Final Report for MAM Strategic Project Grant, February 2001

1. Name of Grantee: T.G. Shepherd, Department of Physics, University of Toronto.

2. Project Title: Modelling of the Middle Atmosphere (Phase 2), Application No. 192938.

3. Co–investigators:

J.–P. Blanchet, Department des sciences de la Terre, Université du Québec à Montréal
I. Folkins, Department of Oceanography and Department of Physics, Dalhousie University
J.C. Fyfe, Canadian Centre for Climate Modelling and Analysis, Meteorological Service of Canada†, Victoria; also School of Earth and Ocean Sciences, University of Victoria
G.P. Klaassen, Department of Earth and Atmospheric Science, York University
J.C. McConnell, Department of Earth and Atmospheric Science, York University
I.C. McDade, Department of Earth and Atmospheric Science, York University
N.A. McFarlane, Canadian Centre for Climate Modelling and Analysis, Meteorological Service of Canada, Victoria; also School of Earth and Ocean Sciences, University of Victoria

4. Budget:

	Amount requested	Amount awarded	Amount spent
Year 1	\$314,600	\$314,600	\$314,600
Year 2	\$272,600	\$272,600	\$272,600
Year 3	\$317,600	\$317,600	\$317,600

N.B. The Year 3 amount includes an additional \$30,000 which was awarded following NSERC's budget increase in 1998, and which was used to increase the salaries of students and post-docs.

5. Amount remaining in the grant account as of 1 February 2001: \$0.

6. Achievement of objectives: The overall objective of the project was the continued development and use of the Canadian Middle Atmosphere Model (CMAM), and this activity proceeded successfully. All key personnel from Phase 1 were retained for Phase 2 of the project, so there was no interruption of progress. The only task that had to be abandoned was the development of a mechanistic version of CMAM (Task II); however the impact on the rest of the project was minimal. Our original time lines were scheduled to complete on 31 March 2000. With the exception of a couple of tasks associated with students and post-docs who started late (due to the inevitable time lag in recruiting) — which was the reason for the 7-month extension of the end date of the project — and Task II, all other tasks were essentially completed on schedule.

The collaborative nature of our project is reflected in the many publications that involve multiple members of the project (see Section 8). The Scientific Steering Committee met in person for at least one full day three times each year, to coordinate the research.

We have contributed to many aspects of the middle atmosphere climate model intercomparison project (called GRIPS) that is being held under the auspices of the World Climate Research Program's SPARC project. In particular, we participated in the first model intercomparison (Pawson *et al.* 2000); J.N. Koshyk led the intercomparison of model kinetic energy spectra (Koshyk *et al.* 1999); S.R. Beagley led the intercomparison of model response to imposed drag; and V.I. Fomichev participated in the first level of radiation module intercomparison. In March 2000 we hosted the annual GRIPS workshop at the University of Toronto.

A major achievement of our project was the extension of CMAM into the thermosphere. This presented many numerical challenges, since heating rates get up to several hundreds of K/day, and wind speeds reach hundreds of m/s. Yet we managed to achieve our goal, and now have a working model with a lid at 200 km which compares well with WINDII observations (see Tasks I and XI below).

Another major aspect of our project involved performing long climate simulations with fully interactive chemistry, i.e. with the prognostic chemical fields feeding directly into the radiation calculation. This was a difficult undertaking. It required getting a reasonable setting of the gravity-wave drag parameterization to obtain acceptable polar night temperatures, and also involved numerical aspects of the radiative-chemical time-stepping (e.g. the infrequent call to the IR cooling routine which is reasonable in the troposphere

† formerly the Atmospheric Environment Service

becomes unacceptable in the mesosphere in fully interactive mode). The results are very satisfactory, with a stable chemical climate; we are one of the few modelling groups in the world to have achieved this. The ozone climatology is quite realistic and has demonstrated the important effects of interactive ozone in the summer stratopause region (de Grandpré *et al.* 2000). This fully interactive simulation was the reference run for doubled CO_2 experiments and for a Mt Pinatubo volcanic eruption experiment (see Tasks V, VIII and IX below).

An unexpected result of our research has been the simulation of a QBO-like oscillation (C. McLandress, SPARC 2000 General Assembly Abstracts volume, p.111). When the project started, no middle atmosphere GCM had ever simulated a QBO. The breakthrough came in very high-resolution idealized GCMs (Takahashi 1996 *GRL*; Horinouchi & Yoden 1998 *JAS*), and then in very high-resolution comprehensive GCMs (the ECMWF and GFDL SKYHI models). Both the UKMO GCM and CMAM, which are of relatively coarse resolution, have recently managed to obtain similar results using suitably tuned parameterized gravity-wave drag. This is very important for climate studies because very high-resolution simulations are not feasible. It must be emphasized that none of these results give a reasonable period (hence the phrase "QBO-*like* oscillations"), and much further work is required.

The progress achieved in MAM Phase 2 has set the stage for a number of future possibilities. The MSC now wishes to use CMAM as the basis with which to implement climate chemistry for the purpose of predicting greenhouse gas lifetimes and distributions. The Canadian Space Agency (CSA) is very interested in CMAM as a key resource and tool for its various space-based middle atmosphere measurement platforms, allowing integration and interpretation of the results as well as improved design of new systems. (There is also a possibility that CMAM might be similarly involved in the American WAVES-MIDEX mission.) Part of this can be accomplished by direct use of CMAM, and part of it by the use of CMAM in data assimilation mode. For the latter, MSC is very interested in developing a middle atmosphere data assimilation system based on CMAM to use in cooperation with the CSA. All these themes have come together in the recently funded NSERC Strategic Project "Modelling of Global Chemistry for Climate" (GCC), based on CMAM as the common tool, which is a partnership between NSERC, the MSC and the CSA.

Looking even further ahead, we have begun to start thinking about using CMAM as the basis for developing comprehensive 3D models of the atmospheres of Mars and Jupiter — something of great interest to the CSA as it prepares for planetary missions — and perhaps also of the Earth's magnetosphere.

A detailed report on the specific objectives of the project now follows, organized according to the various Task Definitions. Referenced publications may be found in Section 8.

Task I (Ward, McFarlane): Upward extension of CMAM. The 200 km version has been documented in Beagley *et al.* (2000) and Fomichev *et al.* (2001). The extended CMAM is the only currently existing climate model extending throughout the neutral atmosphere, although NCAR has recently begun a similar effort and MPI Hamburg is planning to also follow our lead. This is useful not only because it avoids the use of a problematic upper boundary condition, but also because the upper mesosphere/lower thermosphere region turns out to be one of great scientific interest (as has been revealed by the Canadian WINDII instrument).

Task II (Fyfe, McFarlane): Development and use of mechanistic version of CMAM. This task was initiated by Dr. Fyfe's Ph.D. student X. Wang, and a preliminary version of the mechanistic model was transferred to the MSC Middle Atmosphere Initiative (MAI). However, the work for this task was mainly to have been done by a new Research Associate, who could not be hired due to a budget cut from the MSC, so the task was essentially abandoned. Those activities proposed to have been performed with the mechanistic model were therefore performed with the full CMAM instead. The rest of the project was not seriously hampered by this change in development strategy. For the MAI, it proved simpler to use the full version of the CMAM in any case.

Task III (Klaassen): Parameterization of gravity–wave drag. Sensitivity studies were documented in McLandress (1997, 1998), Manzini & McFarlane (1998), Medvedev *et al.* (1998) and Medvedev & Klaassen (2001), and theoretical studies in Sonmor & Klaassen (2000) and as part of K.-H. Yau's M.Sc. and Ph.D. theses. A new orographic parameterization was also developed (Scinocca & McFarlane 2000). Ours is the only group in the world performing lengthy climate simulations with two distinct gravity–wave drag parameterization schemes — Hines and Medvedev-Klaassen — which allows a better understanding of the crucial role of these schemes (and their sensitivities) in modelled climate.

Task IV (McConnell): Chemistry. Task IV.2 was unnecessary. We now have a rudimentary tropospheric chemistry. A simple sulfate heterogeneous chemistry was developed for the volcanic eruption experiment (Task V), and a more complex heterogeneous chemistry for polar conditions. Given the continuing uncertainty over the nature of Type 1a (solid) PSCs, it was decided to implement only Type 1b (ternary solution) PSCs since at least they are understood from a fundamental standpoint.

Task V (Blanchet): Middle atmosphere clouds and aerosols. This work led to a "Mt Pinatubo eruption" experiment with fully interactive chemistry, one of the first such experiments using a 3D interactive chemical climate model (Chartrand *et al.* 2001). Ozone was seen to decrease in the lower stratosphere (as ClO increased) and increase in the upper stratosphere, in accordance with observations and theoretical predictions. It was shown that the chemical memory of a volcanic eruption can last several years, much longer than the radiative memory, due to transport of chemically perturbed conditions through the Brewer-Dobson circulation. This helps account for the long delay in the recovery of observed ozone levels following Pinatubo, supporting earlier conclusions derived from 2D models.

Task VI (Beagley): Model development. Development of CMAM continued throughout the project. The latest version, v.5, has been used for extended climate simulations for Task VIII. The CMAM was "merged" with the CCCma GCM on roughly an annual basis, which ensured a relatively straightforward transfer of technology to MSC.

Task VII (Koshyk): Diagnostic analysis and diagnostic development. Task VII.3 was abandoned in favour of data assimilation studies with CMAM (which were felt to have a higher priority). J.N. Koshyk led a SPARC GRIPS intercomparison of model kinetic energy spectra (Koshyk *et al.* 1999) which demonstrated the ubiquitous transition from steep to shallow spectra between the stratosphere and mesosphere. A chemical correlation diagnostic has been implemented and used to study transport properties in the CMAM; it was also shown that the use of chemical correlations to infer ozone loss is not always justifiable (Sankey & Shepherd 2001). The nature and extent of sudden warmings in CMAM has been studied by Chaffey & Fyfe (2001).

Task VIII (McFarlane, McConnell, Fomichev): Doubled CO_2 studies with CMAM. Suitable sea–surface temperatures (and sea-ice distributions) were required for this work, and we had to wait for coupled ocean–atmosphere runs to be performed with the 3rd-generation CCCma GCM in order to generate these fields. Thus this aspect of the project was delayed. However, a suite of doubled CO_2 runs has now been performed, which show the importance of the interactive ozone feedback in reducing stratospheric cooling in such sensitivity studies (de Grandpré *et al.* 2001). The separate effects of surface changes have been isolated by comparing runs with current and predicted SSTs and sea ice. Changes in the Southern Hemisphere annular mode under doubled CO_2 conditions have also been investigated (Fyfe *et al.* 2001); this is a hot topic in climate change research at the moment. Studies have also been performed with a mechanistic model addressing the profile of CO_2-induced cooling in the upper mesosphere/lower thermosphere (Akmaev & Fomichev 1998, 2000), which will be important for comparison with future simulations using the extended CMAM.

Task IX (McConnell): Ozone depletion studies with CMAM. Ozone variability with the fully interactive model has been documented in de Grandpré *et al.* (2000), and ozone-depletion studies in Chartrand & McConnell (1998, 2000). We were asked to participate in a middle atmosphere model intercomparison, held under the auspices of the Intergovernmental Panel on Climate Change (IPCC), to assess the impact of aircraft emissions on ozone and climate (see McConnell & others 1999).

Task X (Shepherd): Transport and mixing studies with CMAM. Tropical upwelling has been studied by Ph.D. student K. Semeniuk (Semeniuk & Shepherd 2001). Transport barriers in general have been studied through chemical correlations (Sankey & Shepherd 2001), and through the "age of air" diagnostic. Midlatitude transport and mixing has been examined by Ph.D. student D. Pendlebury. The nature of isentropic mixing has been examined using CMAM winds, and the very different behaviour of the stratosphere and mesosphere contrasted (Shepherd *et al.* 2000). This study also noted the contrast between the upper troposphere/lower stratosphere and the deep stratosphere, in terms of the resolution required to adequately quantify transport and mixing. Idealized studies of mixing have continued with Ph.D. students K. Ngan and J.V. Lukovich.

Task XI (McLandress): Analysis of tides in CMAM. Task XI.3 was unnecessary. An analysis of an early two–year CMAM simulation showed that the diurnal tide in the model exhibits a semi-annual amplitude variation at low latitudes in the mesosphere with equinoctial maxima and solsticial minima, in good agreement with WINDII and HRDI measurements (McLandress 1997). However that version of CMAM had a lid at 95 km, right where the tide has maximum amplitude. More recent studies with the extended version of CMAM have confirmed the earlier result, and enabled a systematic identification of the origin of the semi-annual amplitude variation — eliminating a number of previously advanced hypotheses (McLandress 2001).

Task XII (McLandress, Ward): Process studies. McLandress *et al.* (2000) have shown that analysis of satellite gravity-wave measurements can give an error in the climatology due to a bias in the sampling. Ward (1998, 1999) has likewise identified an interesting connection between tidal motions, transport, and atomic oxygen emission that can confound remote (especially ground-based) measurements unless properly accounted for. These studies point to the need to use process-based model analyses to correctly interpret many atmospheric measurements. The study of Shepherd *et al.* (2000) also fits in this context insofar as it quantifies the extent to which one can propagate information in space and time, depending on altitude; it has raised several interesting questions about the challenges for measurement systems proposed for the mesosphere.

Task XIII (Folkins, McDade): Observational studies. Comparison between CMAM fields and UARS observations was performed as part of P. Croteau's M.Sc. thesis, and also as part of A. Jonsson's Ph.D. thesis at Stockholm University (involving interactions with McConnell and Shepherd). J.N. Koshyk has directly compared the CMAM resolved gravity-wave fields with ground-based radar measurements (Manson *et al.* 2001). Studies of chemical observations in the upper troposphere have been performed by Witte *et al.* (1997), Folkins *et al.* (1999), and Folkins & Braun (2001). Analysis of CRISTA measurements relevant to CMAM has been made by Ward *et al.* (1999, 2000).

The only piece of equipment costing over $25,000 was a computer workstation/server at York University, which was used by the many people in the project based at York.

7. Training of research personnel:

N.B. "Full funding" means full funding within the context of the Strategic Project, with the cost sharing as described in the original proposal. Thus, "NSERC" means from the NSERC Strategic Project Grant; "MSC" means from the direct cash support from MSC; and "university" means from supervisors' other sources. "GCC" is the new follow-on NSERC Strategic Project led by Shepherd.

S.R. Beagley, Research Associate, York: Tasks I, VI, VIII (full funding: MSC); now with GCC
C. Braun, M.Sc. student, Dalhousie: Task XIII (full funding: NSERC/university); now at teacher's college
J.D. Chaffey, M.Sc. student, Victoria: Task VII (full funding: NSERC); now RA at Bedford Institute of Oceanography
D. Chartrand, Research Associate, York: Tasks IV, V, IX (full funding: NSERC/MSC); now with Jacques Whitford Environment Ltd
P.C. Croteau, M.Sc. student, York: Task XIII (full funding: NSERC/university); now a schoolteacher
J. de Grandpré, Research Assistant, York: Tasks IV, VI, VIII (full funding: MSC); now with GCC
V.I. Fomichev, Research Associate, York: Tasks I, VIII (full funding: NSERC/MSC); now with GCC
C. Fu, Ph.D. student, York: Task I (no funding); completing soon
J. Jiang, Post–doctoral Fellow, UQAM: Task V (partial funding: NSERC); now RA at Jet Propulsion Lab
J.N. Koshyk, Research Associate, Toronto: Task VII (full funding: MSC); now with TD Bank
J.V. Lukovich, Ph.D. student, Toronto: Task X (no funding); completing soon
C. McLandress, Research Associate, York: Tasks I, XI, XII (partial funding: NSERC/MSC); now with GCC
C.A. McLinden, Ph.D. student, York: Task IV (no funding); now post-doc at UC Irvine
A.S. Medvedev, Research Associate, York: Task III (full funding: NSERC/MSC); now RA at Dalhousie
K. Ngan, Ph.D. student and Post–doctoral Fellow, Toronto: Task X (full funding: NSERC/MSC/university); now at IBM Canada

D. Pendlebury, Ph.D. student, Toronto: Task X (full funding: NSERC/university); completing this summer
D. Plummer, Post–doctoral Fellow, York: Task IV (full funding: NSERC/MSC); now with GCC
D. Sankey, Post–doctoral Fellow, Toronto: Task X (full funding: NSERC/MSC); now with GCC
W. Sandilands, Ph.D. student, York: Task IV (no funding); now forecasting at Ontario Hydro
K. Semeniuk, Ph.D. student, Toronto: Task X (full funding: NSERC/university); now post-doc at MIT
S. Soukhanova, Post–doctoral Fellow, York: Task IV (full funding: NSERC/MSC)
K.–H. Yau, Ph.D. student, York: Task III (full funding: NSERC/university); completing this summer
X. Wang, Ph.D. student, Victoria: Task II (full funding: MSC); now with Sierra Systems in Victoria
W.E. Ward, Project Scientist, CRESTech: Tasks I, XII (partial funding: NSERC/MSC); now Associate Professor at UNB
J. Witte, M.Sc. student, Dalhousie, Task XIII (full funding: MSC); now RA at NASA Goddard

Specific contributions of the above individuals are highlighted in Section 6. In general, the nature of their contributions may be summarized as follows. The Research Assistant and two Research Associates (fully funded by MSC) formed the MAM Core Group, who provided essential support for model development and assistance to students and post-doctoral fellows using the model. Other Research Associates (jointly funded by NSERC and MSC) provided specialized expertise for model development and applications. Most of the post-doctoral fellows fully funded by this grant were responsible for specific aspects of model development. The students and the other post-doctoral fellows were responsible for development of diagnostic methods and tools, and for complementary theoretical studies in support of the model development.

We were extremely pleased with the training aspects of this project. A large number of students and post-doctoral fellows now have expertise at the leading edge of an environmental modelling technology. This training was
facilitated by the fact that the MSC-supported Core Group was located at the universities themselves, rather than at the MSC.

In addition to the direct training within the project, we ran a "Summer School on the Middle Atmosphere", as described in our proposal, during August 25–29, 1997 in Cornwall, Ontario. The school attracted over 40 "students" (a combinaton of graduate students, post–doctoral fellows and public–sector scientists from MSC) and a volume summarizing the lecture material was sent to all participants. (We would be happy to send NSERC a copy if requested.)

8. Accessibility of results to the supporting organizations: The intended user community was the MSC, CRESTech (formerly ISTS), the Canadian Space Agency, and the Canadian atmospheric science university community.

- We have sponsored the following five workshops:

  MAM Scientific Workshop, 15–16 December 1997, University of Toronto

  MAM Scientific Workshop, 14–15 December 1998, University of Toronto

  MAM Scientific Workshop, 15–16 November 1999, University of Toronto

  MAM Users' Workshop, 17–18 November 1999, University of Toronto

  MAM Scientific Workshop, 11-12 December 2000, University of Toronto

The annual MAM Scientific Workshops are basically internal workshops, to which all MAM participants (including students and PDFs) come and present their work. Other interested researchers within the Canadian community are also invited, and we bring in three renowned international experts for longer invited talks. (Typically we have about 50 participants, all told.) The Users' Workshop was targeted specifically at the Canadian measurement community.

- During the time frame of the project, Prof. Shepherd gave 12 invited departmental seminars presenting an overview of scientific results from the Canadian MAM project: 4 in Canada, 1 in Japan, 2 in the UK, 1 in France, and 4 in the US. He also reviewed Canadian capabilities in modelling (including CMAM) at the CSA workshop on the Atmospheric Environment Element of the Canadian Space Plan in January 2000. Dr. Koshyk gave an invited talk describing the MAM project at the DASP Winter Workshop (Canadian Association of Physicists) in February 1999.

• The project resulted in 115 papers presented at national and international conferences, of which 21 were invited. (Our own workshops are not included in this total, of course.)

• Publications and theses arising directly from the project (results listed in the MAM Phase 1 final report but which finally appeared during Phase 2 are *not* included, so as not to double-count)‡:

Publications:

Akmaev, R.A. and V.I. Fomichev, 1998: Cooling of the mesosphere and lower thermosphere due to doubling of CO_2. *Ann.Geophys.*, **16**, 1601–1612.

Akmaev, R.A. and V.I. Fomichev, 2000: A model estimate of cooling in the mesosphere and lower thermosphere due to CO_2 increase over the last 3–4 decades. *Geophys.Res.Lett.*, **27**, 2113–2116.

Beagley, S.R., McLandress, C., Fomichev, V.I. and W.E. Ward, 2000: The extended Canadian Middle Atmosphere Model. *Geophys.Res.Lett.*, **27**, 2529–2532.

Chaffey, J.D. and J.C. Fyfe, 2001: Arctic polar vortex variability in the Canadian middle atmosphere model. *Atmos.–Ocean*, to appear.

Chartrand, D.J., de Grandpré, J. and J.C. McConnell, 1999: An introduction to stratospheric chemistry. *Atmos.–Ocean*, **37**, 309–367.

Chartrand, D.J. and J.C. McConnell, 1998: Evidence for HBr production due to minor channel branching at mid–latitudes. *Geophys.Res.Lett.*, **25**, 55–58.

Chartrand, D.J. and J.C. McConnell, 2000: Heterogeneous chemistry and the O_3 budget in the lower mid-latitude stratosphere. *J.Atmos.Chem.*, **35**, 109–149.

Chartrand, D.J., McConnell, J.C., Beagley, S.R., de Grandpré, J., Jiang, J. and V.I. Fomichev, 2001: A simulation of the long and short term effects of the Mount Pinatubo eruption: Results from the Canadian Middle Atmosphere Model. In preparation.

de Grandpré, J., Beagley, S.R., Fomichev, V.I., Griffioen, E., McConnell, J.C., Medvedev, A.S. and T.G. Shepherd, 2000: Ozone climatology using interactive chemistry: Results from the Canadian Middle Atmosphere Model. *J.Geophys.Res.*, **105**, 26475–26491.

de Grandpré, J., Fomichev, V.I., Beagley, S.R., McConnell, J.C., McFarlane, N.A. and T.G. Shepherd, 2001: CO_2–induced cooling and ozone feedback in the middle atmosphere. In preparation.

Folkins, I. and C. Braun, 2001: Eddy transport of ozone into the upper tropical troposphere. In preparation.

Folkins, I., Loewenstein, M., Podolske, J., Oltmans, S. and M. Proffitt, 1999: A 14 km mixing barrier in the tropics — evidence from ozonesondes and aircraft measurements. *J.Geophys.Res.*, **104**, 22095–22102.

Fomichev, V.I., Ward, W.E., Beagley, S.R., McLandress, C., McConnell, J.C., McFarlane, N.A. and T.G. Shepherd, 2001: The extended Canadian Middle Atmosphere Model: Zonal–mean climatology and physical parameterizations. *J.Geophys.Res.*, submitted.

Fu, C., McLandress, C., McConnell, J.C. and V.I. Fomichev, 2001: Impact of the diurnal tides on MLT O_x transport, chemistry and chemical heating in the CMAM. In preparation.

Fyfe, J.C., Beagley, S.R. and T.G. Shepherd, 2001: Southern Hemisphere circulation changes under global warming. In preparation.

Fyfe, J.C. and E. Manzini, 2001: The influence of the stratospheric circulation on the annular models of climate variability in a middle atmosphere model. *J.Geophys.Res.*, submitted.

Griffioen, E. and J.C. McConnell, 2001: A photolysis model for the Canadian Middle Atmosphere GCM. *J.Geophys.Res.*, submitted.

Hagan, M.E., McLandress, C. and J.M. Forbes, 1997: Diurnal tidal variability in the upper mesosphere and lower thermosphere. *Ann.Geophys.*, **15**, 1176–1186.

Koshyk, J.N., Boville, B.A., Hamilton, K., Manzini, E. and K. Shibata, 1999: The kinetic energy spectrum of horizontal motions in middle atmosphere models. *J.Geophys.Res.*, **104**, 27177–27190.

Koshyk, J.N. and K. Hamilton, 2001: The horizontal kinetic energy spectrum and spectral budget simulated by a high–resolution troposphere–stratosphere–mesosphere GCM. *J.Atmos.Sci.*, **58**, 329–348.

‡ "In preparation" means that the work has been completed and presented at a conference, and that the paper (or thesis) is at least partially written

Koshyk, J.N., Hamilton, K. and J.D. Mahlman, 1999: Simulation of the $k^{-5/3}$ mesoscale spectral regime in the SKYHI general circulation model. *Geophys.Res.Lett.*, **26**, 843–846.

Manson, A., C. Meek, and J.N. Koshyk, 2001: Gravity wave activity and dynamical effects in the middle atmosphere (60–90 km): observations from an MF/MLT radar network and results from the Canadian Middle Atmosphere Model. In preparation.

Manzini, E., and N.A. McFarlane, 1998: The effect of varying the source spectrum of a gravity–wave drag parameterization in a general circulation model.
J.Geophys.Res., **103**, 31523–31539.

McConnell, J.C. and D.J. Chartrand, 1997: Ozone simulation and depletion. In *Ozone science: A Canadian perspective on the changing ozone layer*, editors D.I. Wardle, J.B. Kerr, C.T. McElroy and D.R. Francis, Environment Canada, 57–72.

McConnell, J.C., Fu, C., de Grandpré, J., Fomichev, V.I. and S.R. Beagley, 2001: The mesosphere and lower thermosphere of the Canadian Middle Atmosphere Model. Part I: Comparison with measurements. In preparation.

McConnell, J.C. and 9 others (Lead Authors), 1999: Modeling the chemical composition of the future atmosphere. Chapter 4 of *Aviation and the Global Atmosphere*, Cambridge University Press.

McDade, I.C., 1998: The photochemistry of the MLT oxygen airglow emissions and the expected influences of tidal perturbations. *Adv.Space Res.*, **21** (6), 787–794.

McElroy, C.T., McLinden, C.A. and J.C. McConnell, 1999: Evidence for the
presence of BrO in the free troposphere during the Arctic polar sunrise.
Nature, **397**, 338–341.

McLandress, C., 1997: Seasonal variability of the diurnal tide: Results from the Canadian Middle Atmosphere General Circulation Model. *J.Geophys.Res.*, **102**, 29747–29764.

McLandress, C., 1997: Sensitivity studies using the Hines and Fritts gravity–wave drag parameterizations. In *Gravity Wave Processes and their Parameterization in Global Climate Models*, editor K. Hamilton, Springer–Verlag, 245–256.

McLandress, C., 1998: On the importance of gravity waves in the middle atmosphere and their parameterization in general circulation models. *J.Atmos.Sol.–Terres.Phys.*, **60**, 1357–1383.

McLandress, C., 2001: The seasonal variation of the propagating diurnal tide. Part I: The role of gravity waves and planetary waves. *J.Atmos.Sci.*, submitted.

McLandress, C., 2001: The seasonal variation of the propagating diurnal tide. Part II: The role of tidal heating and zonal–mean winds. *J.Atmos.Sci.*, submitted.

McLandress, C., Alexander, M.J. and D.L. Wu, 2000: Microwave Limb Sounder observations of gravity waves in the stratosphere: A climatology and interpretation. *J.Geophys.Res.*, **105**, 11947–11967.

McLinden, C.A., McConnell, J.C., Griffioen, E., McElroy, C.T. and L. Pfister, 1997: Estimating the wavelength–dependent ocean albedo under clear–sky conditions using NASA ER-2 spectroradiometer measurements. *J.Geophys.Res.*, **102**, 18801–18811.

McLinden, C.A., McConnell, J.C., McElroy, C.T., and E. Griffioen, 1998: Sensitivity of polarized limb radiances to stratospheric aerosols with application to NASA ER-2 spectroradiometer measurements. In *Atmospheric Ozone, Proceedings of the XVIII Quadrennial Ozone Symposium*, editors R.D. Bojkov and G. Visconti, L'Aquila, Italy, 947–950.

McLinden, C.A., McConnell, J.C., McElroy, C.T., Griffioen, E. and J.C. Wilson, 1998: Observations of stratospheric aerosol using CPFM polarized limb radiances. *J.Atmos.Sci.*, **56**, 233–240.

Medvedev, A.S. and G.P. Klaassen, 2000: Parameterization of gravity–wave momentum deposition based on a nonlinear theory of wave spectra. *J.Atmos.Sol.–Terres.Phys.*, **62**, 1015–1033.

Medvedev, A.S. and G.P. Klaassen, 2001: Realistic semiannual oscillation simulated in a middle atmosphere model.
Geophys.Res.Lett., in press.

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Ngan, K. and T.G. Shepherd, 1999: A closer look at chaotic advection in the stratosphere. Part I. Geometric structure. *J.Atmos.Sci.*, **56**,
4134–4152.

Ngan, K. and T.G. Shepherd, 1999: A closer look at chaotic advection in the stratosphere. Part II. Statistical diagnostics. *J.Atmos.Sci.*, **56**, 4153–4166.

Oberheide, J., Hagan, M.E., Ward, W.E., Riese, M. and D. Offermann, 2000: Modeling the diurnal tide for the CRISTA 1 time period. *J.Geophys.Res.*, **105**, 24917–24929.

Ogibalov, V.P., Fomichev, V.I. and A.A. Kutepov, 2000: Radiative heating
effected by infrared CO_2 bands in the middle and upper atmosphere. *Atmos.Oceanic Phys.*, **36**, 454–464.

Pawson, S. & 39 others (including several in the Canadian MAM project), 2000: The GCM-Reality Intercomparison Project for SPARC (GRIPS): Scientific issues and initial results. *Bull.Amer.Met. Soc.*, **81**, 781–796.

Ravishankara, A.R. and T.G. Shepherd (Lead Authors), 1999: Lower Stratospheric Processes. Chapter 7 of *Scientific Assessment of Ozone Depletion: 1998*, World Meteorological Organization.

Sankey, D. and T.G. Shepherd, 2001: Correlations of long-lived chemical species in a general circulation model. In preparation.

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Please note that a complete list of publications, from the beginning of the MAM project, is available at http://www.atmosp.physics.utoronto.ca/MAM/pubs.html.

9. Benefits to Canada and the Non-academic Participating Organizations: The principal benefit of the Canadian MAM project was the development of an improved tool for environmental assessment studies, to reduce the uncertainty of environmental predictions in which the stratosphere plays a role. This was achieved by extending the MSC CCCma General Circulation Model to include a middle atmosphere component, including interactive ozone chemistry. The improved model has now been transferred back to MSC and is fully compatible with their coupled atmosphere-ocean climate system model. In that context it can now be used for novel long climate integrations as part of international environmental assessment efforts, to inform and impact on government policy.

The development of CMAM is also an essential component in the development of a comprehensive, end-to-end, middle atmosphere data assimilation system as part of the MSC's Middle Atmosphere Initiative. This middle atmosphere data assimilation system will provide essential support to Canadian researchers and companies for the development of satellite and other remote sounding instrumentation, enabling them to compete internationally.

The main non–university participants in the project were Drs. N.A. McFarlane and J.C. Fyfe from CCCma in MSC Victoria, and Dr. W.E. Ward at CRESTech (formerly ISTS). (Dr. McLandress was originally with CRESTech, but left the project for two years and upon his return rejoined the project as a Research Associate at York University. Thus, the in-kind support from CRESTech was only one-half of the level originally described.) McFarlane, Fyfe and Ward were all heavily involved in the project as indicated in section 6. The MSC has been the principal recipient of the CMAM technology, as described above. With regard to CRESTech, Dr. Ward's modelling activities within the MAM project provided support for satellite data interpretation (WINDII) and for satellite instrument development (MODE, SWIFT).