suggest that a reduced-rank Kalman filter does not lead to closer fitting of observational data in sensitive areas when compared to the plain 4DVAR indicating that further work is needed in the design of the background error term.

5. NUMERICAL WEATHER PREDICTION TOPICS

5.1 Short- and medium-range prediction

The World Weather Research Programme

Dr. R. Carbone, Chairman of the Scientific Steering Group for the CAS World Weather Research Programme (WWRP), reviewed progress in implementing the programme. Projects already initiated or being conducted under the auspices of WWRP include the Mesoscale Alpine Programme (MAP), the Sydney 2000 Forecast Demonstration Project, and the Aircraft In-Flight Icing Research and Development Project. In MAP, which has the objective of improving understanding of orographically-induced intense precipitation, the quality and quantity of data collected during the Special Observing Period (7 September-15 November 1999) were highly encouraging. The data sets are already widely accessible and new research is underway, particularly in the area of flood prediction, and developing and validating coupled atmospheric and hydrological models. In the Aircraft In-Flight Icing Project, several interesting preliminary findings have also emerged on characterizing the icing environment and in detecting hazardous icing conditions. The preparation of a global climatology of freezing precipitation has also begun.

With regard to the Sydney 2000 Forecast Demonstration Project, a presentation was given to WGNE by Dr. T. Keenan. The goal of the project had been to demonstrate the capability of modern forecast systems and to quantify the associated benefits in the delivery of very short term weather forecasts. As part of the project, various "now-cast" methods were extensively tested during the period of the Sydney Olympic Games. Among systems deployed were Doppler, conventional and polarimetric radars, and enhanced surface synoptic observations were collected. These were coupled to a comprehensive forecast infrastructure. This included: the Australian Bureau of Meteorology "Spec PROG" providing one-hour radar-based precipitation forecasts; the UK Met Office "NIMROD", six-hour automated precipitation forecasts based on radar observations and a numerical model; the (UK) University of Salford "GANDOLF", three-hour thunderstorm forecasts using a conceptual model of their life-cycle; the Meteorological Service of Canada's "CARDS", one-hour severe weather identification (rain, hail, downbursts) based on three-dimensional radar data; NCAR's "Autonowcaster", two-hour thunderstorm and rain forecasts based on Doppler radar, satellite data and low-level winds derived from a computer model; the US National Severe Storms Laboratory "WDSS", automatic two-hour severe weather identification (rain, hail, tornadoes, high winds etc.) from three-dimensional radar data. The Sydney Olympics were, of course, potentially a very "high impact" weather situation, and it was encouraging, for example, that the capability of detecting hail-producing thunderstorms was demonstrated beforehand (although such an event did not occur during the Olympics themselves).

Other WWRP projects in planning are concerned with tropical cyclone landfall, The Hemispheric Observing System Research and Predictability Experiment (THORPEX), and the "Mediterranean Experiment" (MEDEX) with the objective of studying cyclones that produce high impact weather in the Mediterranean. Also being considered are projects on sand and dust storms, urban weather and flood prediction, warm season rainfall and flooding, and an urban forecast demonstration projection, particularly concerned with air quality, in connection with the Olympic Games in Athens in 2004.

WGNE expressed interest in many of the WWRP projects and expected to contribute significantly in various respects. The most important co-operation between WGNE and the WWRP would certainly be in the planning and implementation of THORPEX whose goal is to develop and demonstrate the utility of a mix of in situ and satellite observing systems. Representatives from WGNE, including Dr. A. Lorenc as co-chair, have participated in the International Science Working Group considering the planning of THORPEX, the status of which was reviewed at the WGNE session. Clearly, theoretical and numerical research would be fundamental to the success of THORPEX (including such aspects as identification of atmospheric regimes that produce weather systems with low predictability, localising sensitive areas, development of new observing strategies, and investigation of the practical predictability of different flow regimes). WGNE stressed that the THORPEX science plan should contain a thorough description of the scope of the research envisaged and procedures for co-ordinating this research. Noting that THORPEX would be an organized observing system test of innovative observing technologies, both in situ and satellite, WGNE advised that the following points should be taken into account:

- THORPEX should not be an attempt to redesign the Global Observing System (but restricted to considering new observing technologies and approaches);

- in field campaigns, the deployment of several observing systems to give some possible redundancy was encouraged;

- effective deployment of observing systems based on numerical and theoretical studies of both network design and synoptic targetting when possible, sufficiently in advance to influence the detailed design of the field campaigns: these studies should take into consideration the requirement to improve forecasts of fields with significant societal impacts (with observing system experiments after campaigns to verify this has been achieved);

- adequate resources (preferably from the same sources as the observations themselves) would have to be provided for the numerical experimentation support, since the operational NWP centres could not be expected to put in the considerable efforts required.

The International Science Working Group had now concluded its task and would be replaced by a THORPEX Science Steering Committee, supported by a number of focussed sub-committees in areas such as data assimilation, observing systems and verification, and impacts. Appropriate liaison members to other relevant groups (such as WGNE, CLIVAR, GEWEX/CEOP) would also be appointed. Dr. A. Lorenc agreed to serve as a WGNE representative.

CAS policy statement on "Scientific basis for and limitations of forecasting weather and climate"

As noted in section 1, CAS had been requested by the President of WMO, Dr. J. Zillman, to draft a brief policy statement on the "scientific basis and limitations of forecasting weather and climate". Whilst the final responsibility for the preparation of the statement rested with the CAS Advisory Working Group meeting in May 2000, WGNE and the Scientific Steering Group for the WWRP were expected to contribute much of the basic material. Since the target audience was end-users of weather and climate information, and even lawyers, the statement should not be a technical treatise but convey, in lay terms, a sense of the underlying scientific and technical approaches followed and the overall levels of skill. The length of the statement was envisaged as about 3 to 5 pages.

A number of WGNE members stressed the care that must be taken in drafting such a statement, especially if it were to be used in litigation. Advice from legal experts would be required, and use should be made of similar statements that had already been prepared by such professional groups as the American Meteorological Society. The Chairman of WGNE would contact members following the session concerning the compilation of a summary of the current state of knowledge. The most positive way to proceed would be if a "strawman" statement could be drafted to which all could add individually (in much the same way that the WGNE statement on regional climate modelling had been composed following the session of WGNE in November 1998).

Performance of the main global operational forecasting models

WGNE reviewed the skill of daily forecasts from a number of the main operational centres as presented to the session by Dr. M. Miller. Examples of the twelve-month running means of verification scores (root mean square error) for 500 hPa geopotential in the northern hemisphere at lead-times of one and three, and five and seven days, are shown respectively in Figures 1 and 2. For most centres, in particular ECMWF, a distinct increase in skill is apparent over the past year. This was in contrast to the previous year, where levels of skill actually seemed to decrease temporarily (with the exception of NCEP that benefitted in 1999 from the inclusion of microwave radiances from AMSU-A in their global data assimilation system). In the

Figure 1.

Figure 2.

tropics, it was sobering to note that, despite the major developments in models and data assimilation systems in many centres in recent years, little improvement in skill was evident (in such fields as winds at 850 hPa).

Scores such as rms errors, anomaly correlations, skill scores provide good objective measures of large-scale model performance. However, with global models, attaining higher resolutions and mesoscale models being routinely run at several operational centres, consideration needs to be given to moving beyond these gross scores which are not appropriate for such models. Furthermore, there is an increasing requirement to provide measures of model performance in predicting weather elements and severe weather events. As a first step in this direction, it was agreed that WGNE should draft a position paper on model verification. Dr. P. Bougeault agreed to prepare a text for discussion at the seventeenth session of WGNE.

Intercomparison of typhoon track forecasts

Dr. T. Tsuyuki reported that the intercomparison of forecasts of typhoon tracks in the western North Pacific that has been conducted by the Japan Meteorological Agency on behalf of WGNE for a number of years has now been extended to include Atlantic hurricane forecasts, and will, in the near future, be further extended also to cover the east Pacific and Indian Oceans. Relevant data from operational forecasts have been made available from ECMWF, the UK Met Office, and the Canadian Meteorological Center. The overall gradually improving performance of these models in predicting cyclone tracks and intensity in the western North Pacific over the past few years has been maintained. In the (North) Atlantic, the distance error was on the whole a little less than in the western North Pacific region. However, a bias in the zonal direction of the track prediction seems to be a systematic error common to the participating models for both the western North Pacific and Atlantic regions. A technical report summarizing the results over the period 1991-2000 is being prepared by JMA. WGNE endorsed the call for additional global operational centres to submit forecasts for the intercomparison.

Dr. N. Davidson (BMRC) summarized the main features of and results being obtained from the BMRC Tropical Cyclone Limited Area Prediction System that became operational for the southern summer 1999-2000 (see also section 5.4). The system comprises four main components: a four-dimensional data assimilation to construct the "large-scale environment" and the outer structure of the storm; a specification of the vortex to build a circulation consistent with the observed location, size, intensity and past motion of the storm; a high-resolution objective analysis to incorporate the synthetic vortex into the large-scale environment; a (diabatic, dynamical nudging) initialization to balance the vortex and insert satellite-defined convective asymmetries; and a high resolution prediction with the BMRC limited-area model which includes high-order numerics and advanced physical parameterizations. Generally, an encouraging level of operational performance is being achieved (for 14 storms, mean track errors ranged from 14km at 0 hours, to 144km at 24 hours, and 229km at 48 hours). Although the sample of operational forecasts is somewhat limited, two systematic problems have been noted. Firstly, a low wind speed bias in the boundary layer reduced the skill of the intensity forecasts, and secondly, the system occasionally performed poorly for weak storms (apparently an issue of vertical structure). Hindcasts with a revised boundary layer parameterization indicate that considerably more accurate forecasts of intensity are possible. The system is being developed, including improved data assimilation, upgrades to the vortex specification especially for weak storms, increased horizontal resolution, new parameterizations and a prognostic cloud scheme.

The "COMPARE" project

Dr. T. Hogan relayed a report to WGNE on the results of the third in the series of case studies taken up in the "COMPARE" project (Comparison of Mesoscale Prediction And Research Experiments) that had been reviewed at a workshop in Tokyo, Japan, in December 1999. The Japan Meteorological Agency led the organization of this study, which comprised a series of experiments centred on the Tropical Cyclone Motion/SPECTRUM/TYPHOON Experiment (TCM-90) over the northwest Pacific (Tropical Cyclone "Flo"). Among the main findings were that the position forecast for the tropical cyclone and its structure were extremely sensitive to characteristics of the vortex as defined in the initial conditions (GFDL, JMA and NCEP analyses with and without bogussing). The vortices in GFDL-bogussed analysis appeared to be too large, which resulted in the track of "Flo" being influenced by another tropical cyclone ("Ed") in the same region. In supplemental experimentation with higher resolution models, even with grid spacings as low as 3km, there was difficulty in predicting the intensity of the tropical cyclone with much precision. Moreover, the actual observed cyclone track lay outside the envelope of the ensemble of the forecasts (cf. results of using targetted diabatic singular vectors as initial perturbations in generating ensemble predictions of cyclone tracks noted in section 5.2).

There are still a number of interesting questions relating to the results of the third COMPARE study which merit being followed up. Thus, work on a further COMPARE case has been deferred for the time being. In the future, it is foreseen that the Meso-scale Alpine Programme may well provide a suitable data sets for interesting phenomenological experimentation. However, following advice given by WGNE, the approach adopted in COMPARE is being reconsidered, possibly on the lines of identifying a small number of specific scientific questions to be taken up which groups could address quasi-independently.

Verification and intercomparison of precipitation forecasts

Several centres are now pursuing activities in this loosely co-ordinated WGNE initiative. Dr. E. Ebert described the work at BMRC. A number of numerically-produced quantitative precipitation forecasts over Australia have been verified for a three-year period (September 1997-August 2000) against the Australian operational daily rain gauge analysis. Noticeable differences are apparent in the ratio of forecast to observed rain frequency among various NWP models, especially in cases of higher precipitation amounts. Most models showed a low bias in prediction of rain frequency in the cool season (June, July, August). In the warm season (December, January, February), there was a tendency for models to overestimate rain frequency on all but occasions of the most intense precipitation events. The skill in forecasting the actual rain intensity, measured by an equitable threat score, did not show much variation in the tropics (typical scores of 0.20-0.30 during summer and winter). Greater skills were apparent in mid-latitudes with scores of 0.35-0.50 during winter and 0.30-0.45 during summer. However, this skill was a strong function of intensity, peaking for rainfall rates of less than 5mm/day, but falling off rapidly for higher rates. There was also a strong seasonal trend (but, interestingly, not regional) in the relative skill of different models, with that performing best in winter not showing similar relative skill in summer and vice versa. With respect to the location of rain areas, systematic errors were seen in forecasts in the tropics (rain areas too far to the south). Errors in longitudinal positioning tended to be less marked. Overall, there was no clear trend towards improved skill in the quantitative precipitation skill forecasts over the three-year period studied, although such a trend would in any case be difficult to detect compared to interannual variability. In the tropics, the model forecasts outperformed persistence only during the spring period, but, in mid-latitudes, persistence was bettered in all seasons.

At BMRC, a "poor man's" ensemble of the available quantitative precipitation forecasts has also been constructed and verified. The ensemble mean had lower RMS errors and higher equitable threat scores than any of the individual models in the majority of cases, and the position of the rain areas obtained by meaning was also improved. Probabilistic forecasts from the ensemble of rain rates showed good skill at twenty-four hours, but less at 48 hours. An approach for simultaneously reducing the area bias and increasing the maximum rain rates (which were artificially lowered as a result of averaging) has been explored. This produced ensemble quantitative precipitation forecasts that looked more realistic, but also increased the RMS errors by a small amount. A probability matching method has also now been examined, whereby the spatial distribution of rainfall was determined by the ensemble mean, but rain rates transformed to have the same rain-rate frequency distribution as the ensemble: this appears to give even further improved deterministic forecasts.

At DWD, Dr. W. Wergen reported that quantitative global precipitation forecasts from CMC, DWD, ECMWF and NCEP continued to be verified against the extensive and dense network of German and Swiss stations (4000 locations). Forecasts from JMA had also been included since August 2000. Very little trend in the various scores computed was apparent, except for a reduction in bias in some models.

Dr. G. White noted that NCEP has been routinely verifying short-range forecasts from the NCEP meso-scale "ETA" and global models, as well as from the ECMWF global model against a high density network of raingauges in the continental USA. There is a clear increase in skill over the last seven years.

WGNE was also informed that both the UK Met Office and Météo-France were beginning activities in the area of quantitative precipitation forecasting. WGNE looked forward to a report documenting results from the centres carrying out work in this area being prepared by Dr. E. Ebert (BMRC). (This could possibly lead to an article in, for example, the Bulletin of the American Meteorological Society).

5.2 Ensemble prediction

Use of ensembles to give an idea of the likely spread of predictions, to provide a basis of the probability of different results occurring, and for computing ensemble means which may have more skill is now very much a cornerstone of forecasting or climate projections on all timescales. Recent years have seen remarkable progress in the application and use of ensemble prediction systems underpinned by rapid advances in the provision of singular vectors, initial perturbed states, etc. At its sixteenth session, WGNE reviewed the status of work in this area.

Dr. T. Palmer (ECMWF) led the discussion, showing several examples of the power of the ensemble approach in picking out useful predictability. For example, in increasing the resolution of an ensemble prediction forecast model, probabilistic skill scores such as that of Brier were seen to advance by a much larger margin than the skill of the deterministic control forecast. A possible explanation for this type of finding is that a particular event may be poorly forecast by the control integration, but can be reasonably captured by a number of ensemble members. Increasing resolution may only slightly change the performance of the control integration, but can significantly improve the predicted evolution by ensemble members which had already given some indication of the event.

Another valuable approach has been the use of targetted diabatic singular vectors in the tropics as initial perturbations in generating ensemble predictions of tropical cyclone tracks. It has been found that the ensemble spread may now generally encompass the actual track whereas, previously, there was only a relatively small spread of predictions. Furthermore, preliminary results of using singular vectors with humidity as a component of the initial perturbations show that faster growth rates were achievable in summer than winter, consistent with the observation that forecast error doubling times are shorter in summer than winter.

The use of the concept of "potential economic value" is now coming into use as a measure of ensemble performance. For instance, in the case of extreme weather events, the value of an ensemble-mean forecast is plainly limited. Optimal value can be obtained by using the full probability distribution obtained from the ensemble prediction system. The potential economic value can also be significantly enhanced by increasing the number of members of the ensemble. Generally, ensemble prediction readily lends itself to commercial applications. For example, an electricity forecast demand model can be driven successively by all the members of an ensemble, thereby deriving a forecast probability distribution of electricity demand. The mean of this probability distribution has been shown to be a more skilful prediction of demand than could be obtained either by a state-of-the-art statistical model, or a demand forecast based on a (high-resolution) deterministic NWP model prediction.

The status of, and specific developments, in ensemble prediction systems at a number of centres were presented, in particular the application of "poor man's" ensembles, e.g., the ensemble of quantitative precipitation forecasts over the Australian region created from a number of available operational products (see description above); experiments on multi-model multi-analysis ensembles for medium-range forecasting at the UK Met Office. This latter work has demonstrated that an ensemble of Met Office Unified Model forecasts added to ECMWF's operational ensemble improved Brier skill scores compared to a similar sized ensemble from a single model. The Met Office is also putting substantial efforts into developing methods for displaying and interpreting ensembles (again using the ECMWF operational ensemble). This includes research into techniques for providing automatic guidance for the issue of severe weather warnings up to five days in advance. Furthermore, prompted at least partly by the mixed quality of the forecasts of severe weather in Europe in December 1999, the Met Office and NCEP are jointly leading international collaboration to test a "poor man's" ensemble of near-real time forecasts, particularly of surface parameters such as wind and precipitation, from the main global operational centres. WGNE encouraged the continuing investigation of the "poor man's" ensemble technique in view of the encouraging potential demonstrated and which was, at the same time, a cheap and simple means of obtaining an objective ensemble of forecasts.

Among the developments at other centres, at ECMWF, the model used in the operational ensemble prediction system was being upgraded from a resolution of T159L40 to T255L40, with an extensive range of experimentation having been undertaken to explore the impact. As noted above, increase in resolution produced improvements in skill (as measured by a Brier score) and offered enhanced potential economic value. Other aspects of work going ahead at ECMWF include:

- study of whether improved singular vectors for the ensemble prediction system can be obtained using the reduced rank Kalman filter (see also section 4.3);

- comparison of the ECMWF prediction system to "poor man's" ensembles; unlike results from some other comparisons, the "poor man's" ensemble was not found to give an advantage at any lead time in predicting 500 hPa height anomalies;

- the potential merit of using targetted observations to improve forecasts of severe weather in the short and early medium-range; results suggest that impact from additional observations in the data sparse regions is very much a function of the analysis error that needed to be corrected.

Dr. M. Naughton described the development of the Australian Bureau of Meteorology medium-range ensemble system over the past two years and implemented in a quasi-operational trial since mid-2000. The ensemble is comprised of 33 10-day forecasts from the global spectral model (at resolution T79L19). The perturbations used in generating the initial states for the ensemble numbers are (like the approach of ECMWF) linear combinations of the 16 fastest growing (T42L19) singular vectors for linearized evolution from the basic flow for the initial 48-hour forecast period (localized from 20°S to 90°S). The ECMWF rotation strategy is employed to give a greater geographical spread for each of the initial perturbations than just those from the singular vectors themselves. The ensemble itself then comprises the unperturbed control forecast of the Bureau of Meteorology global spectral model (run at T79L19) with Eulerian advection (although a T119L19 semi-Lagrangian version and longer timestep is being considered), and 32 perturbed forecasts from states with 16 rotated perturbations applied with positive and negative signs. A uniform perturbation scaling coefficient is chosen to give a "reasonable ensemble" spread in the medium-range period, and is intended also to approximate analysis uncertainty. One of the major challenges is to extract in an optimal form for operational meteorologists the information that can be inferred from the dispersion of the ensemble. The standard types of ensemble displays are being utilized (e.g. "spaghetti" diagrams of one or two contours of the 500 hPa field, ensemble means and outlying traces indicating the extremes of the ensemble) together with diagnostics such as ensemble spread and skill. Running on the Bureau of Meteorology's NEC SX-4 supercomputer, the singular vector computation takes about two hours CPU time, and the ensemble forecasts 16 hours, but further optimisation is in hand.

Dr. H. Ritchie reported that the ensemble prediction system used operationally at the Canadian Meteorological Center was based on 16 members, with initial perturbations generated by "breeding of growing modes". Eight members are produced using the Canadian spectral forecast model at T95 resolution and the other eight, added in the past year, from the Global Environmental Multi-scale (GEM) model (see also section 5.4) on a uniform 1.875° grid. One particular feature is the use of different physical parameterization and/or numerical options in each ensemble member in an attempt also to represent the uncertainty resulting from model errors. Products include "spaghetti" plots, charts indicating the probability of precipitation etc. The improved performance of the 16-member system over the earlier 8-member version is definitely apparent. Looking to the future, the intention is to add further probabilistic products, and to increase the resolution of models and the size of the ensemble. Research is also progressing with a Kalman filter ensemble system. Following experiments with simple models, data assimilation cycles are being carried out using the GEM model on a 144x72x23 grid (cycles are being simulated including synthetic radiosonde, SATEM and aircraft data and "reasonable convergence is being obtained with a pair of 50-member ensembles).

Dr. Chen Dehui informed WGNE that a 32-member ensemble prediction system using a T106L19 model at the National Meteorological Centre of the China Meteorological Administration had been implemented in quasi-operational mode in December 1999. Perturbations for generating the initial states for the various ensemble members are based on singular vectors obtained from a T21L19 adjoint model. Information produced includes ensemble mean fields at 500 hPa, "spaghetti" diagrams, probability of precipitation and/or temperature above/below certain limits. The ensemble mean forecast shows some improvement in comparison with the control run, but the ensemble spread is too small, with the predictions for each member often being too similar.

Dr. G. White outlined the implementation of the "Short-range Ensemble Forecast (SREF) project" at NCEP, based on the development of a multi-regional model and 0-3 day ensemble prediction system that would provide operationally relevant and useful guidance on the probability distribution of weather elements or events, in particular quantitative precipitation forecasts. The system was being built round the NCEP "ETA" model (with a 48km horizontal resolution), ten members (regionally-bred initial state perturbations), and twice daily runs out to 60 hours. Products included ensemble mean and spread charts, and "spaghetti" and probability diagrams. Routine runs and systematic evaluation commenced in April 2000. Among questions being actively addressed were the perturbation strategies (both in the initial conditions and model version), the tradeoffs in different model configurations (resolution, ensemble size, domain etc.), and product development. The effect of using different convection schemes would also be tested in the near future. With regard to the NCEP global ensemble prediction system, the effect of a change in resolution of the model from T62 to T126 for the first sixty hours had given a very large positive impact. The ensemble mean was now equal to or better than the control from the outset, the verifying analysis was encompassed considerably more frequently than before, and the T170 forecast was less often "the best member".

5.3 Long-range and seasonal forecasting

A few participants highlighted developments at their home institutions in long-range and seasonal forecasting. At the Canadian Meteorological Centre, an ensemble of twelve forecasts up to a season ahead, comprised of six from the RPN Canadian spectral forecast model and six from the CCCma general circulation model, are produced. Analyses at 5, 4, 3, 2, 1 and 0 days prior to the beginning of the season are used to provide the initial conditions, and forecasts are run with persisted anomaly sea-surface temperatures. The twelve forecasts are combined by a best linear unbiased estimate combination. Temperature anomalies in above, near-normal, or below, equi-probable categories are then produced using a perfect prognosis approach together with precipitation anomalies in a similar three category classification (obtained more directly by comparing forecast precipitation amounts to model climatologies). The projections for a particular season are also accompanied by an indication of the percentage expected to be correct based on the verified performance during a test period 1969-1994. Over the four years the system has been in operation, forecast skill has varied from below the 33% obtainable by chance to a maximum of 88% during the strong El Niño winter 1997-1998. For longer periods ahead (two, three or four seasons), temperature and precipitation anomalies over Canada are obtained from a canonical correlation anomaly method based on the principal components of sea-surface temperature EOFs over a 35-year period (1956-1990). Future plans include preparation of 90-day dynamical forecasts every month, elaborating more probabilistic products, blending dynamical and empirical forecasts, and improving and evaluating new models.

NCEP seasonal predictions employ a coupled system in which the atmospheric component is a version of the operational medium-range global spectral model at resolution T42L28 with modified physics. The oceanic component is Pacific basin model with two tier coupling to the atmosphere. Ocean data assimilation is performed weekly. The atmospheric model is run once a month to produce a 20-member ensemble of 7 month predictions. Forecast sea surface temperature from the ocean model is used as a boundary condition in the equatorial Pacific: elsewhere, the initial sea surface temperature state is damped towards climatology. Over the continents, soil moisture and snow cover are set to climatological conditions initially but evolve in interaction with the predicted changes in the atmospheric circulation. An ensemble mean and model bias (determined from the mean and spread of the model climatology from a 10-member ensemble of 20-year hindcasts) are subtracted from the predictions, allowing a probabilistic anomaly forecast to be inferred. In the warm season, an additional 10-member ensemble of forecasts is prepared with analysed soil moisture over the USA in the continental boundary condition, leading to increased skill in the prediction of the 2m air temperature.

Seasonal forecasts continue to be made on a routine basis at ECMWF. From as early as October 1999, an end to the La Niña conditions that prevailed during 1999 and into 2000 was indicated to occur in the first part of 2000; this has now been observed. Moreover, the model correctly predicted a halt to the rapid temperature rise in December 1999, and that this would not lead to an El Niño situation. Overall, the observed sea surface temperature has lain in the range of the forecast ensemble over the past year (there were several earlier periods when this was not the case). A new configuration (Version 2) of the ECMWF seasonal forecasting system is now nearing completion, with an updated version of the atmospheric model (as being used in the ECMWF reanalysis, see section 4.1, except that there are only 40 levels) and a different approach used in determining the ocean initial conditions. Monthly forecasting, using the same coupled system as for seasonal forecasting, is now also being planned. Ocean perturbations for generating the forecast ensemble have been implemented and tested; the atmospheric perturbations will be generated as for the medium-range ensemble prediction system.

The UK Met Office is developing a coupled forecast version of its Unified Model system, and is participating in the "Development of a European Multi-model Ensemble system for seasonal to inTERannual prediction" (DEMETER) that is aiming to assemble a multi-model ensemble of seasonal forecasts (the models are being installed at ECMWF). The UK Met Office operational monthly and seasonal forecast ensembles use an atmosphere-only system with persisted sea surface temperature anomalies.

5.4 Recent developments at operational forecasting centres

As well as the information on developments in operational data assimilation/analysis systems presented in section 4.3, ensemble prediction systems in 5.2 and some details on progress in long-range and seasonal forecasting in section 5.3, a number of reports were given by participants in the WGNE session from the main operational forecasting centres. As usual, constructive discussions on problems or aspects of mutual interest took place.

Deutscher Wetterdienst

After several years preparation, the new fourth generation NWP system became operational at DWD on 1 December 1999. The system comprises a global model (triangular grid, 55km resolution) and a non-hydrostatic regional model (formulated on a rotated lat/long grid with a spacing of 7km). The initial state for the global model is prepared by an intermittent three-dimensional multivariate assimilation scheme

(6-hour cycling), an optimum interpolation analysis and an incremental digital filter initialization. The regional model uses a nudging method of assimilation. December 1999 was, of course, a very challenging time for all forecasting systems. The short-range predictions of the storm that swept across central Europe on 26 December from the new DWD system fell short in capturing the exceptional intensity of the event. However, the longer-range predictions (beyond 36 hours) gave a much better indication. Subsequent experimentation revealed that the length of the observation window used in the assimilation for the global model was crucial. The traditional window of three hours centred around the analysis time can lead to a "smearing" of sharp structures in fast evolving systems. Reducing the window to ninety minutes resulted in dramatic improvements in the quality of the forecast. The shorter window has been used operationally since May. There have also been a number of problems with the NESDIS retrievals used in the global model assimilation, leading to the exclusion of SATEM data between 19 November 1999 and 3 May 2000. For the first six weeks, the lack of data did not appear to cause significant degradation, but from January onward, the skill of forecasts in the southern hemisphere was adversely affected.

China Meteorological Administration

A significant upgrade of the operational system at the National Meteorological Centre of the China Meteorological Administration is planned for 2001. The resolution of the global model, currently T106L19 will be increased to T213L31, and a quasi-3DVAR assimilation system will be implemented in place of the existing optimum interpolation scheme. The high resolution limited-area forecast system, currently running at a resolution of 55km with 20 levels, will be essentially unchanged, but the supporting optimum interpolation data assimilation will also be carried out at 55km instead of 110km as at present. It was also foreseen that the resolution of the typhoon track prediction model would be increased from 50 to 25km, and the number of levels from 16 to 20.

JMA

As noted in section 4.3, JMA was acquiring a new computer system in March 2001 (a Hitachi SR8000/E1 with 80 nodes, a peak performance of 768 Gflops, and main memory of 640 Gbytes). The number of levels in the global model (T213) would be increased from 30 to 40 (top level 10 hPa to 0.4 hPa), and the forecast period extended (from 8 to 9 days for the 12Z run, from 84 to 90 hours for the 00Z run). Four extra levels (36 to 40) would be added to the regional model (horizontal resolution 20km) and the domain expanded from 257 x 217 points to 325 x 257. The meso-scale model (horizontal resolution 10km), which has been run experimentally since 1998, would be implemented operationally (with 40 levels and a domain of 361 x 289 points). The horizontal resolution of the typhoon model would become 24km (instead of 40) (domain size 271 x 271) and the number of levels increased from 15 to 25. The ensemble prediction system, running experimentally with a T63L30 model and 9 members, would come into operational production (T106L40 model and 25 members). Significant changes in physical parameterizations were also planned in late 2001, including revision of land-surface processes (updated snow scheme, introduction of frozen soil, multi-level model for soil temperature calculation), and implementation of a prognostic cloud water scheme in the regional, mesoscale and typhoon models.

Bureau of Meteorology

It was noted that the current operational suite of global and limited area models at the Australian Bureau of Meteorology consisted of:

- the global prediction assimilation system, horizontal resolution T_L239 and 29 levels;
- the limited area prediction system, horizontal resolution 0.375°x 0.375° and 29 levels;
- the tropical limited area prediction system with the same resolution;
- the mesoscale limited area prediction system, horizontal resolution 0.125°x 0.125° and 29 levels;
- the tropical cyclone limited area prediction system with the same horizontal resolution as the tropical system and 19 levels (see section 5.1 for more details of the tropical cyclone system).

The meso-scale model is now used for a wide range of applications. In particular, the real-time availability of predictions from this model, and from an experimental 0.05°x 0.05° version during the Sydney Olympics and Paralympics, provided very useful forecast guidance. The operational implementation of the tropical cyclone limited area model, including a detailed generation and initialization of the vortex, has given significant improvements in forecasts of the track and intensity of cyclones.

Another recent initiative has been the development of an air quality forecasting system as a collaborative project between BMRC, CSIRO and the Environment Protection Authorities, with funding from Environment Australia. The 0.05°x 0.05° version of the mesoscale model is being run twice daily for domains covering Melbourne and Sydney, with hourly output then being used to drive a CSIRO photochemical model. Results in the form of two-dimensional fields, time series and time-height cross sections are provided to the Environmental Protection Authorities. The overall system was being evaluated over the four month period August-December 2000 covering the period of the Olympics and Paralympics in Sydney. The performance was generally encouraging, particularly in the simulations of sea breezes and other topographically forced flows, and of boundary layer heights.

Meteorological Service of Canada

Development (jointly by Recherche en Prévision Numérique, RPN and the NWP Development Division of the Canadian Meteorological Center) of the unified Global Environmental Multiscale (GEM) system continues. The basic concept is a single model for all applications - data assimilation (3DVAR and 4DVAR), forecasting at various scales/ranges, climate simulation, prediction of air quality, emergency response, coupling with the ocean etc. The basic system, semi-Lagrangian, fully implicit, offers a wide variety of options: running with uniform or variable resolution; various grids (global, regional, a "VORTEX" grid, limited area); hydrostatic or non-hydrostatic. A range of forecasts are produced at a range of resolutions and lead times (to 1 day, 10km resolution once per day; to 2 days, 24km resolution twice per day; to 8 days, 100km resolution, once per day; to 10 days, 200km resolution once per day; to 30 days, 250km resolution twice per month; to 90 days, 250-400km resolution four times per year). The computing facilities comprise 2 SX-4 (32 processor) machines and 2 SX-5 (16 processor) machines and a parallel shared memory GEM model is currently operational; a new distributed version is being developed.

NCEP

The CRAY C-90 at NCEP was replaced in November 1999 by an IBM-SP configuration with 896 processors and 256 Gbytes of memory, offering a fivefold increase in computing power. This configuration was being further upgraded in November 2000 to 2048 processors and 1024 Gbytes of memory, offering a further six-fold increase of power. Taking advantage of the extra computer capacity, the resolution of the operational medium-range forecast system was increased from T126L28 to T170L42 in January 2000, and in May the aviation forecasts from 00Z to 12Z were both extended to 126 hours. In June, the resolution of the ensemble forecasts was increased from T62 to T126 up to 60 hours (see also section 5.2). Several model changes have also been introduced or are being planned. As from October 2000, a new orography, filtered in the highest wave number to limit "ringing", has been employed. Over polar regions, a reduced grid has been implemented. A new albedo climatology and aerosol shortwave radiative properties are now being used. Changes have been made to the radiative transfer scheme to reduce a warm bias over northern hemisphere continents. During 2001, refinements in the pipeline include a prognostic cloud water/ice scheme (together with other related improvements to the radiative scheme), a cumulus momentum mixing scheme (which should help reduce false forecasts of tropical storms), and a modification to cloud overlap assumptions (if clouds are not in contiguous layers, a random overlap assumption is made, this having the effect of increasing total cloudiness and further contributing to removing the warm bias over northern hemisphere continents). In the longer-term, a new model dynamical core (with a hybrid vertical co-ordinate and with entropy as a thermodynamic variable), a new long-wave radiation scheme (GFDL), a resolution increase to T254L64, and an extension of the high resolution ensemble up to 3 days are all being planned.

With regard to the mesoscale "ETA" model, the 00 and 12Z forecasts have been prolonged to 60 hours as from March 2000, the use of VAD wind observations (with a new quality control) was reinstated, the analysis has been modified to allow RAOB balloon drift, and the deep convection parameterization changed to reduce bias in the quantitative precipitation forecasts. In September 2000, the resolution of the "ETA" model was increased (from 32km to 22km horizontally, and from 45 to 50 levels in the vertical) and the domain extended by 900km westward. Direct assimilation of satellite radiances over the ocean has now been included. Other model changes made were a reduction in horizontal diffusion and the addition of vertical advection of cloud. In the next few months, the 00Z and 12Z runs will be further extended (up to 84 hours). Furthermore, the land-surface model (see also section 4.3) will be updated as a step in improving the treatment of frozen soil and land surface fluxes, and to be able to introduce the assimilation of precipitation. The resolution will be increased to 12km, and, in the vertical, to 60 levels.

ECMWF

In parallel with the developments in the operational data assimilation at ECMWF (as reported in section 4.3), a range of model changes was also made. In October 1999, sixty levels in the vertical were introduced for the analysis and deterministic forecast, and forty for the ensemble prediction scheme. The cloud and deep convective parameterizations were modified, and a new global orography and associated subgrid fields came into use. In April 2000, a limit was placed on the stratospheric tendency from the gravity-wave drag parameterization, and two errors, one in the calculation of the clear-sky precipitation fraction, the other in the (diagnostic) stratocumulus scheme, were rectified. In June 2000, more substantial changes were made (which also defined the model for the ERA-40 reanalysis, see section 4.1). These included a tiling parameterization scheme for the land surface, lying snow and sea ice, offering considerable potential to improve near surface forecasts and the use of sounding data over land. A new longwave radiation computation (the Rapid Radiation Transfer Model) having an accuracy comparable with the best line-by-line models), a refined ozone model, and an improved treatment of precipitation processes in the first timestep were also introduced. Much other work is in hand, including particularly the development of a new treatment of entrainment into cumulus updraughts, based on a revised vertical velocity equation, as well as revisions to the triggering of convective downdraughts and the formulation of the convective momentum transport. Tests are underway to prepare for operational implementation. Further investigation is aimed at understanding and correcting the model failure to predict correctly the diurnal cycle of convection over land. Several data assimilation and forecast experiments have been run at a resolution of T_L511L60 in preparation for implementation of such a deterministic model operationally. The mean scores of a set of 200 cases indicate a consistent improvement over the current operational system that is statistically significant at 99% level. An important issue is the adequacy of atmospheric circulation models in simulating flows over and near complex terrain (as already identified at this session of WGNE, see section 3.7). An extensive numerical study has been conducted of the treatment of stratified and rotating flows using the Scandinavian peninsula as an example. It has been found that present NWP models are able to capture "smooth" flow (i.e. on scales of 50km) very well, although the effective model resolution may be two to four times lower than the actual grid depending on the methods employed and the character of the flow itself. At finer scales (e.g. 5km) where the natural terrain may be truly complex, the semi-Lagrangian approach becomes unsatisfactory as a result of difficulties with accurate representation of the lower boundary conditions. Finite volume Eulerian schemes may also require a higher degree of implicitness than anticipated in this context.

6. OTHER WGNE ACTIVITIES AND FUTURE EVENTS

Publications

One publication has been produced in the WGNE "blue-cover" numerical experimentation report series since the fifteenth session of the group, namely the annual summary of research activities in atmospheric and oceanic modelling (No. 30, produced in February 2000). The next publication (No. 31) would be the latest annual summary of research activities, which it was planned again to print and distribute directly from Montreal. However, it was agreed that it would now be timely to offer the possibility of electronic submission of contributions, and to make available an electronic version of the complete publication. The WGNE mailing list also needed to be updated. Thus numerical modellers and the other scientists on the list would be asked in the usual annual call for contributions to confirm addresses and electronic co-ordinates and whether an electronic version of "Research Activities in Atmospheric and Oceanic Modelling" would in the future be acceptable or whether a hard copy was preferred. (In any case, report No. 31 would be prepared in hard copy only). It was also agreed that future calls for contributions to "Research Activities in Atmospheric and Oceanic Modelling" (as well as other communications from WGNE such as notification of workshops, conferences etc.) will be distributed electronically, and thus the importance of providing an up-to-date e-mail address should be emphasized. With regard to the content of the reports, WGNE suggested that any information, notification of, or reports on workshops of interest to the numerical modelling community as a whole should be included (e.g., the next report would certainly include the summary of the Workshop on Model Systematic Errors in Melbourne, 16-20 October, see section 3.1).

Next session of WGNE (and GMPP)

At the kind invitation of Deutscher Wetterdienst, the next session of WGNE, the seventeenth, would be held in Offenbach, Germany, 29 October-2 November 2001. Information on detailed arrangements for the session would be distributed in due time. The session would be held jointly with the (fifth) meeting of the GEWEX Modelling and Prediction Panel. As well as the usual agenda, other items that could be taken up included an assessment of the performance of models in high latitudes, data assimilation in relation to THORPEX, and further discussion of the use of "poor man's" ensembles. Verification of cloud forecasts and representations in models was another key issue that had not received much attention but which was becoming increasingly important. Another point made was that the presentations of centres operational activities in the areas of data assimilation and developments of forecasting systems should be refined, and, in particular, that a synthesis or overview of the main thrusts, state of the art, outstanding problems at operational centres generally should be prepared. The possibility of organizing a short workshop just preceding the WGNE in Offenbach (e.g. from 24-26 October) will also be explored. One subject suggested that could be usefully reviewed and discussed was that of verification generally and how this should be approached (scores that could be used for the varying range of fields produced by models, e.g., geopotential fields, precipitation, clouds).

7. CLOSURE OF SESSION

All participants expressed deep gratitude to Dr. K. Puri and the staff of BMRC for all the work put in and efforts made that had made the two weeks stay (for the Workshop on Systematic Errors and the WGNE session itself) so productive and enjoyable. All had very much appreciated the excellent support, facilities and hospitality that had been offered. Participants particularly asked that their thanks be relayed to Dr. J. Zillman, Director of Meteorology, for having agreed to host these meetings at the Bureau of Meteorology and to Dr. M. Manton, Chief Scientist of BMRC. The opportunity to interact with so many leading scientists at BMRC and to hear first hand of the excellent research and work going ahead had also been very valuable.

The sixteenth session of WGNE was closed at 1307 hours on 27 October 2000.

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MAIN FINDINGS AND CONCLUSIONS FROM WORKSHOP ON MODEL SYSTEMATIC ERRORS Melbourne, Australia, 16-20 October 2000

The problem of model errors was assessed from many different perspectives. The workshop was organized in five principal sessions on atmospheric circulation and structure, the tropics and representation of variability, fluxes, alternative methods and diagnoses, and the treatment of physical processes. The topic of alternative approaches to analysing and diagnosing model errors was particularly the subject of attention and discussion. This represented a considerable contrast to an earlier workshop on model systematic errors organized by WGNE (Toronto, Canada, October 1988) which had mainly been a succession of papers looking at errors on time scales up to a few days in NWP products and in atmospheric climate integrations on a relatively simple time- or spatially-meaned basis. Now, a far greater range of techniques and diagnostic tools was available, and being exploited, to explore characteristics and causes of model systematic errors.

Comparing the results from the present workshop to that in Toronto in 1988 demonstrated strikingly what had been achieved over the past twelve years, what had been learned and where difficulties remained. Most notable is the marked decrease in errors, especially in short- and medium-range weather forecasts. Thus a majority of studies at this workshop were concerned with errors in longer time-range predictions (up to extended and seasonal) and in long-term atmospheric climate and coupled model integrations. However, there may be merely a delay in onset, since errors, with the same sort of signature, still appear (with gradually increasing magnitude) at around ten days or so. What has undoubtedly helped is a general improvement in understanding the nature of model errors, allied with practical advances such as the finer model resolutions that can now be employed in the vertical and horizontal. There has also been much progress in the representations of physical processes, in particular of radiative transfer and cloud/radiation interaction, of deep convection and of the surface and boundary layer. The major steps forward in data assimilation (especially use of variational methods) and in model initialisation will also have contributed significantly to a reduced error growth in the early stages of predictions. The workshop agreed that there had not been any one single "breakthrough", but rather incremental advances resulting from detailed work and study of individual aspects of models one by one. Certain shortcomings that remained persistent, pointed to by many workshop participants, are in the treatment of marine stratus and the representation of the polar tropopause. A new problem since the Toronto workshop are the large errors and climate drift that appear in the coupled ocean-atmosphere models that have been developed over the past ten to twelve years. These are naturally more complex than those in atmospheric models alone, and are proving to be even more intractable.

Another major change since 1988 has been the organisation of many co-ordinated model intercomparison projects (in particular, the Atmospheric Model Intercomparison Project, AMIP and the Coupled Model Intercomparison Project, CMIP at PCMDI, Lawrence Livermore National Laboratory). These projects have provided a crucial framework for diagnosing model errors, intercomparing the performance of different models, and, in some cases, an improved understanding of the nature of errors. Nevertheless, as demonstrated by results presented at the workshop, model intercomparison projects are only a starting point, and there is no substitute to investigating in detail model simulations and the parameterisations of the physical processes employed, and how they may contribute to errors. In this respect, the increased degree of unification/co-operation between NWP and climate model development was a very positive development. Examining changes at as high frequencies as possible (even timestep by timestep) could be very revealing of non-physical behaviour. Careful evaluation of the treatment of synoptic weather systems by models was also required. In this context, short model integrations, but saving much more diagnostic information, could complement the analysis of long runs. For this type of in-depth diagnostic study, the re-analysis data are particularly useful, and the workshop strongly encouraged and supported the ERA-40 and NCEP regional analysis initiatives. Data assimilation statistics also contained a wealth of information and the differences between the first-guess field and observations at few hours could indicate areas of sensitivity.

At the same time, it was fully realised that observations and data from field experiments were essential to tie down specific uncertainties in fields such as surface fluxes, as well as in assessing and improving the representation of model physical processes (e.g. TOGA-COARE had provided a wide range of information on air-sea interaction and the role of convection in tropical ocean areas, and pointed the way to the type of physics that should be included in models).

Although many presentations illustrated that the treatment of clouds and radiation in models continued to be a fundamental source of error, the workshop recognized that other potential sources of error should not be overlooked. Amongst these, the parameterisation of the effects of orography (based on the use of variances to capture sub-grid scale effects) was inadequate in some circumstances, and attention should be paid to this. There also remained fundamental questions on the interaction between the different physical processes in models, as well as with model dynamical cores. Aqua-planet experiments could be a useful tool in this respect. In coupled models, it was seen that there is a very wide variation in the relative resolutions used for the atmosphere and ocean. A basic assessment of the appropriate relative (optimum) resolutions was needed. Furthermore, research into the extent to which model systematic errors impact climate sensitivities should be urgently undertaken.

Consideration was given to the possibility that neglect of sub-grid variability could influence significantly large-scale variability and mean systematic error. Non-local stochastic parameterizations have been proposed to account for these effects. Preliminary results indicate that these schemes can have a significant effect on coupled-model systematic error on seasonal and longer timescales. Current schemes are somewhat crude and ad hoc, but more sophisticated schemes are under development.

The question of exchanging parameterizations between models as a means of assessing the performance of parameterization of models was raised, in turn leading to a discussion of "plug compatibility". Several pointed out that parameterizations schemes are intimately coupled with other aspects of the model formulation and thus can behave poorly when removed from their host model. On the other hand, this lack of inter-operability and interchange draws into question the reproducibility of model results. Furthermore, without intercomparison and interchange, many groups may follow exactly the same line of development, and not derive the (potential) value from the differences in development paths.

The use of empirical corrections as a remedy to systematic errors was briefly discussed. This was generally considered undesirable, although possibly serving a purpose to correct mean fields for certain applications and for specific diagnostics.

The issue of errors in regional climate models was also briefly reviewed. As well as several basic technical questions that had been raised by WGNE (although these were not considered too serious by some groups), a basic concern was that unless the large-scale variability (ENSO, seasonal cycle etc.) was properly represented in the driving global model, there could only be limited confidence in the variability of, or changes in, local climate simulated by regional models. It was suggested that other means of downscaling might also be explored such as statistical methods (but these were subject to the criticism that the statistics may alter in a situation of changed climate).

Looking to the future, the workshop stressed the importance of continuing and refining model intercomparison projects. Not only were such intercomparisons of great assistance in pointing to model errors, but they reinforced the credibility of the modelling community in being seen to be seriously assessing the verisimilitude of model performance. Furthermore, through these projects, sets of model results were readily available to the general scientific community and were an important means of involving developing countries in using model results and, thereby, for "capacity building". Nevertheless, there was some concern about the "proliferation" of model intercomparisons, and the workshop advised that intercomparisons should be carefully and comprehensively designed and co-ordinated to maximise their effectiveness. In particular, it was noted that the atmospheric component of the models included in CMIP were not in general those that had been submitted for AMIP; the desirability of carrying out the AMIP exercise with CMIP atmospheric models was underlined.

The workshop observed that the strength of model intercomparisons could only be realised by accompanying diagnostic sub-projects and these should be vigorously pursued. It was emphasised that an improved range of standard diagnostics should be readily obtainable (derived using standard readily available software), especially for monitoring features such as the diurnal cycle and the strength of the Madden-Julian Oscillation. It was recognised that another important application of model intercomparison projects was a basis for multi-model ensembles and studying results of model simulations and climate change predictions in a probabilistic manner, offering the prospect of many new valuable insights in the future. There was, however, no doubt that an innovative approach to handling the ever-increasing amounts of data involved was required (probably based on the use of distributed data serving systems with a meta-data Centre). This was especially the case with coupled models, where it was becoming necessary to look at long periods of ocean/atmosphere model fields at relatively high time resolutions (e.g. for studying variability at interannual to decadal time scales). This again linked to the requirement of standard data formats and diagnostic tools.

All participants agreed that the workshop had been helpful and productive, with many useful interactions and discussions. The idea of having a further such workshop in three to four years time was strongly supported. In addition to the type of discussions at this workshop, it was expected that ocean modellers could also contribute in an important manner.