DIAGNOSIS OF THE PERFORMANCE OF TROPOSPHERE-MIDDLE ATMOSPHERE MODELS

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Abstract

An overview is given of our ability to simulate the state of the middle atmosphere. Results from the GRIPS project suggest that while most of the large-scale features of the atmosphere can be simulated, the details are subject to great uncertainty. Important feedbacks between chemical processes, radiation and climate are discussed.

1 Introduction

Over the past two decades, the increasing recognition of the radiative impacts of ozone have motivated the development of general circulation models (GCMs) which extend up to the stratopause and beyond. This allows investigation of the climatic impacts of ozone change, first studied in the GCM context by Fels et al. (1980), as well as interactions between stratospheric cooling caused by CO_2 increases and the ozone problem (e.g., Shindell et al. 1998). It also allows the radiative impacts of middle atmospheric ozone and temperature to be accounted for in the retrieval of temperature and trace gas distributions from satellite radiance measurements. Further, locating the upper boundary well above the region of primary interest minimizes the impacts of unphysical wave absorption and/or reflection, giving more confidence in simulations of the troposphere.

Recognizing the need for detailed study of the role of middle atmospheric processes in the climate system, the World Climate Research Programme (WCRP) supported the project "Stratospheric Processes and their Role in Climate" (SPARC). The importance of model simulations of the coupled middle atmosphere/climate system has been recognised by SPARC by the initiation of the "GCM-Reality Intercomparison Project for SPARC" (GRIPS): details are given in WCRP (1998) and Pawson et al. (2000). Some results from this model intercomparison will be given in section 2 of this manuscript. Section 3 contains a discussion of important areas of current research for climate modelling, forecasting and data assimilation.

Table 1: Modelling groups which are participating in GRIPS, showing details of the group and its location along with the primary reference for the paper.

Acronym	Length (years)	Group and location	Reference
MA/CCM2	5	NCAR, Boulder, CO, USA	Boville (1995)
UCLA	5	Univ. of California, Los Angeles, CA, USA	Kim et al. (1998)
CMAM	10	Canadian Middle Atmosphere Model (AES, University of Toronto and York University)	Beagley et al. (1997)
SKYHI	12	GFDL, Princeton, NJ, USA	Hamilton et al. (1995)
GISS	10	NASA GISS, New York, NY, USA	Rind et al. (1988)
MRI/lrf	10	MRI, Tsukuba, Japan (Long-Range Forecasting)	Chiba et al. (1996)
MRI/clim	10	MRI, Tsukuba, Japan Climate Group	Kitoh et al. (1995)
FUB	10	Freie Univ. Berlin, Germany	Langematz and Pawson (1997)
ARPEGE-climate	20	CNRM, Météo France, Toulouse, France	Déqué et al. (1994)
MA/ECHAM4	10	MPI für Meteorologie, Hamburg, Germany	Manzini et al. (1997)
GSFC GEOS-2 (Version 6.0)	5	NASA GSFC, Greenbelt, MD, USA	DAO (1996)
UK-UM	5	UK Unified Model (UKMO and Univ. of Reading)	Swinbank et al. (1998)
LaRC IMPACT	4	NASA LaRC, Hampton, VA, USA	Fairlie et al. (1997)

2 The SPARC-GRIPS initiative

2.1 GRIPS: first results

The Atmospheric Model Intercomparison Project (AMIP: Gates 1992; Gates et al. 1999) aims to assess our ability to simulate the terrestrial atmosphere over about the past two decades, using observed distributions of sea-surface temperature and sea ice, prescribed boundary conditions on the radiative exchange with the surface and the sun, and fixed concentrations of the well-mixed trace gases. AMIP has led to a deeper understanding of how well climate models perform, examining standard meteorological fields as well as features of the atmospheric energy budget

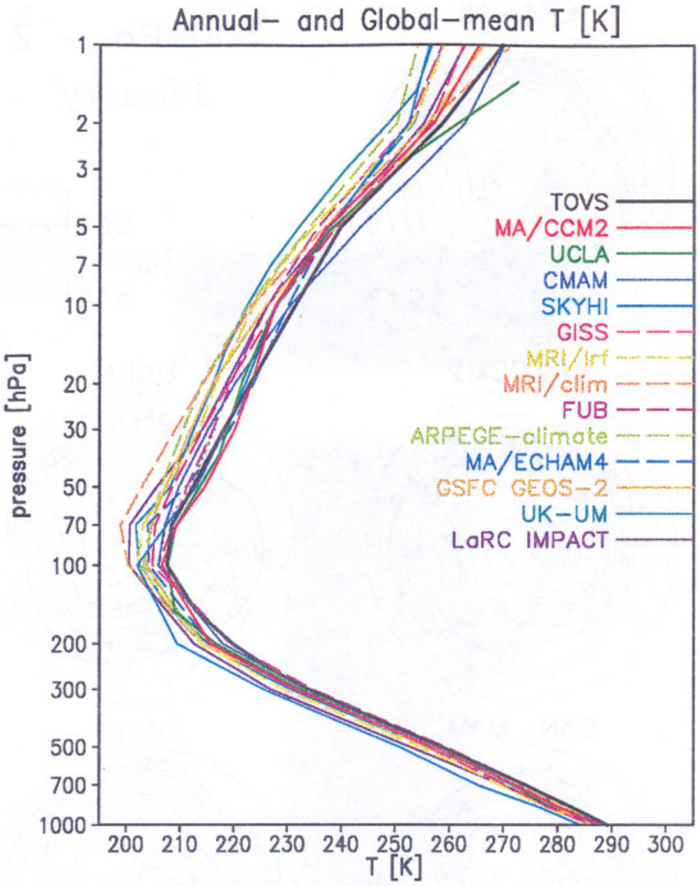

Fig. 1: Global-mean temperatures for January in all of the GRIPS models, along with climatological values (black line).

(more details are given in Gates et al. 1999 and references therein).

Like AMIP, GRIPS aims to validate our ability to simulate the terrestrial climate. The most significant difference from AMIP is that GRIPS concentrates on the middle atmosphere and its climatic impacts. Participation in GRIPS is restricted to climate models (which must include complete representations of the hydrological cycle and radiation transfer) with upper boundaries located at 1 hPa or below. Presently, thirteen models have contributed data to the project (Table 1). A comparison of the basic climatologies of these models (Pawson et al. 2000) reveals the following dominant features:

1. A global-mean cold bias in most models at most levels. This is illustrated by the global-mean temperatures for January in Fig. 1, where the reference climatology is a composite climatology using ERA-15 data (Gibson et al. 1997) at pressures higher than 30 hPa and

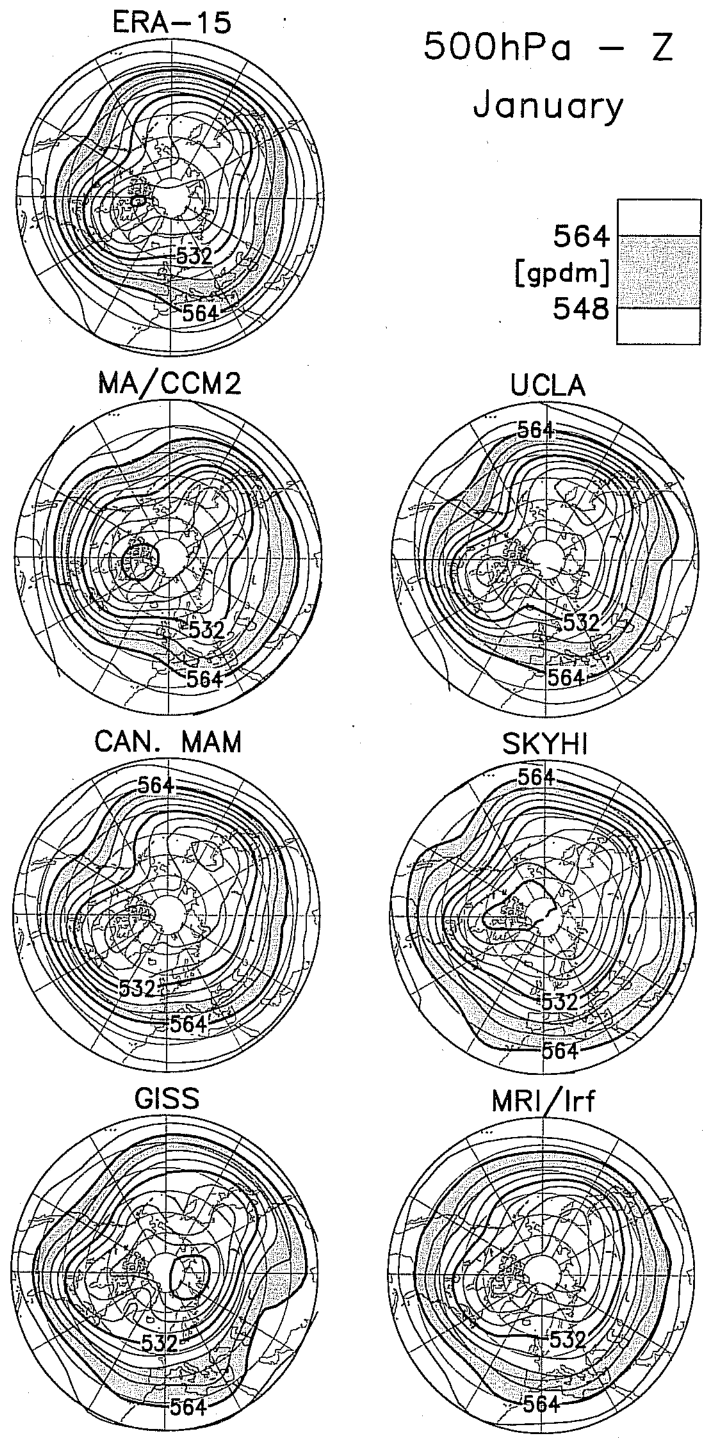

Fig. 2: Polar stereographic projections, from 20°N–90°N, of the multi-year mean geopotential height (gpdm) at 500 hPa in January. The contour interval is 16 gpdm and values in the range 2872–2936 gpdm are shaded. The observational estimate is a 14-year mean from ERA-15 data (Gibson et al. 1997). From Pawson et al. (2000).

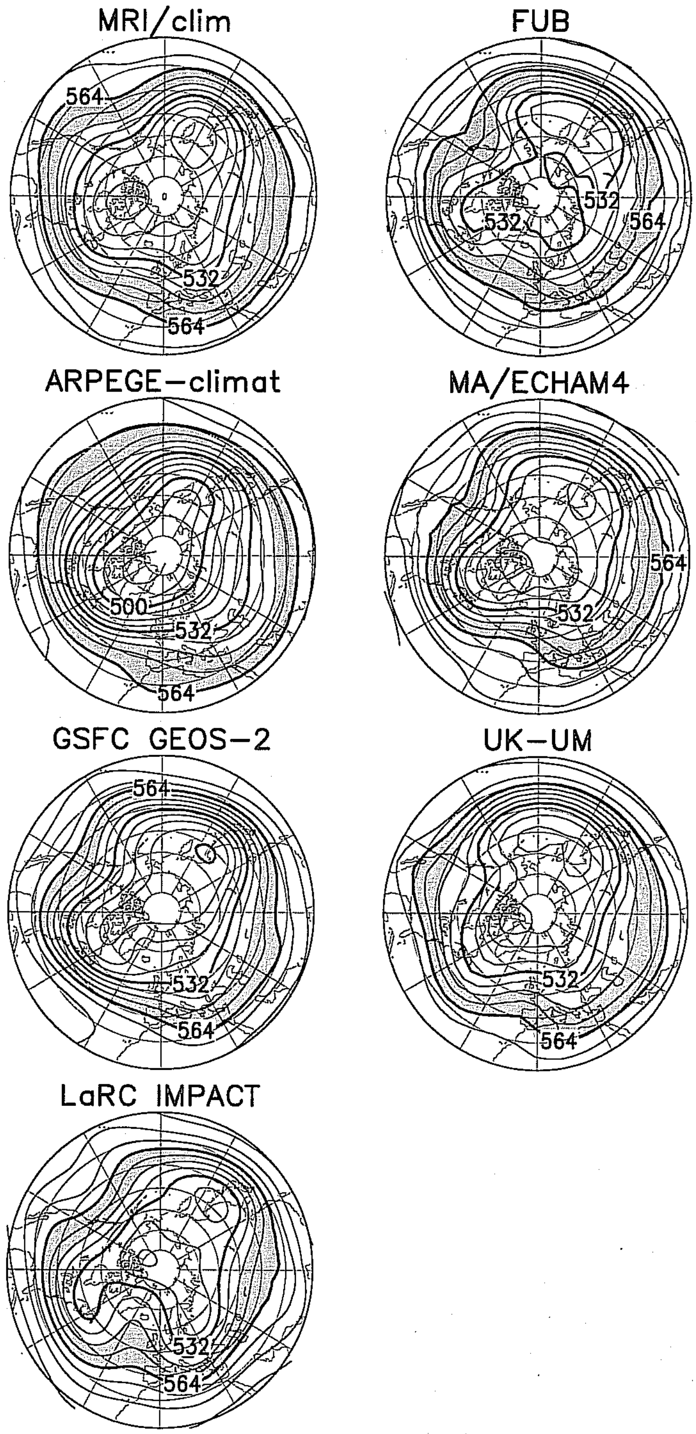

Fig. 2 (continued)

values derived from the Tiros Operational Vertical Sounder (see Bailey et al. 1993) at lower pressures. The cold bias in the stratosphere is indicative of a radiative problem. An initiative has been started to provide a comprehensive evaluation of present radiation schemes: radiative heating and cooling rates calculated using identical input data will be compared to line-by-line models. This comparison will complement the ICRCCM (Ellingson et al. 1991). A further issue which this raises is the sensitivity of the heating and cooling rates to the ozone distribution: many models specify an ozone distribution from observations. One question to be examined is how much the different ozone distributions used by different modelling groups impacts the net heating rates (is this a larger or smaller effect than uncertainties in the radiation codes?).

2. Near 100 hPa, which is in the lower stratosphere at high latitudes but near the tropopause in the tropics, simulated temperatures differ greatly between the models. At high latitudes there is a general cold bias in most models: the magnitude varies from a few degrees to almost 30 K. The persistent nature of the cold bias implies that it arises from physical parametrizations (especially the radiative bias already discussed). Dynamical factors tend to result in warm/cold dipole patterns (caused by anomalous adiabatic descent/ascent at different latitudes). In the tropics, the models can have a temperature bias of either sign: for the zonal-mean temperature at 100 hPa in January the spread is about 5 K in each direction, but most models are able to simulate a temperature within 2 K of the ERA-15 data. Note that the magnitude and nature of the tropical bias is sensitive to the choice of reference dataset: ERA-15 data are close to radiosonde estimates (e.g., Pawson and Fiorino 1998) and are 2–3 K cooler than estimates from the NCEP/NCAR reanalyses (Kalnay et al. 1996): use of this latter dataset would imply that almost all models simulated an overly cold tropical tropopause.

3. The models simulate substantially different planetary wave structures in the troposphere and stratosphere. At 500 hPa most models represent the dominant troughs and ridges which are evident in climatology, but their strength and location can vary substantially (Fig. 2). Some of this bias can arise from (a) the length of the simulation (documented in Table 1) being too short when the natural variability of the atmosphere is considered and (b) the lack of variations in external forcing, since all models were integrated with annually repeating lower boundary conditions (unlike the AMIP experiment which uses year-to-year variations). In the stratosphere there are large departures from observations in some models. Substantial zonal-mean biases in the height fields are related to the thermal structure at lower levels, while differences in the planetary wave structures reflect the upward propagation of disturbances from the troposphere: this is impacted by the strengths of the tropospheric waves themselves and by their ability to propagate on a potentially biased background state. At 10 hPa in January (Fig. 3), typical biases include: (a) an overly

strong wavenumber 2 pattern; (b) an almost zonally symmetric state, more indicative of the southern hemisphere; (c) incorrect phase alignment of the dominant wavenumber 1.

These results clearly show that while many of the models are capable of simulating a reasonably reasonable climate in the troposphere and stratosphere, some models fall far short of this. This would mean that climate prediction experiments, examining the sensitivity of climate to changing trace gas concentrations, would be more meaningful with some of these models than with others. Similarly for the purposes of data assimilation, models with small climatic biases are likely much more suitable than models with large climatic biases, since a bias would continuously require correction by the merging process between observations and model forecasts.

2.2 GRIPS plans for model validation

Apart from the results discussed above, GRIPS aims to evaluate different aspects of the simulations in more detail. In the tropics, models have been unable to simulate a realistic quasi-biennial oscillation (QBO). Horinouchi and Yoden (1998) used a simplified GCM to analyse the requirements for QBO simulations: essentially, an adequate vertical resolution is needed to maintain the vertical shears of zonal wind associated with the QBO; since the QBO is forced by upward-propagating waves forced by convection in the troposphere (e.g., Lindzen and Holton 1968), it is necessary for the GCM to resolve an adequate spectrum of waves to provide the necesary momentum source. Dunkerton (1997) showed that a large part of this momentum must be carried by relatively small scale gravity waves rather than planetary scale Kelvin waves (see Holton and Lindzen 1972), consistent with the analysis of Horinouchi and Yoden (1998) who found that waves of many horizontal scales transport momentum into the middle atmosphere. Takahashi (1996) also found it necessary to reduce the vertical diffusion in his model of a self-maintained QBO. Few complete GCMs have simulated a QBO-like oscillation. Only recently, the ECMWF model (Untch and Simmons 1999) could generate such an oscillation, which proves sensitive to the dynamical core used. Hamilton et al. (1999) showed that doubling the vertical resolution of the GFDL SKYHI model enabled a self-sustaining downward-propagating oscillation to develop. The GRIPS investigation of tropical dynamics will examine the oscillations in the mean flow as well as the upward-propagating wave spectra and their relationship to forcing from the troposphere.

Another important issue concerns the interannual variability at high latitudes. Many models display a realistic coupled link between the troposphere and stratosphere (Kodera, personal communication, 1998), but a full investigation in the GRIPS experiment is restricted by the lengths of the model runs: it turns out that 20 years of integration are necessary to obtain a stable correlation, and few of the models have been integrated for so long. On shorter timescales, the ability of models to generate stratospheric sudden warmings is being investigated; Rind et

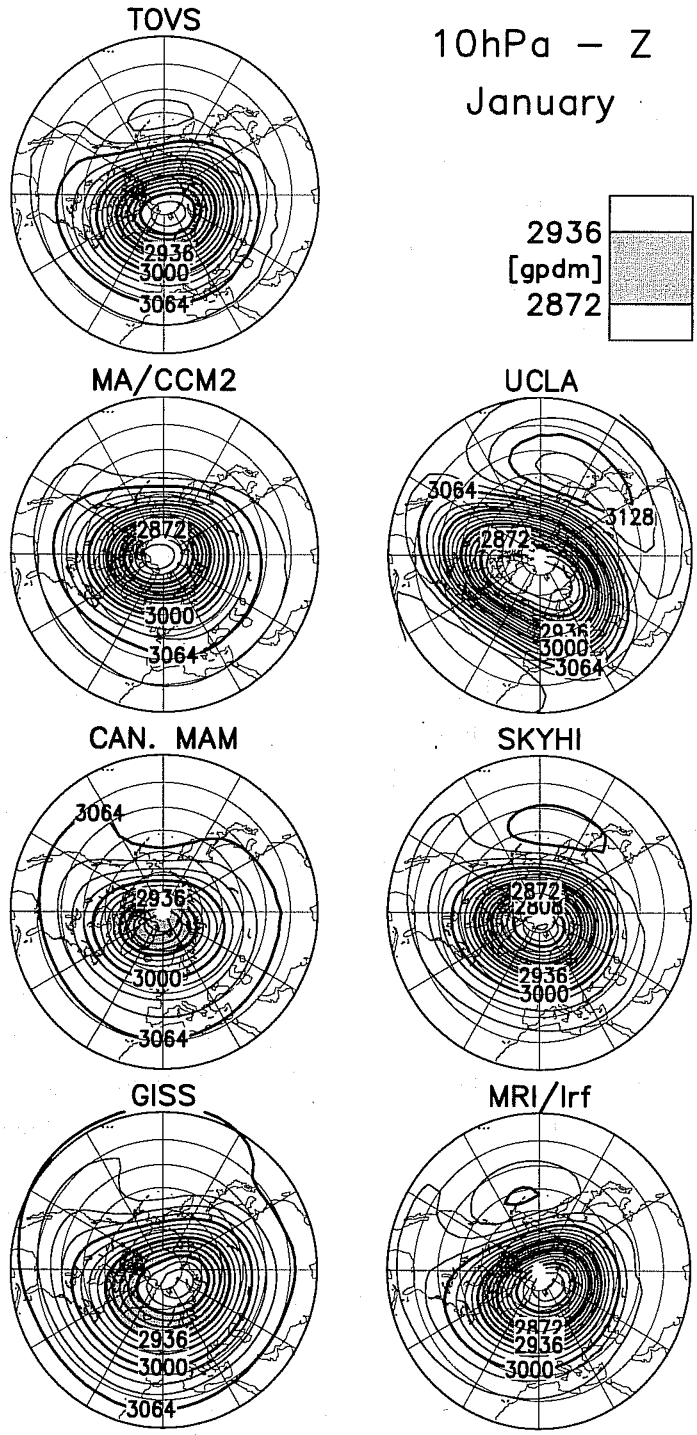

Fig. 3: Polar stereographic projections, from 20°N–90°N, of the multi-year mean geopotential height (gpdm) at 10 hPa in January. The contour interval is 16 gpdm and values in the range 2872–2936 gpdm are shaded. The observational estimate is a 17-year mean from UKMO TOVS analyses (Bailey et al. 1993). From Pawson et al. (2000).

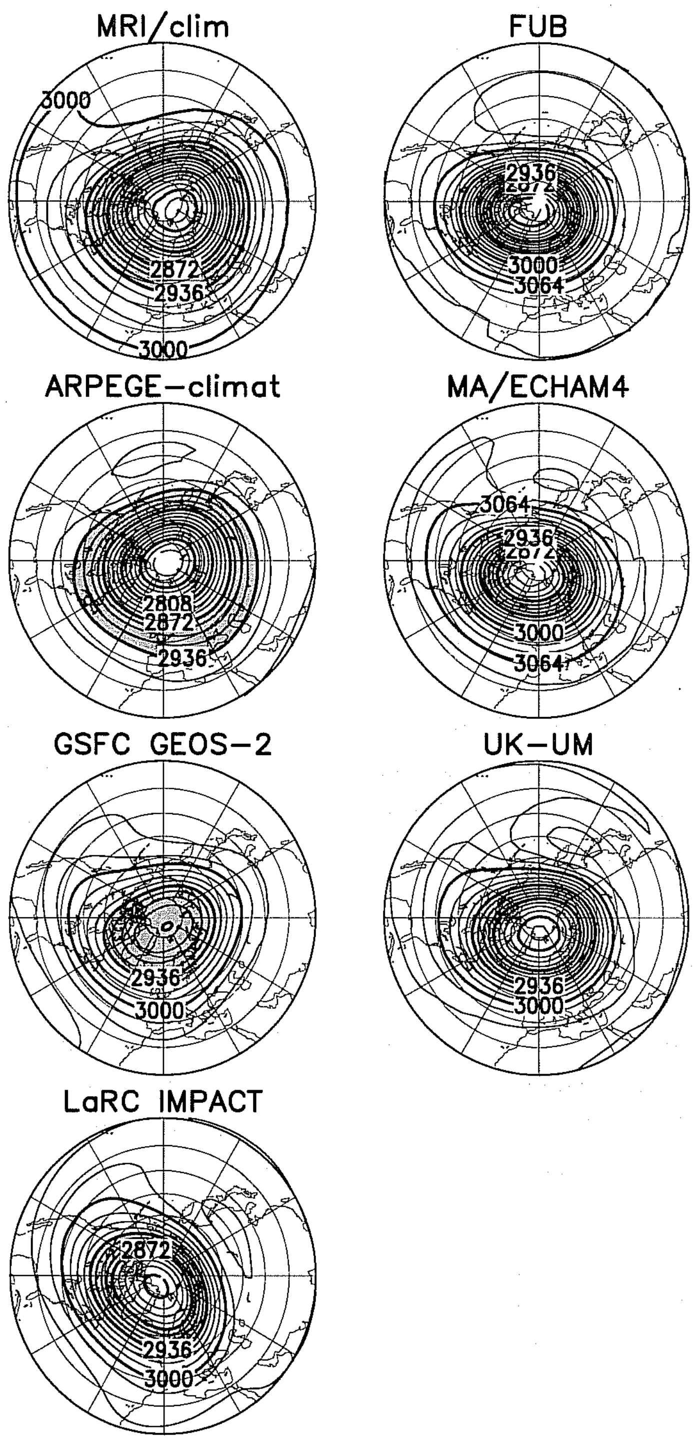

Fig. 3 (continued)

al. (1988a) found that a parametrization of convectively forced gravity waves, which have a direct impact on the tropical middle atmosphere, was essential for major warmings to occur in the GISS model. More recent studies by Hamilton (1995) and Erlebach et al. (1996) examined major warmings in long climate runs of the SKYHI and FUB models, finding about the correct frequency of warmings compared to reality. The ability of a model to deform the winter polar vortex in major (and minor) warming events is an essential part of the climatic variability, and it is also an essential part of the assimilation and forecasting process. Simmons and Strüfing 1983) showed how the introduction of hybrid vertical coordinates improved the stratospheric performace of the ECMWF model. An assessment of warmings is being made within GRIPS.

A central issue to simulations of the middle atmosphere is the role played by gravity wave drag. Early studies (Palmer et al. 1986) emphasized the role played by orographically forced gravity waves which dissipate in the lower stratosphere in forecasting the troposphere and stratosphere. As models are developed into the mesosphere, the role played by waves with non-zero phase speeds, which are generated by convective systems (among other forcing mechanisms), becomes important (Rind et al. 1988). These waves are generally not resolved, so must be parametrized in the models, although the amount of momentum transport which needs to be represented is not yet well understood. It depends on the amount of momentum transport by resolved waves (which increases as horizontal resolution is improved: Hamilton et al. 1999) and which differs between models (Koshyk et al. 1999). Considerable effort is presently being devoted to understanding this issue: a major problem is the limited amount of observational data available for validation and the development of parametrizations.

2.3 Forcing-response experiments

Alongside investigations into the performance of the GRIPS models and their component parts, a set of forcing-response experiments are being performed. The fundamental issues are to understand which factors have impacted the climate over the past few decades and to establish how changes in middle atmospheric forcing have affected the troposphere. A set of controlled experiments is being defined; these include (i) the impact of volcanic aerosols in the lower stratosphere; (ii) effects of long-term variations in solar ultra-violet irradiance; and, (iii) impacts of anthropogenically induced ozone trends. These factors all impact the radiative balance of the middle atmosphere, thereby changing the radiative forcing of the troposphere and the circulation of the atmosphere.

If we can use models to understand which factors have had important climatic consequences over the past two decades, this gives confidence in predictions of climate change over the next half century. This is likely to be impacted by changes in CFC emissions, CO_2 increases, and other factors which impact the middle atmospheric ozone distribution. GRIPS will define experiments for use in model studies of climate prediction.

3 Discussion

Many groups are actively involved in the development and analysis of general circulation models which extend to the middle atmosphere. These models are to be used for: climate studies – understanding processes and predicting possible future changes; data assimilation – combining short model forecasts with observations in an optimal manner to produce high-quality analyses of the troposphere and middle atmosphere; weather prediction – forecasts of the atmospheric time scale on timescales of days to weeks. Clearly, the ability of models to perform these tasks is limited by the accuracy of the numerical scheme used to predict the resolved fields and of the parametrizations of physical processes included.

There is a need to couple chemical processes into the circulation models. For the middle atmosphere, the main objective is to produce accurate simulations of the ozone distribution, since this is a radiatively active gas with important climatic consequences. It also absorbs harmful ultraviolet radiation. Ozone forecasts are used to predict the amount of ultraviolet radiation reaching the surface of Earth. Assimilation helps determine the radiative balance of the atmosphere more accurately. Prediction of future ozone changes and their links to other anthropogenic activity is important for both of these reasons. The transport scheme used in models clearly impacts the sucess of the simulated ozone distribution. In the Data Assimilation Office at NASA's Goddard Space Flight Center, a coupled dynamics-radiation-chemistry model is being developed, based on the dynamical core of Lin and Rood (1996, 1997) and Lin (1997). As well as the accurate treatment of transport in that scheme, the vertical velocities are derived from the vertical movements of Lagrangian pressure levels (Lin 1997). This is a very physical method of computing vertical motion, which results in a smooth vetical velocity field. This appears to give a much more physically realistic performance in the transport of stratospheric trace gases, including water vapour. Simmons et al. (1999) show that while the ECMWF model (like many others) can simulate the vertical advection of successive positive and negative water vapour anomalies in the tropical lower stratosphere, the ascent rate of these anomalies is too fast. In contrast, the Lin-Rood scheme can advect these anomalies with the correct propagation speed.

Detailed studies of the terrestrial radiation budget require accurate transport of trace gases, so it is extremely important that details such as water vapour advection are treated correctly. In the stratosphere, this depends in part on the physical nature of the vertical motion, as just discussed, but also on the reality of the simulated mean meridional circulation. Climate predictions can only be realistic if the meridional circulation is accurate. This depends on the forcing mechanisms at work (e.g., Rind et al. 1999). In particular, the body forces exerted by breaking gravity waves have a large impact on the simulated middle atmosphere, since they induce meridional circulations which affect trace gas distributions. These gases then interact with the radiation scheme. There are many feedback processes, which make the prediction of future climate, including the interaction with chemical processes, extremely uncertain. A major coordinated research effort is needed to develop a much better understanding of these coupling mechanisms.

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References

Bailey, M.J., A. O'Neill and V.D. Pope, 1993: Stratospheric analyses produced by the United Kingdom Meteorological Office. *J. Appl. Meteorol.*, **32**, 1472–1483.

Beagley, S.R., J. de Grandpré, J.N. Koshyk, N.A. McFarlane and T.G. Shepherd, 1997: Radiative-dynamical climatology of the first-generation Canadian middle atmosphere model. *Atmos. Ocean*, **35**, 293–331.

Boville, B.A., 1995: Middle atmospheric version of CCM2 (MACCM2): Annual cycle and interannual variability. *J. Geophys. Res.*, **100**, 9017–9039.

Chiba, M., K. Yamazaki, K. Shibata and Y. Kuroda, 1996: The description of the MRI atmospheric spectral GCM (MRI-GSPM) and its mean statistics based on a 10-year integration. *Papers in Meteorol. and Geophys.*, **47**, 1–45.

DAO, 1996: *Algorithm theoretical basis document version 1.01.* Data Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, MD, 276pp.

Déqué, M., C. Dreveton, A. Braun and D. Cariolle, 1994: The ARPEGE/IFS atmospheric model: a contribution to the French Community climate modelling. *Clim. Dyn.*, **10**, 249–266.

Dunkerton, T.J., 1997: The role of gravity waves in the quasi-biennial oscillation. *J. Geophys. Res.*, **102**, 26053–26076.

Ellingson, R.G., J. Ellis and S. Fels, 1991: The intercomparison of radiation codes used in climate models: Long wave results. *J. Geophys. Res.*, **96**, 8929–8953.

Erlebach, P., U. Langematz, and S. Pawson, 1996: Simulations of Stratospheric Sudden Warmings in the Berlin Troposphere-Stratosphere-Mesosphere GCM. *Ann. Geophysicae*, **14**, 443–463.

Fairlie, T.D.A., J.A. Al-Saadi, W.L. Grose, R.B. Pierce and R.S. Eckman, 1997: Simulation of inorganic chlorine reservoirs during winter in the low stratosphere using a 3D model of the middle atmosphere with coupled chemistry. *Proc. Quad. Ozone Symp., L'Aquila, Italy, 12–21 Sept 1996*, Eds. R. Bojkov and G. Visconti, International Ozone Commission, **2**, 707–710.

Fels, S.B., J.D. Mahlman, M.D. Schwarzkopf and R.W. Sinclair, 1980: Stratospheric sensitivity to perturbations in ozone and carbon dioxide: radiative and dynamical response. *J. Atmos. Sci.*, **37**, 2265–2297.

Gates, W.L., 1992: AMIP: The atmospheric model intercomparison project. *Bull. Amer. Meteorol. Soc.*, **73**, 1962–1970.

Gates, W.L., J.S. Boyle, C.C. Covey, C.G. Dease, C.M. Doutriaux, R.S. Drach, M. Fiorino, P.J. Gleckler, J.J. Hnilo, S.M. Marlais, T.J. Phillips, G.L. Potter, B.D. Santer, K.R. Sperber, K.E. Taylor and D.N. Williams, 1999: An overview of the results of the atmospheric model intercomparison project (AMIP). *Bull. Amer. Meteorol. Soc.*, **80**, 29–55.

Gibson J.K., P. Kållberg, S. Uppala, A. Hernandez, A. Nomura and E. Serrano, 1997: ECMWF re-analysis project report series, 1: ERA description. ECMWF, Reading, UK, 72pp.

Hamilton, K., 1995: INterannual variability in the northern hemisphere winter middle atmosphere in control and perturbed experiments with the GFDL SKYHI general circulation model. *J. Atmos. Sci.*, **52**, 44–66.

Hamilton, K., R.J. Wilson, J.D. Mahlman and L.J. Umscheid, 1995: Climatology of the GFDL SKYHI general circulation model. *J. Atmos. Sci.*, **52**, 5–43.

Hamilton, K., R.J. Wilson and R.S. Hemler, 1999: Climatology of the middle atmosphere simulated with high vertical and horizontal resolution versions of a general circulation model: Improvements in the cold pole bias and generation of a QBO-like oscillation in the tropics. *J. Atmos. Sci.*, **56**, 3829–3846.

Holton, J.R., and R.S. Lindzen, 1972: An updated theory for the quasi-biennial cycle of the tropical stratosphere. *J. Atmos. Sci.*, **29**, 1076–1080.

Horinouchi, T., and S. Yoden, 1998: Wave-mean flow interaction associated with a QBO-like oscillation in a simplified GCM. *J. Atmos. Sci.*, **55**, 502–526.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woolen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, A. Leetma, R. Reynolds, R. Jenne and D. Joseph, 1996: The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc., 77*, 437–471.

Kim, Y.-J., J. D. Farrara and C. R. Mechoso, 1998: Sensitivity of AGCM simulations to modifications in the ozone distribution and refinements in selected physical parameterizations. *J. Meteor. Soc. Japan*, **76**, 695-709.

Kitoh, A., Y. Noda, Y. Nikaidou, T. Ose and T. Tokioka, 1995: AMIP simulations of the MRI GCM. *Pap. Met. Geophys.*, **45**, 121–148.

Koshyk. J.N., B.A. Boville, K. Hamilton, E. Manzini, and K. Shibata, 1999: The kinetic energy spectrum of horizontal motions in middle-atmosphere models. *J. Geophys. Res.*, in press.

Langematz, U., and S. Pawson, 1997: The Berlin troposphere-stratosphere-mesosphere GCM: climatology and annual cycle. *Q. J. R. Meteorol. Soc.*, **123**, 1075–1096.

Lin, S.-J., 1997: A finite-colume integration method for computing pressure gradient forces in general vertical coordinates. *Q. J. Royal. Meteorol. Soc.*, **123**, 1749–1762.

Lin, S-J., and R.B. Rood, 1996: Multidimensional flux-form semi-Lagrangian transport schemes. *Mon. Weath. Rev.*, **124**, 2046–2070

Lin, S-J., and R.B. Rood, 1997: An explicit flux-form semi-Lagrangian shallow water model on the sphere. *Q. J. Royal. Meteorol. Soc.*, **123**, 2477–2498

Lindzen, R.S., and J.R. Holton, 1968: A theory of the quasi-biennial oscillation. *J. Atmos. Sci.*, **25**, 1095–1107.

Manzini, E., N.A. McFarlane and C. McLandress, 1997: Impact of the Doppler-spread parametrization on the simulation of the middle atmosphere circulation using the MA/ ECHAM4 general circulation model. *J. Geophys. Res.*, **102**, 25751–25762.

Palmer, T.N., G.J. Shutts and R. Swinbank, 1986: Alleviation of a systematic westerly bias in general circulation and numerical weather prediction models through an orographic gravity wave drag parametrisation. *Q. J. R. Meteorol. Soc.* **112**, 1001–1039.

Pawson, S., and M. Fiorino, 1998: A comparison of reanalyses in the tropical stratosphere. Part 1: Thermal structure and the annual cycle. *Clim. Dyn.*, **14**, 631–644.

Pawson, S., K. Kodera, K. Hamilton, T.G. Shepherd, S.R. Beagley, B.A. Boville, J.D. Farrara, T.D.A. Fairlie, A. Kitoh, W.A. Lahoz, U. Langematz, E. Manzini, D.H. Rind, A.A. Scaife, K. Shibata, P. Simon, R. Swinbank, L. Takacs, R.J. Wilson, J.A. Al-Saadi, M. Amodei, M. Chiba, L. Coy, J. de Grandpre, R.S. Eckman, M. Fiorino, W.L. Grose, H. Koide, J.N. Koshyk, D. Li, J. Lerner, J.D. Mahlman, N.A. McFarlane, C.R. Mechoso, A. Molod, A. O'Neill, R.B. Pierce, W.J. Randel, R.B. Rood, and F. Wu, 2000: The GCM-Reality Intercomparison Project for SPARC: Scientific Issues and Initial Results. Bull. Am. Meteorol. Soc., in press.

Randel, W.J., 1992: Global atmospheric circulation statistics, 1000-1mb., NCAR technical note, TN-366+STR, 198pp.

Rind, D., R. Suozzo, N.K. Balachandran, A. Lacis and G. Russell, 1988: The GISS Global Climate-Middle atmosphere model. Part 1: Model structure and climatology. *J. Atmos. Sci.*, **45**, 329–370.

Rind, D., J. Lerner, K. Shah and R. Suozzo, 1999: Use of on-line tracers as a diagnostic tool in general circulation model development, 2, Transport between the troposphere and stratosphere. *J. Geophys. Res.*, **104**, 9151–9167.

Shindell, D.T., D. Rind and P. Lonergan, 1998: Increased polar stratospheric ozone losses and delayed eventual recovery owing to increasing greenhouse-gas concentrations, *Nature*, **392**, 589–592.

Simmons, A.J., and R. Strüfing, 1983: Numerical forecasts of stratospheric warming events using a model with a hybrid vertical coordinate. *Q. J. R. Meteorol. Soc.* **109**, 81–111.

Simmons, A.J., A. Untch, C. Jakob, P. Kållberg, and P. Undén, 1999: Stratospheric water vapur and tropical tropopause temperatures in ECMWF analyses and multi-year simulations. *Q. J. Royal. Meteorol. Soc.*, **125**, 353–386

Swinbank, R., W.A. Lahoz, A. O'Neill, C.S. Douglas, A. Heaps and D. Podd, 1998: Middle atmosphere variability in the UK Meteorological Office Unified Model. *Q. J. R. Meteorol. Soc.*, **124**, 1485–1525.

Takahashi, M., 1996: Simulation of the stratospheric quasi-biennial oscillation using a general circulation model. *Geophys. Res. Lett.*, **23**, 661–664.

Untch, A., and A. Simmons, 1999: Increased stratospheric resolution in the ECMWF forecasting system. *SPARC Newsletter.* **13**, 18–21.

World Climate Research Programme, 1998: Stratospheric Processes and Their Role in Climate: Implementation plan. WMO/TD-No. 914, WCRP-105, 161pp.