STRATEGIC PROJECT GRANTS FINAL REPORT

Due Date: **March 31, 2006**

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Please verify the project information below and make any necessary corrections:

Project Title: Modelling of global chemistry for climate

File No: STPGP 235109-00

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Supporting Organization(s):
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1. PROGRESS TOWARDS OBJECTIVES/MILESTONES

To what extent were the objectives of the Strategic Project achieved? Please rate your answer on a scale from 1 to 7, where 1 means not at all, the mid-point means somewhat, and 7 means to a great extent.

NOT AT ALL			SOMEWHAT				TO A GREAT EXTENT
					X		
1	2	3	4	5		6	7

Using approximately 7 pages, please provide:

- a brief description of the overall objectives of the research project as awarded;
- a description of the progress made towards these objectives as a result of the grant;
- a description and justification for any deviations from the original objectives;
- a description of the scientific and/or engineering significance of the results; and
- a brief discussion of the potential benefits to Canada.

Task I: Tropospheric chemistry

At York, Research Associate D. Plummer, working in close collaboration with J. McConnell's group, began the extension of the CMAM chemistry into the troposphere. Application of chemistry in the troposphere required the addition of two new physical parameterizations in the GCM: dry deposition of chemical species at the surface and washout of soluble species by modelled precipitation. In addition, the range of chemical species represented by the chemical package was extended beyond the methane-based chemistry used in the stratosphere to include some simple organics, and the fixed-concentration lower boundary condition used in the stratospheric chemistry package was replaced with an emission-based boundary condition. This effort resulted in a simplified intermediate version of the GCC tropospheric chemistry package. When Plummer was hired by Environment Canada a few years into the project, this work was continued by post-doc G. Folberth, working in Victoria. (Plummer generously continued to offer some assistance in a consultative capacity.) This arrangement proved fortunate because the close proximity to CCCma enabled a closer link with the AGCM to be established. The primary focus of Folberth's effort was to extend the tropospheric chemistry package to include non-methane volatile organic compounds. This required a significant increase in the complexity of the chemical mechanism and in the number of chemical tracers employed. Progress in the development of this version of tropospheric chemistry for CMAM was, unfortunately, severely impacted by the supercomputer changes that took place during the project (see below), which were not anticipated at the time of the proposal. By the end of the project, this version of the tropospheric chemistry was performing stably in extended (multi-year) integrations and some basic comparisons with tropospheric ozone and CO observations indicated that its representation was reasonable. In that respect, our primary goal was achieved. However, there was not time to perform a full evaluation of this most complete tropospheric chemistry package and document it in a publication.

For the same reason, the plan to develop a SOx chemistry for CMAM and merge it with the CCCma simplified sulfate chemistry had to be dropped. This would have required carrying too many tracers, making it computationally infeasible given the resources available to the project during this period.

P. Ariya and her group at McGill contributed to the GCC project through process studies involving (a) the importance of water clusters with Criegee intermediate formed upon ozonolysis reactions, and their impact on generation of radicals; and (b) the role of bio-organic compounds as ice nuclei and cloud condensation nuclei.

(a) Ozonolysis reactions: Reactions with ozone play an important role in the atmospheric sink of unsaturated compounds along with reactions initiated by HO, NO_3 or Cl radicals. This reaction is assumed to lead to the formation of atmospherically important species like HO_x and RO_x radicals, hydrogen peroxide and organic peroxides. The first step of ozonolysis forms a Criegee intermediate. A theoretical investigation was performed of the reactions of Criegee intermediate (CI) with water, monomer, dimer trimer and tetramer at B3LYP/6-311+G(2d,2p) level of theory. Eight different configurations of complexes CI…$(H_2O)_3$ and six of CI…$(H_2O)_4$ were found. Their subsequent reactions were considered, and the corresponding activation barriers determined. The results indicate that reactions with larger water clusters could be important under atmospheric conditions. It seems the most kinetically favourable pathway is the CI with water dimer reactions.

(b) Bioaerosol Modelling: A review study and modelling work on bioaerosols was performed. The aim of the review study was to assess the current state of knowledge regarding the role of organic aerosols (including bioaerosols) as cloud condensation nuclei (CCN), as well as to compare the existing theoretical and experimental data. It seems that classical Köhler theory does not adequately describe the hygroscopic behaviour of predominantly identified organic CCN such as pure dicarboxylic acid particles. Factors such as surface tension, impurities, volatility, morphology, contact angle, deliquescence, and the oxidation process should be considered in the theoretical prediction of the CCN ability of organic carbon and the interpretation of experimental results. The modelling work addressed the role of bacteria as potential ice nuclei. Bacteria are recognized as one of the most effective ice nuclei at temperatures warmer than -15ºC. The work considered bacterial vertical distribution and size spectra relating to ice nucleating potential in warm-based convective clouds at relatively warm temperatures using a cloud model. Based on preliminary results, concentrations of ice active bacteria between -3°C and -8°C have a seemingly significant impact on the ice crystal multiplication, and thus their existence should be considered.

Task II: Aerosol effects

Research was conducted into the physical state (i.e. solid versus liquid) of typical multi-component tropospheric aerosols by J. Abbatt and his group at Toronto, to better understand their role in direct radiative forcing, reactivity and also cloud activation. Particular attention was given to the role of the organic component which was found to suppress the likelihood of particle crystallization when present in large quantities. In a second direction, via CCN closure experiments, the cloud droplet activation of multicomponent particles was also studied where it was found that the organic component also played a significant role, by increasing the aerosol size distribution making the particles more likely to activate. A simple Köhler model was developed to describe the observed CCN levels, at a simple enough level that it could ultimately be included in global climate models.

At Dalhousie, U. Lohmann and her group investigated the role of in-atmosphere transformations (ageing) of black carbon (BC) and particulate organic matter (POM) in predicting the global atmospheric burdens of these aerosols. Specifically, the research focused on the processes that convert carbonaceous aerosols from the insoluble to the soluble/mixed state. One of the research goals was to introduce a physically based representation of these processes of oxidation, condensation, and coagulation into the Canadian atmospheric general circulation model (AGCM). This was done in cooperation with the research group at CCCma.

The pre-existing representation of the ageing of carbonaceous aerosols in the CCCma AGCM assumed a conversion from the insoluble to soluble state following an exponential decay with a fixed half-life of 24 hours. During the project, three physically based parameterizations of this ageing process were implemented in the CCCma AGCM, and the predicted BC and POM burdens were compared. Surface based observations were also used to validate the parameterizations. The parameterization that represented the processes of condensation and coagulation was recommended as the best improvement to the pre-existing ageing treatment. The BC and POM ageing was found to be slightly faster than that predicted by the fixed half-life approach.

While a preliminary attempt to represent the impact of oxidation on the BC and POM ageing was completed, there was found to be considerable uncertainty in regard to how efficient this process was under actual atmospheric conditions, and in competition with condensation and coagulation. Further laboratory and field studies are needed to fill this knowledge gap before oxidation can be effectively represented in an AGCM.

Improvements to the representation of the BC and POM ageing in AGCMs ultimately improves the confidence in the predicted global burdens of BC and POM. These aerosols both scatter and absorb radiation, and modify cloud properties when they act as cloud condensation and ice nuclei. More accurate quantification of the global burdens of the carbonaceous aerosols leads to greater confidence in the predictions of how these aerosols may either counteract or add to the global warming caused by greenhouse gases.

A size-segregated multicomponent stratospheric cloud model with detailed Polar Stratospheric Cloud (PSC) microphysics and comprehensive chemistry has been developed at York University by D. Michelangeli and post-doc X. Wang. The microphysics accounts for the particle-size dependent processes of homogeneous freezing of liquid particles, heterogeneous nucleation by vapour deposition, condensation/ evaporation, sedimentation, and coagulation. Five aerosol and PSC types are treated in the model as distinct interactive elements: background sulphate droplets, Supercooled Ternary Solution (STS), frozen Sulfuric Acid Tetrahydrate (SAT), Nitric Acid Trihydrate (NAT)/Nitric Acid Dihydrate (NAD), and water ice crystals. The chemical package includes 41 species which are involved in 97 gas-phase reactions, 28 photochemical reactions and 6 heterogeneous reactions on PSCs and liquid aerosols.

One-dimensional column simulations were performed to investigate the capability of the model at capturing PSC events by comparison with satellite and balloon-borne measurements. The modelled proportions of PSCs are consistent with the observations of volume, number, size distributions and extinction coefficients derived from the in situ balloon-borne optical particle counter and the Improved Limb Atmospheric Spectrometer (ILAS) satellite sensor, demonstrating the capability of the model to capture PSC events (Wang and Michelangeli, 2006).

Task III: Transport

In terms of technical advances, J. Scinocca developed and installed a specialized filter (Lander and Hoskins, 1997) to inhibit the production of negative tracer mixing ratios caused by threshold processes in the physics package. Work was also performed in collaboration with CCCma on testing the implementation of a hybrid variable approach to handle multiple tracers in the tropospheric chemistry package.

The annual cycle in the column ozone distribution has been used as one benchmark to assess the validity of the transport of constituents in the model. The comparison with ground based and satellite measurements has shown a good agreement, within 10% in most regions. Multi-year simulations with semi-Lagrangian (S-L) transport at the same resolution have shown a degradation of the results — for example, insufficient isolation of the Antarctic polar vortex — which is attributed to the diffusive aspects of the S-L scheme for long-term integrations. Given the quality of the results and also to maintain consistency with the model's spectral dynamical core, it was decided early in the project to continue with the use of a spectral scheme and a family approach for transport of constituents.

The accuracy of CMAM spectral transport for maintaining realistic horizontal mixing barriers was investigated by comparison of tracer-tracer correlations with aircraft and space-based observations (Sankey and Shepherd, 2003). However a detailed comparison with MANTRA balloon observations of various species during the quiet late-summer period showed that vertical profiles of long-lived species in the lower stratosphere were seriously compromised when the vertical diffusivity was set at its original 1 m^2/s. Reducing the value to 0.1 m^2/s (which is more in line with the values estimated from detailed tracer-structure measurements) resulted in a much better agreement with MANTRA observations, and also removed a significant bias in the global column ozone distribution. More detailed investigations of transport in CMAM using this reduced value of the vertical diffusivity have been undertaken as part of the CCMVal intercomparison for SPARC conducted in the context of the recent WMO/UNEP Ozone Assessment (Eyring et al., 2006). Various transport diagnostics, including age of air, the tropical tape recorder, and horizontal gradients, confirm that CMAM has a representation of stratospheric transport that is comparable to that of the leading chemistry-climate models world-wide.

Theoretical studies of transport were pursued in T. Shepherd's group at Toronto by Ph.D. students D. Pendlebury, who assessed the relationship between the Lagrangian and residual circulations (Pendlebury and Shepherd, 2003), and J. Lukovich, who examined the impact of divergent motions associated with gravity waves on the stirring arising from balanced motion (Lukovich and Shepherd, 2005).

Task IV: Radiative processes

There was a significant delay in this task due to problems with the implementation of the correlated k-distribution code at CCCma. This code finally became available to us only in the Fall of 2005. Since then we have only developed an off-line version of the scheme, which is applicable for extension into the mesosphere. Therefore, instead of working with the correlated k-distribution code, through most of the project we have worked on improving the existing radiation scheme. Implementation of new radiative energy sources into the model (cooling in the infrared H_2O bands, sphericity effect in solar heating, chemical heating, and solar heating in the near-IR CO_2 bands) led to a better agreement between the model temperature field and observations (Fomichev et al., 2004). A first-ever parameterization of solar heating in the near-IR CO_2 that takes into account non-LTE processes and is applicable in the mesosphere was developed (Ogibalov and Fomichev, 2003). Implemention of this parameterization in the CMAM resulted in a warmer model mesosphere (a region where most models have a significant cold bias), in better agreement with observations (Fomichev et al., 2004). We have also participated in the SPARC radiation intercomparison project (which has not yet completed), both with the scheme used in the current version of CMAM and also, most recently, with a new scheme based on the correlated k-distribution method.

Task V: Development and validation of middle atmosphere data assimilation capability

and

Task XI: Data assimilation studies in support of Canadian instruments

After coupling CMAM to MSC's 3D variational (3D-Var) data assimilation scheme (referred to as CMAM-DAS), CMAM-specific background error statistics were defined and the 3D-Var code was generalized for hybrid vertical coordinates. Although an analysis of the early UARS period was originally planned, the lack of appropriate data precluded this. Instead, it was decided to analyse a more recent period, which would also have the added benefit of making the CMAM-DAS product useful for current activities. It was specifically decided to produce analyses for January-March and August-October of 2002, in order to support the Canadian high Arctic (winter-spring) and MANTRA (late summer) measurement campaigns — as well as to assimilate the unprecedented Antarctic ozone hole of 2002. In early 2003 the CMAM-DAS was adapted to use the latest version of the CMAM with T47L65 resolution and interactive, heterogeneous chemistry. There was a slowdown of system development in 2004 while CMAM was rewritten for the new IBM machine. During this time, considerable progress on species assimilation was made. By March 2006, the new CMAM-DAS had delivered a 1.5 year assimilated run, developed an improved assimilation set-up for a re-run of this period, and provided fields to measurement teams. Technology transfer to EC includes (1) 3D-Var improvements (such as generalized vertical coordinates, species assimilation and improved radiance assimilation) some of which helped to obtain a contract to EC from ESA to develop a chemical data assimilation scheme around GEM (EC's operational weather forecast model), and (2) new species observations in EC's assimilation-ready format along with conversion software (started under GCC and continued by EC for the ESA-contract). Scientifically, the CMAM-DAS is at the forefront of research in middle atmosphere data assimilation, being the first such system based on an interactive GCM as well as the first with mesospheric assimilation capability (Polavarapu et al., 2005). This position leads to a unique perspective on the challenges ahead in middle atmosphere data assimilation (Polavarapu et al., 2006; Polavarapu and Shepherd, 2006). The GCC work also led to further insight into gravity wave filtering schemes employed by assimilators (Polavarapu et al., 2004) and their impact on the mesosphere where gravity waves are ubiquitous (in preparation). Advances in data assimilation techniques were also made.

CMAM-DAS system advances: generalized vertical coordinates, adaptation to 71-level model with interactive chemistry including heterogeneous and tropospheric methane chemistry, adaptation to IBM supercomputer, digital filter replaced by IAU, improved interpolation to radiative transfer model levels.

Extension for species assimilation: new forward observation operators, new data in CMC format (BURP) including ACE, MAESTRO, OSIRIS, GOME, TOMS, SBUV, ozonesondes, Brewers, new libraries for chemical DA code, proposed updates to WMO format for species observations. Note that the technical work on chemical assimilation was continued in March 2005-March 2006 outside of GCC by EC, as required by the contract to ESA.

Deliverables:
- 1.5 year set of assimilated fields (Dec. 15, 2001 – July 15, 2003) using CMAM8 T47L71 with heterogeneous chemistry, digital filter, on-line background check (called FDAM v.1). Dynamic fields were validated against radiosondes and ozonesondes in the troposphere and lower stratosphere, AMSU-A in the stratosphere and SABER in the mesosphere.
- A second version of assimilation products (FDAM v.2) from 15 Dec. 2001 was launched in March 2006. Includes improvements to CMAM (incl. tropospheric methane chemistry), 3D-Var (vertical interpolation), digital filter replaced by IAU.
- Provision of CMAM-DAS fields (incl. species) for Eureka, TAO (Toronto), Odin-SMR researchers.
- A preliminary assimilation of OSIRIS data.

Task VI: Model validation

During the project a major process-oriented validation initiative for chemistry-climate models was developed under the auspices of SPARC, called CCMVal (Eyring et al., 2005). Shepherd has been centrally involved in this activity, including the program committee for the two CCMVal workshops in 2003 and 2005, and serves on the CCMVal Steering Committee. A first set of validation diagnostics was published in Eyring et al. (2006). While no model is perfect, it must be said that CMAM fared very well.

We have also been developing our own validation activities (some of which are also covered under other Tasks).

I. Folkins at Dalhousie compared model tropospheric chemical fields with available measurements, especially in situ and those from MOPITT. He has compared chemical measurements (including from ACE-FTS) with simulated tropical profiles from a variety of convective schemes, including Zhang and McFarlane, which is used in CMAM. The chemical scheme of CMAM has not been in a position to allow tropospheric comparisons until recently but the comparisons he has produced have direct implications for CMAM, as well as other models. With regard to tropical tropopause temperatures, Folkins has not done any direct work with CMAM, but has been engaged in process studies attempting to define the rate of convective outflow in the TTL, something which has an influence on cold point temperatures. This work will play a role in future assessment of models including CMAM.

At Toronto, post-doc T. Birner has compared the thermal structure of the extratropical tropopause region in CMAM with that from high-resolution radiosondes. The comparison (Birner et al., 2006) shows that CMAM exhibits a tropopause inversion layer of realistic strength, though it is too thick and too far from the tropopause itself (presumably because of limited vertical resolution in CMAM). Comparison with the CMAM-DAS analyses shows that the data assimilation process smoothes out this feature, especially in the southern hemisphere where there is a paucity of radiosonde observations. The feature is similarly weak in the NCEP-NCAR reanalysis. This work thus not only helps to validate CMAM, but shows how data assimilation can sometimes degrade a model's representation of the atmosphere.

RA C. McLandress was involved in a collaboration with Prof. Alan Manson of the University of Saskatchewan in which mean winds, tides and planetary waves from CMAM were compared to observations from a network of ground-based radar stations (Manson et al., 2006). This built on an earlier CMAM collaboration between RA J. Koshyk and Prof. Manson (Manson et al., 2002a,b). McLandress also compared the diurnal tide in the extended version of CMAM with WINDII observations (McLandress 2002a,b). This provided a validation of the representation of the diurnal tide in CMAM; and then, with the CMAM tide validated, CMAM could be analysed to provide an understanding of the mechanisms for the annual cycle in tidal amplitude observed by WINDII and previously unexplained. This example clearly illustrates the two-way synergy that is possible between models and measurements, to the mutual benefit of both.

C. McLandress and T. Shepherd were also involved in collaborations with students in Prof. Kim Strong's group at Toronto, providing chemical species from CMAM V7 at selected locations for comparison to ground based data. One paper (Farahani et al., 2006) has been accepted for publication, and another (Melo et al.) is in preparation.

Visiting student S. Tegtmeier from AWI Potsdam worked with T. Shepherd to apply the diagnostics developed by Fioletov and Shepherd (2003, 2005) for total ozone observations to validate the persistence and photochemical decay of ozone anomalies in

CMAM (Tegtmeier and Shepherd, 2006). Also post-doc M. Hegglin worked with T. Shepherd using ACE-FTS observations to validate the structure and seasonal dependences of O_3-N_2O correlations in CMAM (in preparation).

W. Ward obtained CRISTA stratospheric data, but because of the short time period of the mission it proved difficult to compare to CMAM climate. We considered using an assimilation run for this comparison, but the tropospheric observations for this period were saved in a now-obsolete format and the effort required to transform this data to a usable format was considered too great, given the other work required for the assimilation effort.

Comparisons between the extended CMAM data and ground-based observations in the mesosphere/lower thermosphere are underway as part of Ph.D. candidate J. Du's thesis.

The results from the vertically extended version of CMAM are among the first GCM results allowing the dynamical structures and energy balance in the mesopause region to be analysed (e.g. Fomichev et al., 2002; Ward et al., 2005; McLandress et al., 2006). Tidal components dominate the dynamics of this region and their impact and signatures in models and in observations is only now being realized.

Task VII: Simulation of pre-industrial and future climate

Due to serious limitations in supercomputer resources associated with the several changes made to the MSC supercomputer system during the project (see below), progress in this area was significantly delayed and work with the slab ocean had to be abandoned. However, we were able to re-direct our efforts and some very important achievements were made by the end of the project.

We were able to perform a set of three 20-year time-slice experiments with CMAM for the 2002 WMO/UNEP Ozone Assessment. This was a significant effort for us in terms of both human and computational resources (mainly by RA S. Beagley and T. Shepherd, though others also contributed), but we felt it was important for Canada to contribute to this activity. The results are described in Austin et al. (2003), and had a major impact on the conclusions of the 2002 Assessment, as well as on the 2005 IPCC/TEAP Special Report on Ozone and Climate (see Pyle and Shepherd, 2005). Taken together, the new simulations predicted that there would not be a severe Arctic ozone hole (resulting from climate change) rivalling that of the Antarctic in the coming decades; this was in contrast to simpler calculations considered in the 1998 Assessment. This underscores the importance of participating in international assessments, because the collective result was much stronger than an individual model result could ever be.

We subsequently performed a series of doubled-CO_2 experiments with CMAM, which enabled a number of process-oriented studies. Because of resource limitations with the MSC supercomputer, these experiments had to be performed with only gas-phase ozone chemistry (i.e. no heterogeneous chemistry). Thus, there was no polar ozone depletion. However the experiments help to understand some of the processes involved in chemical-climate change, especially in the upper stratosphere and mesosphere, but also dynamical processes in the lower stratosphere. The radiative-photochemical response of the middle atmosphere to the doubling of CO_2 and a detailed analysis of the processes responsible was given in Jonsson et al. (2004). It was shown that the mesospheric diurnal tide is amplified in response to the CO_2 increase (McLandress and Fomichev, 2006), mainly as a result of increased water vapour in the troposphere. This provides the first self-consistent example of a change in the coupling processes between the lower and upper atmosphere that occurs in response to climate change. Also, we participated (by invitation) in an intercomparison of mesospheric temperature trends by providing CMAM data. The resulting paper (Beig et al., 2003) won the WMO's Norbert-Gerbier Mumm Award for 2005.

Fomichev et al. (J. Clim., in press) found that the middle atmosphere response to the CO_2 doubling and to the associated changes in sea-surface temperatures (SSTs) was largely additive. The former can be considered the intrinsic middle atmosphere radiative-chemical response, and the latter the dynamical response to tropospheric changes. (If tropospheric SSTs are held fixed, then the troposphere is largely unchanged even when CO_2 doubles.) In this way, the dynamical impact on the middle atmosphere can be isolated. It was found that there was a discernible increase in tropical lower stratospheric upwelling associated with an increase in wave drag, a result that is consistent with the intercomparison study performed under the SPARC GRIPS initiative (Butchart et al., 2006), which included CMAM. It was also found that the Arctic response was not possible to discern with a 30-year integration, due to decadal-timescale variability. This highlights a major challenge in identifying climate change in the Arctic stratosphere.

This work set the stage for some transient climate-change experiments performed (with heterogeneous chemistry) during 2005-6 for the 2006 WMO/UNEP Ozone Assessment, to investigate the combined effects of ozone depletion/recovery and climate change. This was done within the context of the SPARC CCMVal activity, according to two reference simulations. Because of computer issues we got a late start, but in the end were able to contribute a full set of runs. This involved a concerted effort from RAs K. Semeniuk and S. Beagley, as well as D. Plummer and J. Scinocca at CCCma. We performed one REF1 simulation, focusing on the past from 1960-2004, and including effects of observed SSTs and volcanic eruptions (Eyring et al., 2006). We also performed three REF2 simulations, extending to the future and covering 1960-2100, and driven by SSTs from three transient coupled AOGCM simulations from CCCma. The CMAM results were only just completed by the end of the GCC project, so there was no time to analyse them within the project, but the results provided a key element in the model intercomparison performed for the 2006 Ozone Assessment (especially since CMAM proved to be one of the half-dozen models most trusted for this purpose by the panel).

Task VIII: Simulation of solar cycle effects

This task was supposed to be done with a new radiation scheme based on the correlated k-distribution method, which will have a much better spectral resolution in the shortwave part of spectrum — a necessary condition for studying the effects of solar variability. The current CMAM shortwave scheme is not adequate for this purpose. As noted above under Task IV, delays at CCCma prevented the development of the correlated k-distribution scheme for CMAM. Thus, this task had to be abandoned.

Task IX: Simulation of effects of volcanic eruptions

Due to resource limitations associated with the changes to the supercomputing system, this work was not performed. The effects of volcanic eruptions were included in the REF1 simulation described under Task VII. However, their impact has yet to be analysed.

Task X: Use of CMAM to interpret Canadian measurements and aid in design of new Canadian measurement systems

C. McLandress used CMAM data to assess the representativeness of SWIFT winds and ozone-flux measurements. This was done by adding prescribed levels of random noise to the model data before computing various quantities such as mean winds and planetary waves in the tropics, the residual circulation and the meridional flux of ozone. These results demonstrated that for achievable levels of instrument noise, useful information about these geophysical quantities can be obtained from SWIFT. This study proved to be crucial in developing the measurement requirements for SWIFT as part of ESA's Stratospheric Dynamics Mission Requirements Document. SWIFT will now be flown by CSA aboard Chinook, but the same mission requirements are being used.

Work on developing a measurement strategy for MIMI (now called WaMI) was started by Ward, and forward-model software for this instrument has been developed. It is capable of including input from the extended CMAM. In 2001, CSA funding for this effort ceased and the team of scientists dispersed. Recently funding for a new project has become available and this activity has started again. The amplitudes and phases of the large scale wave features diagnosed in CMAM will be used to drive the wind and temperature structures in the forward model and allow an evaluation of the capabilities of this instrument. Work on trajectory analyses of CMAM data are currently under way and constitute part of Ph.D. candidate J. Du's thesis. This analysis will provide a clear idea of how best to operate the WaMI instrument. This work will be valuable for supporting the inclusion of WaMI in scientific missions directed toward the observation of the mesosphere and lower thermosphere.

This sort of work supports the development of Canadian satellite instrumentation and its inclusion as part of international payloads. It is thus important to Canada's space industry and for developing new technologies.

Analysis of CMAM fields has also proved important for interpreting Canadian atmospheric measurements and, in particular, assessing their representativeness. Sankey and Shepherd (2003) showed that simulated ACE measurements could be used to define a climatology of chemical correlations for long-lived species despite the severe sampling limitations imposed by the solar occultation measurement technique, and that higher latitude profiles were superior in this respect to low-latitude profiles. Work with M.

Hegglin at Toronto using CMAM has furthermore shown that ACE sampling is sufficient to define the structure and seasonal evolution of O_3-N_2O correlations (manuscript in preparation). K. Semeniuk at York has used CMAM to help understand aspects of ACE polar measurements, including the response to a major Solar Proton Event (Semeniuk et al., 2005; Jin et al., 2005). Several Toronto Ph.D. students from the experimental group have used CMAM data to further their research: M. Toohey to understand sampling and variability of ACE ozone measurements, E. Farahani to define a climatology of various species from sparse ground-based measurements at Eureka, and D. Wunch to help predict turnaround conditions for the launch of the MANTRA balloon mission. Finally, C. McLandress has been working with G. Shepherd and S. Zhang at York University (manuscripts in preparation) to use CMAM data to assess the quality of the mean meridional winds obtained from WINDII measurements, which is a challenging task because of tidal aliasing in the WINDII measurements.

Task XII: Modelling of the quasi-biennial oscillation

C. McLandress examined the role of parameterized gravity wave drag (GWD), including its finite difference scheme, on the simulated QBO. While the simulated QBO may not be credible because of sensitivity to numerical aspects, it does allow study of the impact of the QBO on other fields. In that spirit, McLandress (2002) was able to study the impact of the QBO on middle atmosphere tides. McLandress visited CCCma for an extended period and worked with J. Scinocca on an improved representation of the QBO in CMAM, which required an increased vertical resolution. An extended simulation with this improved QBO is being studied by Ph.D. student J. Anstey at Toronto, to understand the impact of a QBO on polar vortex biases.

Because of the sensitivity of the QBO in climate models to parameterized GWD, it is important to understand this dependence. This was explored in idealized studies by post-doc L. Campbell at Toronto (Campbell and Shepherd, 2005a,b).

Task XIII: Resolution sensitivity experiments

Because of resource limitations, extensive resolution sensitivity experiments could not be performed. However, some multi-year simulations were performed to investigate the impact of resolution on the transport of constituents. Results have shown a minor impact of resolution on the column ozone distribution, and on the speed of the water-vapour tape recorder which characterises vertical transport in the tropical lower stratosphere. Based on these results (and bearing in mind our computational limitations), we decided that T32 provided an acceptable horizontal resolution during this project. However, we did make some effort to increase vertical resolution, especially in the lower stratosphere, moving from 50 to 71 vertical levels during the course of the project. The increase of vertical resolution still requires a minimum background eddy diffusivity to prevent numerical effects such as undershoots and overshoots caused by the transport of water vapour in the vicinity of the tropical tropopause. The annual mean downward transport of ozone into the lowermost stratosphere has been estimated at 716 Tg/year, in reasonable agreement with observation-based estimates

Although not strictly a resolution issue, we have also explored some dependences on the representation of parameterized physical processes.

Scinocca and McFarlane (2004) investigated the role of parameterized deep convection and resolved stratiform precipitation in the forcing of resolved tropical waves. This built on an earlier SPARC GRIPS intercomparison involving CMAM (Horinouchi et al., 2003), which showed the dependence of the frequency spectrum of resolved tropical waves (which are important, among other things, for driving the QBO) on the nature of the convection parameterization scheme.

One of the great uncertainties of middle atmosphere climate modelling is the representation of gravity-wave drag (GWD). We made a number of significant advances which considerably narrow the uncertainties arising from the use of GWD schemes in climate models. McLandress and Scinocca (2005) used CMAM to show that different GWD parameterizations give virtually identical results (for mean climate) provided the same GW source spectra are used and that the "saturation altitude" is similar. In fact, they show that one can dispense with *ad hoc* saturation mechanisms altogether and let the model determine the breaking heights. Toronto Ph.D. student T. Shaw, working with T. Shepherd, showed theoretically that provided the implementation of GWD in climate models is momentum conserving, the downward influence of changes in GWD arising from middle atmosphere climate perturbations is very limited (Shepherd and Shaw, 2004). However non-conservative implementations, as are commonly found in climate models, can lead to spurious downward influence. They went on to show, using idealized modelling, that momentum conservation ensures a robust response to climate perturbations, whereas non-conservation can lead to a strong sensitivity to factors such as model lid height (Shaw and Shepherd, in press).

Task XIV: Transfer of modelling technology to MSC

This work involved the transfer of model code and diagnostics to MSC, including the merging and development of a new MPI CMAM code suite suitable for the new IBM architecture at MSC. In particular, the older CMAM chemistry, radiation, physics, and dynamics components had to be ported and tested in a series of versions of the newer CCCma code suites as the latter were developed at Victoria. While this took much time and effort to achieve, the final product — run on the new IBM architecture and based on a frozen CCCma model configuration which is entirely supported by MSC — was used for the simulations performed in support of the 2006 WMO/UNEP Ozone Assessment. The fact that we were able to produce one 55-year simulation and three 150-year simulations confirms that we are now running on one of the fastest computers available and makes long simulations with CMAM a practical option.

Considered together with its options for tropospheric chemistry and for vertical extension into the thermosphere, CMAM now represents a very significant and unique modelling capability for Canada throughout the neutral atmosphere, which is competitive at an international level and which provides an essential tool for assessment of chemical-climate coupling, including the coupling between ozone depletion/recovery and climate change.

The data assimilation version of CMAM likewise represents a unique modelling capability for Canada, insofar as the CMAM-DAS is the only such system with fully interactive chemistry and a model domain extending above the mesosphere. This system is likewise fully supported within the MSC environment.

2. Research Team

Please provide an overview of the participation in, and scientific contributions to, the project by each member of the research team (principal investigator, co-investigators, senior research associates, company and government scientists, collaborators and students etc.).

- T.G. Shepherd, Principal Investigator, Toronto: Tasks III, V, VII
- J.C. McConnell, Co-investigator, York: Tasks I, VI, VII
- N.A. McFarlane, Co-investigator, Environment Canada/Victoria: Tasks IV, VII
- I.A. Folkins, Co-investigator, Dalhousie: Task VI
- J.F. Scinocca, Co-investigator, Environment Canada/Victoria: Tasks III, XIII, XIV
- S.M. Polavarapu, Co-investigator, Environment Canada/Toronto: Tasks V, XI
- W.E. Ward, Co-investigator, New Brunswick: Tasks VI, X
- P.A. Ariya, Co-investigator, McGill: Tasks I, II
- D.V. Michelangeli, Co-investigator, York: Tasks I, II, IX
- J. Li, Co-investigator, Environment Canada: Task IV
- U. Lohmann, Co-investigator, Dalhousie: Tasks II, IX
- J.P.D. Abbatt, Co-investigator, Toronto: Task II

- R. Ménard, Collaborator, Environment Canada: Tasks V, XI
- Y. Rochon, Collaborator, Environment Canada: Tasks V, XI

- J. Anstey, Ph.D. student, Toronto: Task VII
- S.R. Beagley, Research Associate, York: Tasks VII, XIV
- F. Bender, undergrad summer student, Toronto: Task X
- T. Birner, Post-doctoral fellow, Toronto: Task VI
- C. Braban, Ph.D. student, Toronto: Task II; now a post-doc at the University of Cambridge
- C. Braun, Research Assistant, Dalhousie: Task VI
- K. Broekhuisen, Post-doctoral fellow, Toronto: Task II; now Assistant Professor at Colgate University
- L. Campbell, Post-doctoral fellow, Toronto: Task XII; now Assistant Professor at Carleton
- D. Chartrand, Research Associate, York: Tasks IX, X; now with Jacques Whitford Environmental Consultants
- S. Codoban, Ph.D. student, Toronto: Task III
- B. Croft, Ph.D. student, Dalhousie: Task II
- J. Du, Ph.D. student, UNB: Task VI

- J. de Grandpré, Research Assistant, McGill: Tasks III, XIII; now a post-doc at Environment Canada
- G. Folberth, Post-doctoral fellow, Victoria: Task I
- V.I. Fomichev, Research Associate, York: Tasks IV, VIII, X
- M. Fruman, Ph.D. student, Toronto: Task III; now a post-doc at IFREMER, France
- C. Fu, Ph.D. student, York: Task VI
- R. Hallman, undergrad summer student, Toronto: Task VI
- M. Hegglin, Post-doctoral fellow, Toronto: Task VI
- A. Jonsson, Ph.D. student, Stockholm (long-term visitor at York): Task VI
- J.N. Koshyk, Research Associate, Toronto: Tasks V, VI; now with TD Bank
- E. Leon, Research Assistant, Toronto: Task VI; now a computer programmer at Toronto
- J. Liang, undergrad summer student, Toronto: Task V; now a grad student at York
- J.V. Lukovich, Ph.D. student, Toronto: Task III; now an RA at Manitoba
- B.D. MacKenzie, M.Sc. student, UNB: Task VI
- D. Matthews, M.Sc. student, McGill: Task II
- C. McLandress, Research Associate, Toronto: Tasks X, XII
- L. Neef, M.Sc. and Ph.D. student, Toronto: Task V
- M. Neish, Research Assistant, Toronto: Task V
- D. Pendlebury, Ph.D. student, Toronto: Task III; now Project Scientist with the SPARC International Project Office, Toronto
- D. Plummer, Research Associate, York: Task I; now Research Scientist with Environment Canada
- M. Pritchard, undergrad summer student, Toronto: Task VI; now a grad student at Alberta
- G. Probst, M.Sc. student, McGill: Task I
- C. Reader, Research Associate, Victoria: Task II
- S. Ren, Research Associate, Toronto: Task V
- M. Reszka, Post-doctoral fellow, Toronto: Task V; now a post-doc at Environment Canada
- B. Revenaz, M.Sc. student, McGill: Task I; now with an environmental consulting company in the US
- J. Russell, Post-doctoral fellow, UNB: Task VI; currently working as a Physics Instructor at the Department of Physics, UNB
- A. Ryzhkov, Post-doctoral fellow, McGill: Task I
- D. Sankey, Research Associate, Toronto: Tasks III, V, X, XI; now working in industry (software engineering)
- K. Semeniuk, Research Associate, York: Task IX, X
- T. Shaw, undergrad summer student and then grad student, Toronto: Task XIII
- J. Sun, Ph.D. student, McGill: Task II
- A. Tang, Ph.D. student, York: Task X
- J. Taylor, undergrad summer student, UNB: Task X; now a grad student at Toronto
- Y. Tomikawa, Post-doctoral fellow, Toronto: Task VI; now a Research Scientist at NIPR, Tokyo
- D. Vyushin, Research Assistant, Toronto: Task III; now a grad student at Toronto

- M. Wahid, M.Sc. student, Dalhousie: Task II; now a government meteorologist in Bangladesh
- X. Wang, Post-doctoral fellow, York: Task IX
- Y. Yang, Research Associate, Toronto: Task V
- X. Zhang, M.Sc. student, York: Task VI; now an RA at York

3. TRAINING

3.1 Please list how many of each type of trainee were involved in the strategic project and the number of person years each type of trainee spent on this project.

	NUMBER	NUMBER OF PERSON YEARS
UNDERGRADUATE STUDENTS	6	1.5
MASTER'S STUDENTS	8	8
DOCTORAL STUDENTS	14	42
POSTDOCTORAL FELLOWS	10	18
RESEARCH ASSOCIATES	11	50
TECHNICIANS		
OTHER (RESEARCH ASSISTANTS)	5	9
TOTAL	53	

To further our training, we had originally proposed to hold a summer school during the course of the project. On further reflection it became clear that it would work better to have two summer schools, one focused on the chemistry-climate side of the project and one focused on the measurements-modelling side. Each was one week long (actually six days). The first (chemistry and climate) was held in Montréal during August 2003, and the lecturers were Jon Abbatt, Parisa Ariya, Ian Folkins, Glen Lesins, Ulrike Lohmann, Norm McFarlane, Diane Michelangeli, David Plummer, John Scinocca, Ted Shepherd, and Knut von Salzen. There were other 50 participants, the majority of which were from Canada, but there were several international applicants from both the USA and Europe. The second school (measurements and modelling) was held in Banff during May 2004, and the lecturers were Jack McConnell, Ted Shepherd, Ian McDade, Dylan Jones, William Ward, Saroja Polavarapu, Michelle Santee, Tom McElroy, Charles McLandress, Stella Melo, and Richard Ménard. There were 35 other participants. The latter school in particular was a tremendously successful event and we therefore decided to hold a third summer school, again in Banff, during May 2005, on the use of models for the interpretation of measurements. The lecturers were Dylan Jones, Paul Kushner, Markus Rex, Richard Rood, Anne Douglass, Adam Sobel, and Charles McLandress, and once again we had approximately 35 other participants, the majority from Canada but including several from the USA and Europe.

3.2 What type(s) of interaction did the highly qualified personnel (HQP) have with the partners during the project? (Select all that apply.)

☒ HQP presented research results to the partners
☒ HQP discussed the project directly with partners to obtain input
☒ Partners jointly supervised thesis projects of HQP
☒ HQP worked regularly in the partner's facilities
☐ Other (specify)________________________________
☐ HQP did not interact with the partners

3.3 To the best of your knowledge, please complete the following table on the employment of HQP involved in the project.

TYPE OF HQP	# HIRED BY PARTNER	# HIRED BY INDUSTRY	# HIRED BY GOVERNMENT LABS	# EMPLOYED IN ACADEMIA (FACULTY)	# HIRED BY OTHER (RES ASSOC/ASST)	# IN ACADEMIC TRAINING
Undergraduate Students		1				5
Master's Students		1	1		1	5
Doctoral Students					2	12
Postdoctoral Fellows			1	3	2	3
Research Associates	1	3	1		7	
Technicians						
Other (Res Asst)		1			2	2

4. DISSEMINATION OF RESEARCH RESULTS AND KNOWLEDGE OR TECHNOLOGY TRANSFER

Please list all publications (specify if submitted, accepted or published), conference presentations, workshops, patents (applied for and/or granted) and licences arising from the research project supported by the grant.

4.1 PUBLICATIONS, CONFERENCE PRESENTATIONS, ETC.

☐ None to date
-or-

FULL CITATION (TITLE/REFERENCE)	REFEREED JOURNAL ARTICLES	CONFERENCE PRESENTATION /POSTER	OTHER (INCLUDING TECHNICAL REPORTS, NON-REFEREED ARTICLES, ETC.)
Accepted/Published:			
Akmaev, R.A., Fomichev, V.I. and X. Zhu, 2006: Impact of middle-atmospheric composition changes on greenhouse cooling in the upper atmosphere. *J. Atmos. Solar-Terr. Phys.*, accepted.	**YES**		
Andersen, S.B., Stevermer, A., Weatherhead, E.C., Austin, J., Brühl, C., Fleming, E.C., de Grandpré, J., Grewe, V., Isaksen, I., Pitari, G., Portmann, R.W., Rognerud, B., Rosenfield, J.E.,	**YES**		

Smyshlayev, S., Nagashima, T., Velders, G.J.M., Weisenstein, D.K. and J. Xia, 2006: Comparison of recent modeled and observed trends in total column ozone. *J. Geophys. Res.*, **111**, 10.1029/2005JD006091.			
Austin, J., Shindell, D., Beagley, S.R., Brühl, C., Dameris, M., Manzini, E., Nagashima, T., Newman, P., Pawson, S., Pitari, G., Rozanov, E., Schnadt, C. and T.G. Shepherd, 2003: Uncertainties and assessments of chemistry-climate models of the stratosphere**.** *Atmos. Chem. Phys.*, **3**, 1-27.	**YES**		
Avzyanova, E. and P.A. Ariya, 2002: Kinetic studies of ozonolysis of selected terminal and internal alkenes: evaluation of HO yield. *Int. J. Chem. Kinet*., **34,** 678-684.	**YES**		
Beig, G., Keckhut, P., Lowe, R.P., Roble, R.G., Mlynczak, M.G., Scheer, J., Fomichev, V.I., Offermann, D., French, W.J.R., Shepherd, M.G., Semenov, A.I., Remsberg, E.E., She, C.Y., Lubken, F.J., Bremer, J., Clemesha, B.R., Stegman, J., Sigernes, F. and S. Fadnavis, 2003: Review of mesospheric temperature trends. *Rev. Geophys*., **41**, 10.1029/2002RG000121.	**YES**		
Birner, T., Sankey, D. and T.G. Shepherd, 2006: The tropopause inversion layer in models and analyses. *Geophys. Res. Lett.*, **33**, 10.1029/2006GL026549.	**YES**		
Braban, C.F., Carroll, M.F., Styler, S.A. and J.P.D. Abbatt, 2003: Phase transitions of malonic and oxalic acid aerosols. *J. Phys. Chem*., **107**, 6594-6602.	**YES**		
Braban, C. and J.P.D. Abbatt, 2004: A study of the phase transition behaviour of mixed ammonium sulfate - malonic acid aerosols. *Atmos. Chem. Phys.*, **4**, 1451-1459.	**YES**		
Broekhuizen, K., Chang, R., Abbatt, J.P.D., Leaitch, W.R. and S.-M. Li, 2006: Closure between measured and modeled cloud condensation nuclei (CCN) using size-resolved aerosol compositions in downtown Toronto, *Atmos. Chem. Phys.*, **6**, 2513-2524.	**YES**		
Butchart, N., Scaife, A.A., Bourqui, M., de Grandpré, J., Hare, S.H.E., Kettleborough, J., Langematz, U., Manzini, E., Sassi, F., Shibata, K., Shindell, D. and M. Sigmond, 2006: Simulations of anthropogenic change in the strength of the Brewer-Dobson circulation. *Clim. Dyn*., **27**, 727-741.	**YES**		
Campbell, L.J. and T.G. Shepherd, 2005: Constraints on wave-drag parameterization schemes for simulating the quasi-biennial oscillation. Part 1: Gravity wave forcing. *J. Atmos. Sci*., **62**, 4178-4195.	**YES**		
Campbell, L.J. and T.G. Shepherd, 2005: Constraints on wave-drag parameterization schemes for simulating the quasi-biennial oscillation. Part 2: Combined effects of gravity waves and equatorial planetary waves. *J. Atmos. Sci*., **62**, 4196-4205.	**YES**		
Codoban, S. and T.G. Shepherd, 2003: Energetics of a symmetric circulation including momentum constraints. *J. Atmos. Sci.*, **60**, 2019-2028.	**YES**		
Codoban, S. and T.G. Shepherd, 2006: On the available energy of an axisymmetric vortex. *Meteorol. Z.*, **15**, 401-407.	**YES**		
Croft, B., Lohmann, U., and K. von Salzen, 2005: Black carbon ageing in the Canadian Centre for Climate modeling and analysis atmospheric general circulation model. *Atmos. Chem. Phys.*, **5**, 1931-1949.	**YES**		

Eyring, V., Harris, N.R.P., Rex, M., Shepherd, T.G. *et al*., 2004: Comprehensive summary of the workshop on "Process-oriented validation of coupled chemistry-climate models". *SPARC Newsletter*, **No. 23,** 5-11.			**YES**
Eyring, V., Harris, N.R.P., Rex, M., Shepherd, T.G. and 16 others, 2005: A strategy for process-oriented validation of coupled chemistry-climate models. *Bull. Amer. Met. Soc.*, **86**, 1117-1133.	**YES**		
Eyring, V., and 36 others (including D. Plummer and T.G. Shepherd), 2006: Assessment of coupled chemistry-climate models: Evaluation of dynamics, transport characteristics and ozone. *J. Geophys. Res*., **111**, 10.1029/2006JD007327.	**YES**		
Farahani, E., Fast, H., Mittermeier, R.L., Makino, Y., Strong, K., McLandress, C., Shepherd, T.G., Chipperfield, M.P., Hannigan, J.W., Coffey, M.T., Mikuteit, S., Hase, F., Blumenstock, T. and U. Raffalski, 2006: Lunar and solar FTIR nitric acid measurements at Eureka in winter 2001/2002: Comparisons with observations at Thule and Kiruna and with CMAM and SLIMCAT model calculations. *J. Geophys. Res*., accepted.	**YES**		
Fioletov, V.E. and T.G. Shepherd, 2003: Seasonal persistence of midlatitude total ozone anomalies. *Geophys. Res. Lett.*, **30**, 10.1029/2002GL016739.	**YES**		
Fioletov, V.E. and T.G. Shepherd, 2005: Summertime total ozone variations over middle and polar latitudes. *Geophys. Res. Lett.*, **32**, 10.1029/2004GL022080.	**YES**		
Folberth, G.A, Hauglustaine, D.A., Ciais, P. and J. Lathiere, 2005: On the role of atmospheric chemistry in the global CO_2 budget, *Geophys.Res.Lett.*, **32**, 10.1029/2004GL021812.	**YES**		
Folkins, I., 2002: Origin of lapse rate changes in the upper tropical troposphere. *J. Atmos. Sci.*, **59**, 992-1005.	**YES**		
Folkins, I. and C. Braun, 2003: Tropical rainfall and boundary layer moist entropy. *J. Clim*., **16**, 1807-1820.	**YES**		
Folkins, I., Braun, C., Thompson, A.M. and J.C. Witte, 2002: Tropical ozone as an indicator of deep convection. *J. Geophys. Res*., **107**, 10.1029/2001JD001178.	**YES**		
Folkins, I., Kelly, K.K. and E.M. Weinstock, 2002: A simple explanation for the increase in tropical relative humidity between 11 and 14 km. J. *Geophys. Res.*, **107**, 10.1029/2002JD002185.	**YES**		
Folkins, I. and R. Martin, 2005: The vertical structure of the tropical troposphere. *J. Atmos. Sci*., **62**, 1560-1573.	**YES**		
Fomichev, V.I., Ward, W.E., Beagley, S.R., McLandress, C., McConnell, J.C., McFarlane, N.A. and T.G. Shepherd, 2002: The extended Canadian Middle Atmosphere Model: zonal--mean climatology and physical parameterizations. *J. Geophys. Res*., **107**, 10.1029/2001JD000479.	**YES**		
Fomichev, V.I., Fu, C., de Grandpré, J., Beagley, S.R., Ogibalov, V.P. and J.C. McConnell, 2004: Model thermal response to minor radiative energy sources and sinks in the middle atmosphere. *J. Geophys. Res*., **109**, 10.1029/2004JD004892.	**YES**		
Fomichev V.I., Ogibalov, V.P. and S.R. Beagley, 2004: Solar heating by the near-IR CO2 bands in the mesosphere. *Geophys. Res. Lett.*, **31**, 10.1029/2004GL020324.	**YES**		
Fomichev, V.I., Jonsson, A.I., de Grandpré, J., Beagley, S.R., McLandress, C., Semeniuk, K., and T.G. Shepherd, 2006: Response of the middle atmosphere to CO2 doubling: results from	**YES**		

the Canadian Middle Atmosphere Model. *J. Clim.*, accepted.			
Forbes, J.M., Zhang, X., Ward, W.E. and E. Talaat, 2002: Climatological features of stationary planetary waves in the stratosphere, mesosphere and lower thermosphere between 40° latitude. *J. Geophys. Res.*, **107**, 10.1029/2001JD001232.	**YES**		
Forbes, J.M., Zhang, X., Talaat, E. and W.E. Ward, 2002: Nonmigrating diurnal tides in the thermosphere. *J. Geophys. Res.*, **108**, 10.1029/2002JA009262.	**YES**		
Fruman, M.D., 2005: Equatorial symmetric stability. PhD Thesis, Department of Physics, University of Toronto.			**THESIS**
Hauglustaine, D.A., Lathiere, J., Szopa, S. and G.A. Folberth, 2005: Future tropospheric ozone simulated with a climate-chemistry model. *Geophys. Res. Lett.*, **32**, L24807, 10.1029/2005GL024031.	**YES**		
Haynes, P.H. and T.G. Shepherd, 2001: Report on the SPARC Tropopause Workshop. *SPARC Newsletter*, **No. 17**, 3-10.			**YES**
Haynes, P.H., J.F. Scinocca and M. Greenslade, 2001: Formation of the mid-latitude tropopause through the action of baroclinic eddies. *Geophys. Res. Lett.*, **28**, 4179-4182.	**YES**		
Hendricks, J., Kärcher, B., Döpelheuer, A., Feichter, J., Lohmann, U. and D. Baumgardner, 2004: Simulating the global atmospheric black carbon cycle: A revisit to the contribution of aircraft emissions, *Atmos. Chem. Phys.*, **4**, 2521-2541.	**YES**		
Hendricks, J., Kärcher, B., Lohmann, U. and M. Ponater, 2005: Do aircraft black carbon emissions affect cirrus clouds on the global scale? *Geophys. Res. Lett.*, **32**, doi: 10.1029/2005GL022740.	**YES**		
Horinouchi, T., Pawson, S., Shibata, K., Langematz, U., Manzini, E., Sassi, F., Wilson, R.J., Hamilton, K.P., de Grandpré, J. and A.A. Scaife, 2003: Tropical cumulus convection and upward propagating waves in middle atmospheric GCMs. *J. Atmos. Sci.*, **60**, 2765-2782.	**YES**		
Jin, J.-J., Semeniuk, K., Jonsson, A., McConnell, J.C., Beagley, S.R., Boone, C.D., Walker, K.A., Bernath, P.F., Rinsland, C., Dupuy, E. and D. Murtagh, 2005: A comparison of co-located ACE-FTS and SMR stratospheric-mesospheric CO measurements during 2004 and comparison with a GCM. *Geophys. Res. Lett.*, **32**, L15S03, 10.1029/2005GL022433.	**YES**		
Jonsson, A., de Grandpré, J. and J.C. McConnell, 2002: A comparison of mesospheric temperatures from the Canadian Middle Atmosphere Model and HALOE observations: zonal mean and signature of the solar diurnal tide. *Geophys. Res. Lett.*, **29**, 10.1029/2001GL014476.	**YES**		
Jonsson, A.I., de Grandpre, J., Fomichev, V.I., McConnell, J.C. and S.R. Beagley, 2004: Doubled CO2-induced cooling in the middle atmosphere: Photochemical analysis of the ozone radiative feedback, *J. Geophys. Res.*, **109**, D24103, 10.1029/2004JD005093.	**YES**		
Kaplan, J.O., Folberth, G.A. and D.A. Hauglustaine, 2006: Glacial-interglacial changes in atmospheric methane concentrations are modulated by BVOC emissions. *Glob. Biogeochem. Cyc.*, accepted.	**YES**		
Kärcher, B. and U. Lohmann, 2002: A parameterization of cirrus cloud formation: homogeneous freezing of supercooled aerosols. *J. Geophys. Res.*, **107**, 10.1029/2001JD000470.	**YES**		
Kärcher, B. and U. Lohmann, 2002: A parameterization of cirrus	**YES**		

cloud formation: homogeneous freezing including effects of aerosol size. *J. Geophys. Res*., **107**, 10.1029/2001JD001429.			
Kärcher, B. and U. Lohmann, 2003: A parameterization of cirrus cloud formation: heterogeneous freezing. *J. Geophys. Res*., **108**, 10.1029/2002JD003220.	**YES**		
Kärcher, B., Hendricks, J. and U. Lohmann, 2006: Physically-based parameterization of cirrus cloud formation for use in global atmospheric models. *J.Geophys.Res*., **111**, 10.1029/2005JD006219	**YES**		
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.	**YES**		
Li, J. and H. Barker, 2005: A radiation algorithm with correlated k-distribution. Part I: Local thermal equilibrium. *J. Atmos. Sci*., **62**, 286-309.	**YES**		
Li, J.J., Dobbie, S., Raisanen, P. and Q. Min, 2005: Accounting for unresolved cloud in solar radiation. *Q. J. R. Meteor. Soc*., **131**, 1607-1629.	**YES**		
Lesins, G. and U. Lohmann, 2003: GCM aerosol forcing estimates using geographically varying aerosol sizes deduced from AERONET measurements. *J. Atmos. Sci*., **60**, 2747-2764.	**YES**		
Lin, J.L., Kiladis, G.N., Mapes, B.E., Weickmann, K.M., Sperber, K.R., Lin, W., Wheeler, M. and J.F. Scinocca, 2006: Tropical Intraseasonal Variability in 14 IPCC AR4 Climate Models. Part I: Convective Signals. *J. Clim*., **19**, 2665-2690.	**YES**		
Lohmann, U., 2002: Possible aerosol effects on ice clouds via contact nucleation. *J. Atmos. Sci*., **59**, 647--656.	**YES**		
Lohmann, U., 2002: A glaciation indirect aerosol effect caused by soot aerosols. *Geophys. Res. Lett*., **29**, 10.1029/2001GL014357.	**YES**		
Lohmann, U. and B. Kärcher, 2002: First interactive simulations of cirrus clouds formed by homogeneous freezing in the ECHAM GCM. *J. Geophys. Res*., **107**, 10.1029/2001JD000767.	**YES**		
Lohmann, U., Kärcher. B. and C. Timmreck, 2003: Impact of the Mt. Pinatubo eruption on cirrus clouds formed by homogeneous freezing in the ECHAM GCM. *J. Geophys. Res*., **108**, 10.1029/2002JD003185.	**YES**		
Lohmann, U., Broekhuizen, K., Leaitch, R., Shantz, N. and J. Abbatt, 2004: How efficient is cloud droplet formation of organic aerosols? *Geophys. Res. Lett*., **31**, 10.1029/2003GL018999.	**YES**		
Lohmann, U., Kärcher, B. and J. Hendricks, 2004: Sensitivity studies of cirrus clouds formed by heterogeneous freezing in the ECHAM GCM. *J.Geophys.Res*., **109**, 10.1029/2003JD004443.	**YES**		
Lorant, V., McFarlane, N.A. and J.F. Scinocca, 2006: Variability of precipitation intensity: sensitivity to treatment of moist convection in an RCM and a GCM. *Clim. Dyn*., **26**, 183-200.	**YES**		
Lukovich, J.V, 2001: Large-scale mixing in the middle atmosphere. PhD Thesis, Department of Physics, University of Toronto.			**THESIS**
Lukovich, J.V. and T.G. Shepherd, 2005: Stirring and mixing in two-dimensional divergent flow. *J. Atmos. Sci*., **62**, 3933-3954.	**YES**		
Manson, A.H., Meek, C.E., Hagan, M., Koshyk, J.N. *et al*., 2002: Seasonal variations of the semi-diurnal and diurnal tides in the MLT: multi-year MF radar observations from 2-70°N, modelled tides (GSWM, CMAM). *Ann. Geophys*., **20**, 661-677.	**YES**		
Manson, A.H., Meek, C.E., Koshyk, J.N. *et al*., 2002: Gravity-	**YES**		

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 (CMAM). *J. Atmos. Sol.-Terr. Phys*., **64**, 65-90.			
Manson, A.H., Meek, C.E., Chshyolkova, T., McLandress, C. *et al*., 2006: Winter warmings, tides and planetary waves: comparisons between CMAM (with interactive chemistry) and MFR-MetO observations and data. *Ann. Geophys*., **24**, 2493-2518.	**YES**		
McLandress, C., 2002: The seasonal variation of the propagating diurnal tide. Part I: The role of gravity waves and planetary waves. *J. Atmos. Sci*., **59**, 893-906.	**YES**		
McLandress, C., 2002: The seasonal variation of the propagating diurnal tide. Part II: The role of tidal heating and zonal-mean winds. *J. Atmos. Sci*., **59**, 907-922.	**YES**		
McLandress, C., 2002: Interannual variations of the diurnal tide in the mesosphere induced by zonal-mean wind oscillations in the tropics. *Geophys. Res. Lett*., **29**, 10.1029/2001GL014551.	**YES**		
McLandress, C. and J. Scinocca, 2005: A self-consistent intercomparison of gravity wave drag parameterizations. *J.Atmos.Sci*., **62**, 2394-2413.	**YES**		
McLandress, C. and V.I. Fomichev, 2006: Amplification of the mesospheric diurnal tide in a doubled CO_2 atmosphere. *Geophys.Res.Lett*., **33**, L06808, doi:10.1029/2005GL025345.	**YES**		
McLandress, C., Ward, W.E., Fomichev, V.I., Semeniuk, K., Beagley, S.R., McFarlane, N.A. and T.G. Shepherd, 2006: Large-scale dynamics of the MLT: an analysis using the extended Canadian Middle Atmosphere Model. *J. Geophys. Res*., **111**, 10.1029/2005JD006776.	**YES**		
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Ménard, R., Yang, Y. and S. Polavarapu, 2004, Model error estimation: Its application to chemical data assimilation. Proceedings of the ECMWF/SPARC Workshop on Modelling and Assimilation for the Stratosphere and Tropopause, June 23-26, 2003, 137-145.			**YES**
Neef, L.J., Polavarapu, S.M. and T.G. Shepherd, 2006: 4D data assimilation and balanced dynamics, *J.Atmos.Sci*., **63**, 1840-1858.	**YES**		
Ogibalov, V.P. and V.I. Fomichev, 2003: Parameterization of solar heating by near IR CO2 bands in the mesosphere. *Adv. Space Res*., **32**, 759-764.	**YES**		
Pal, B. and P.A. Ariya, 2004: Gas-phase reaction of hydroxyl initiated reaction of elemental mercury: kinetics and product studies. *Env. Sci. Tech*., **38**, 5555-5566.	**YES**		
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Pendlebury, D. and T.G. Shepherd, 2003: Planetary-wave-induced transport in the stratosphere. *J. Atmos. Sci*., **60**, 1456-1470.	**YES**		
Polavarapu, S., Ren, S., Clayton, A., Sankey, D. and Y. Rochon, 2004: On the relationship between incremental analysis updating and incremental digital filtering. *Mon. Wea. Rev*., **132**, 2495-2502.	**YES**		

Polavarapu, S., Ren, S., Rochon, Y., Sankey, D., Ek, N., Koshyk, J. and D. Tarasick, 2005: Data assimilation with the Canadian Middle Atmosphere Model. *Atmos.-Ocean*, **43**, 77-100	YES		
Polavarapu, S., Shepherd, T.G., Rochon, Y. and S. Ren, 2006: Some challenges of middle atmosphere data assimilation. *Q. J. Royal Met. Soc.*, **131**, 3513-3527.	YES		
Polavarapu, S. and T.G. Shepherd, 2006: Report on the Joint SPARC Workshop on Data Assimilation and Stratospheric Winds. *SPARC Newsletter*, **No. 26**, 20-27.			YES
Pyle, J.A. and T.G. Shepherd (Coordinating Lead Authors), 2005: Ozone and Climate: A Review of Interconnections. Chapter 1 of *IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System (SROC)*, Cambridge University Press, pp. 83-132.			YES
Reeves, C.E., Cunnold, D.M., Derwent, R.G., Dlugokencky, E., Edouard, S., Granier, C., Ménard, R., Novelli, P. and D. Parrish, 2004: Determination of emissions from observations of atmospheric compounds. In "Emissions of Atmospheric Trace Compounds", eds C. Granier, P. Artaxo and C. Reeves, Kluwer Academic Publishers, Dordrecht, The Netherlands, 544 pp.	YES		
Revenaz, B., 2001: Box modelling of HOx formation upon ozonolysis of alkenes, MSc Thesis, Department of Chemistry, McGill University.			THESIS
Russell, J.P. and R.P. Lowe, 2003: Atomic oxygen profiles (80-94 km) derived from Wind Imaging Interferometer/Upper Atmospheric Reseatch Satellite measurements of the hydroxyl airglow: 1. Validation of technique. *J.Geophys.Res.*, **108**, 10.1029/2003JD003454.	YES		
Russell, J.P., Lowe, R.P. and W.E. Ward, 2004: Atomic oxygen annual and semi-annual oscillations in the mesopause region for mid and equatorial latitudes, *J.Atmos.Sol.-Terr.Phys.*, **66**, 451-461.	YES		
Russell, J.P., Ward, W.E., Lowe, R.P., Roble, R.G., Shepherd, G.G. and B.H. Solheim, 2005: Atomic oxygen profiles (80-115 km) derived from WINDII/UARS measurements of the hydroxyl and greenline airglow II: Local time-latitude dependence, *J.Geophys.Res.*, **110**, D15305, 10.1029/2004JD005570.	YES		
Ryzhkov, A.B. and P.A. Ariya, 2003: A theoretical study of the reactions of carbonyl oxide with water in atmosphere: the role of water dimer. *Chem. Phys. Lett.*, **367**, 423-429.	YES		
Ryzhkov, B. and P.A. Ariya, 2004: A theoretical study of the reactions of parent and substituted Criegee intermediates with water and the water dimer. *J.Phys.Chem.-Chem.Phys.*, **6**, 5042-5050.	YES		
Ryzhkov, B. and P.A. Ariya, 2006: The importance of water clusters $(H_2O)_n$ (n=2..4) in the reaction of Criegee intermediate with water in the atmosphere. *Chem. Phys. Lett.*, **419**, 479-485.	YES		
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Scinocca, J.F., 2002: The effect of back-reflection in the parametrization of non-orographic gravity-wave drag. *J. Meteor. Soc. Japan*, **80**, 939-962.	**YES**		
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Scinocca, J.F. and N.A. McFarlane, 2004: The variability of modelled tropical precipitation. *J. Atmos. Sci.,* **61**, 1993-2015.	**YES**		
Semeniuk, K. and T.G. Shepherd, 2001: The middle atmosphere Hadley circulation and equatorial inertial adjustment. *J. Atmos. Sci*., **58**, 3077-3096.	**YES**		
Semeniuk, K. and T.G. Shepherd, 2001: Mechanisms for tropical upwelling in the stratosphere. *J. Atmos. Sci*., **58**, 3097-3115.	**YES**		
Semeniuk, K. and T.G. Shepherd, 2002: The effect of non-uniform radiative damping on the zonal-mean dynamics of the extratropical middle atmosphere. *Quart. J. Roy. Meteor. Soc*., **128**, 259-284.	**YES**		
Semeniuk, K., McConnell, J.C. and C. Jackman, 2005: Simulation of the October-November 2003 solar proton event in the CMAM GCM: comparison with observations. *Geophys. Res. Lett.*, **32**, L15S02, 10.1029/2005GL022392.	**YES**		
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Shepherd, T.G., 2002: Issues in stratosphere-troposphere coupling. *J. Meteor. Soc. Japan*, **80**, 769-792.	**YES**		
Shepherd, T.G., 2003: Large-scale atmospheric dynamics for atmospheric chemists. *Chem. Reviews*, **103**, 4509-4531.	**YES**		
Shepherd, T.G., 2004: Issues for stratospheric modelling and assimilation. Proceedings of the ECMWF/SPARC Workshop on Modelling and Assimilation for the Stratosphere and Tropopause, June 23-26, 2003, 29-36.			**YES**
Shepherd, T.G. and T.A. Shaw, 2004: The angular momentum constraint on climate sensitivity and downward influence in the middle atmosphere. *J. Atmos. Sci*., **61**, 2899-2908.	**YES**		
Sun, J. and P.A. Ariya, 2006: Atmospheric organic and bio-aerosols as cloud condensation nuclei (CCN): a review, *Atmos.Env*., **40**, 795-820.	**YES**		
Tegtmeier, S. and T.G. Shepherd, 2006: Persistence and photochemical decay of springtime total ozone anomalies in the Canadian Middle Atmosphere Model. *Atmos. Chem. Phys. Disc.*, **6**, 3403-3417.	**YES**		
Thompson, D.W.J., Furtado, J.C. and T.G. Shepherd, 2006: On the tropospheric response to anomalous stratospheric wave drag and radiative heating. *J. Atmos. Sci*., **63**, 2616-2629.	**YES**		
Tomikawa, Y., Sato, K. and T.G. Shepherd, 2006: A diagnostic study of waves on the tropopause. *J. Atmos. Sci*., **63**, 3315-3332.	**YES**		
Wang, D.Y., Ward, W.E., Rochon, Y.J. and G.G. Shepherd, 2001: Airglow intensity variations induced by gravity waves. Part I: Generalization of the Hines-Tarasick theory. *J. Atmos. Sol.-Terr. Phys*., **63**, 35-46.	**YES**		
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Wang, D.Y., Ward, W.E., Solheim, B.H. and G.G. Shepherd, 2002: Longitudinal variations of green line emission rates observed by WINDII at altitudes 90-120 km during 1991-1996. *J. Atmos. Sol.-Terr. Phys*., **64**, 1273-1286.	**YES**		
Wang, X. and D.V. Michelangeli, 2006: Comparison of microphysical modeling of PSCs against balloon-borne and ILAS satellite observations. *J. Geophys. Res.*, **111**, 10.1029/2005JD006222.	**YES**		
Ward, W.E., Fomichev, V.I. and S.R. Beagley, 2005: Non-migrating tides in equinox temperature fields from the extended Canadian Middle Atmosphere Model (CMAM). *Geophys. Res. Lett.*, **32**, L03803, 10.1029/2004GL021466.	**YES**		
Wunch, D., Tingley, M.P., Shepherd, T.G., Drummond, J.R., Moore, G.W.K. and K. Strong, 2005: Climatology and predictability of the late summer stratospheric zonal wind turnaround over Vanscoy, Saskatchewan. *Atmos.-Ocean*, **43**, 301-313	**YES**		
Zhang, X., 2002: A comparison of CMAM and HALOE mesospheric data, MSc Thesis, Department of Earth and Atmospheric Science, York University			**THESIS**
GRIPS WORKSHOP (HAMBURG, GERMANY, 26 FEBRUARY-1 MARCH, 2001)			
de Grandpré, J.: Transport of constituents in the lower stratosphere.		**ORAL**	
McFarlane, N.A.: Update on the CMAM.		**ORAL**	
McFarlane, N.A.: Resolved wave driving of tropical oscillations.		**ORAL**	
JAPAN-U.S. SEMINAR ON COUPLING OF THE TROPOSPHERE AND STRATOSPHERE BY DYNAMICAL, RADIATIVE AND CHEMICAL PROCESSES (KYOTO, JAPAN, 13-17 MARCH, 2001)			
Scinocca, J.F.: Nonhydrostatic effects in the parameterization of non-orographic gravity-wave drag (INVITED).		**ORAL**	
Shepherd, T.G.: Issues in stratospheric-tropospheric coupling (INVITED).		**ORAL**	
WORKSHOP ON NITROGEN OXIDES IN THE LOWER STRATOSPHERE AND UPPER TROPOSPHERE (UNIVERSITY OF HEIDELBERG, HEIDELBERG, GERMANY, 19-22 MARCH, 2001)			
Plummer, D.A., McConnell, J.C., Beagley, S.R., and J. de Grandpré: Simulation of tropospheric chemistry in the Canadian Middle Atmosphere Model.		**ORAL**	
26TH GENERAL ASSEMBLY OF THE EUROPEAN GEOPHYSICAL SOCIETY (NICE, FRANCE, 25-30 MARCH, 2001)			
Plummer, D.A., McConnell, J.C., Beagley, S.R. and J. de Grandpré: Simulation of tropospheric chemistry in the Canadian Middle Atmosphere Model.		**ORAL**	
SPARC TROPOPAUSE WORKSHOP (BAD TÖLZ, GERMANY, 17-21 APRIL, 2001)			
Folkins, I.: Upper tropospheric chemical budgets (INVITED).		**ORAL**	
CANADIAN CHEMICAL SOCIETY (MONTRÉAL, QUÉBEC, CANADA, 26-30 MAY, 2001)			
Avzianova E.V. and P.A. Ariya: Temperature dependence kinetics and product studies of selected tropospheric ozonolysis reactions of		**ORAL**	

alkenes.			
CONFERENCE ON ATMOSPHERIC AND OCEANIC FLUID DYNAMICS (BRECKENRIDGE, COLORADO, 4-8 JUNE, 2001)			
Campbell, L.: Wave-mean-flow interactions in a gravity wave packet critical layer.		**ORAL**	
Fruman, M. and T.G. Shepherd: The traditional approximation and equatorial inertial instability.		**ORAL**	
Pendlebury, D.: A comparison of wave-induced residual and Lagrangian transport in the stratosphere.		**ORAL**	
Scinocca, J.: Nonhydrostatic effects in the parameterization of non-orographic gravity-wave drag.		**ORAL**	
WAVE PHENOMENA III (UNIVERSITY OF ALBERTA, 11-15 JUNE, 2001)			
Campbell, L.: Wave-mean-flow interactions in a Rossby wave packet critical layer.		**ORAL**	
Scinocca, J.: Nonhydrostatic effects in the parameterization of non-orographic gravity-wave drag.		**ORAL**	
Shepherd, T.G.: Wave-vortex interactions and implications for mixing in the middle atmosphere (INVITED PLENARY TALK).		**ORAL**	
8TH SCIENTIFIC ASSEMBLY OF IAMAS (INNSBRUCK, AUSTRIA, 10-18 JULY, 2001)			
Beagley, S.R.: Chemical-dynamical and transport impacts in the middle atmosphere of green-house-gas forcing.		**ORAL**	
Fomichev V.I., Ward, W.E., Beagley, S.R., and C. McLandress: Energy budget of the middle atmosphere produced by the Extended Canadian Middle Atmosphere Model.		**ORAL**	
Lohmann, U.: Possible effects on clouds by aerosol-induced changes in heterogeneous and homogeneous ice nucleation.		**ORAL**	
McLandress, C.: The seasonal variation of the diurnal tide: results from a middle atmosphere GCM and a linear mechanistic model (INVITED).		**ORAL**	
FIRST INTERNATIONAL CONFERENCE ON GLOBAL WARMING AND THE NEXT ICE AGE (HALIFAX, 19-24 AUGUST, 2001)			
Lohmann, U.: The magnitude of different aerosol-cloud effects between pre-industrial times and present day.		**ORAL**	
AGU FALL MEETING, SAN FRANCISCO (CALIFORNIA, 10-14 DECEMBER, 2001)			
Rochon, Y., Polavarapu, S., Ren, S., Sankey, D. and D. Tarasick: Data Assimilation with the Canadian Middle Atmosphere Model.		**ORAL**	
UK NERC UTLS OZONE WORKSHOP (CAMBRIDGE, UK, 17-19 DECEMBER, 2001)			
Shepherd, T.G.: Transport processes in the UTLS (INVITED).		**ORAL**	
MOLECULAR MODELLING SYMPOSIUM (MONTRÉAL, QUÉBEC, 17-19 JANUARY 2002)			
Ryzhkov, A. and P.A. Ariya: Reaction of CH2OO radicals with atmospheric water vapour.		**ORAL**	
AMS OBSERVATIONS, DATA ASSIMILATION AND PROBABILISTIC PREDICTION MEETING (ORLANDO, FLORIDA, 14-17 JANUARY 2002)			
Polavarapu, S., Ren, S., Rochon, Y. and D. Sankey: Middle atmosphere data assimilation with a climate model.		**ORAL**	

IGAC WORKSHOP (STOCKHOLM, SWEDEN, 27-30 JANUARY, 2002)			
Lohmann, U.: Interactions between atmospheric chemistry and the hydrological cycle (INVITED).		**ORAL**	
DASP WINTER WORKSHOP (FREDERICTON, NB, 21-23 FEBRUARY, 2002)			
Fomichev, V.I., Ward, W.E., Beagley, S.R. and C. McLandress: Energy processes in the Extended Canadian Middle Atmosphere Model.		**ORAL**	
GRIPS WORKSHOP (TSUKUBA, JAPAN, 12-15 MARCH, 2002)			
de Grandpré, J., Beagley, S.R. and J. C. McConnell: Transport and chemistry processes in the Canadian Middle Atmosphere Model.		**ORAL**	
McLandress, C.: Report on the gravity wave parameterization assessment (task 2D).		**ORAL**	
INTERNATIONAL SYMPOSIUM ON EQUATORIAL PROCESSES INVOLVING COUPLING (EPIC) (UJI, Kyoto, Japan, 18-22 March, 2002)			
McLandress, C.: Mechanisms responsible for the seasonal variation of the diurnal tide in the mesosphere and lower thermosphere (INVITED).		**ORAL**	
XVII EGS GENERAL ASSEMBLY (NICE, FRANCE, 21-26 APRIL, 2002)			
Braban, C.F. and J.P.D. Abbatt: Studies of deliquescence and efflorescence phase transitions of dicarboxylic acid particles.		**ORAL**	
Fomichev V.I., Beagley, S.R. and J. de Grandpré: Temperature changes in the upper stratosphere and mesosphere due to doubling of CO2 as simulated by the CMAM.		**ORAL**	
Scinocca, J.F.: The nonlinear forcing of large-scale internal gravity waves by stratified shear instability (INVITED).		**ORAL**	
Scinocca, J.F.: An accurate spectral non-orographic gravity-wave drag parameterization for general circulation models.		**ORAL**	
5TH WORKSHOP ON ADJOINT APPLICATIONS IN DYNAMIC METEOROLOGY (MOUNT BETHEL, PENNSYLVANIA, 21-26 APRIL 2002)			
Polavarapu, S.: Balance issues in data assimilation (INVITED).		**ORAL**	
SPARC DATA ASSIMILATION WORKSHOP (BALTIMORE, MARYLAND, 10-12 JUNE 2002)			
Polavarapu, S., Ren, S., Rochon, Y. and D. Sankey: Recent developments in the data assimilation system for the Canadian Middle Atmosphere Model (CMAM).		**ORAL**	
WE-HERAEUS-SEMINAR ON TRENDS IN THE UPPER ATMOSPHERE (KUEHLUNGSBORN, GERMANY, MAY 13-16, 2002)			
Fomichev, V.I., de Grandpré, J. and S.R. Beagley: Cooling of the middle atmosphere and ozone radiative feedback induced by doubling of CO2 in the CMAM (INVITED).		**ORAL**	
4TH CANADIAN SPACE AGENCY ATMOSPHERIC ENVIRONMENT WORKSHOP (UNIVERSITY OF WESTERN ONTARIO, 15-17 MAY, 2002)			
Polavarapu, S.: Data assimilation with the Canadian Middle Atmosphere Model (INVITED).		**ORAL**	
Shepherd, T.G.: Earth system science (INVITED).		**ORAL**	

36TH CMOS CONGRESS (RIMOUSKI, QUEBEC, CANADA, 22-25 MAY, 2002)			
Beagley, S.R., de Grandpré, J., Fomichev, V.I. and J.C. McConnell: Simulating lower stratospheric ozone loss in a GCM: dynamical issues.		**ORAL**	
de Grandpré, J.: Ozone change in the middle atmosphere.		**ORAL**	
CHEMICAL SOCIETY OF CANADA (VANCOUVER, 1-5 JUNE, 2002)			
Kwemena, N., Meritis, D. and P.A. Ariya: Product studies of peroxide formation upon ozonolysis of alkenes.		**ORAL**	
Ryzhkov, A., Leighton, H. and P.A. Ariya: Theoretical studies of criegee radical with water.		**ORAL**	
SPARC DATA ASSIMILATION WORKSHOP (WASHINGTON D.C., 10-12 JUNE, 2002)			
Polavarapu, S., S. Ren, Y. Rochon and D. Sankey: Recent developments in the data assimilation system for the Canadian Middle Atmosphere Model (CMAM).		**ORAL**	
SUMMER SCHOOL OF THE ADVANCED STUDY PROGRAM OF THE NATIONAL CENTER FOR ATMOSPHERIC RESEARCH (BOULDER, CO, 8-19 JULY, 2002)			
Lohmann, U.: Influence of aerosols on ice clouds (INVITED).		**ORAL**	
IGAC CONFERENCE (CRETE, 18-25 SEPTEMBER, 2002)			
Lohmann, U.: Sensitivity of cloud droplet nucleation to kinetic effects and varying updraft velocity.		**ORAL**	
AMERICAN METEOROLOGICAL SOCIETY 12TH CONFERENCE ON THE MIDDLE ATMOSPHERE (SAN ANTONIO, TEXAS, 4-7 NOVEMBER, 2002.)			
Campbell, L. and T.G. Shepherd: Wave drag parameterization in simple models of the quasi-biennial oscillation.		**ORAL**	
Lukovich, J.V. and T.G. Shepherd: Large-scale mixing in the middle atmosphere.		**ORAL**	
Sankey, D. and T.G. Shepherd: Quantifying the tropopause mixing barrier in the Canadian Middle Atmosphere Model.		**ORAL**	
Semeniuk, K. and R.A. Plumb: Isolation from planetary wave breaking of the lower tropical stratosphere.		**ORAL**	
Shepherd, T.G.: Understanding past and future northern hemisphere ozone.		**ORAL**	
ACE SCIENCE TEAM MEETING (UNIVERSITY OF WATERLOO, ONTARIO, CANADA, 2-5 DECEMBER, 2002)			
Semeniuk, K.: ACE validation by trajectory and photochemical box modelling.		**ORAL**	
Wang, X. and D.V. Michelangeli: Model development of polar stratospheric clouds and their effect on stratospheric chemistry.		**ORAL**	
AMERICAN GEOPHYSICAL UNION (SAN FRANCISCO, 6-10 DECEMBER, 2002)			
Abbatt, J.P.D.: Are Organic Aerosols Good Cloud Condensation Nuclei? (INVITED)		**ORAL**	
3RD CERMM COMPUTATIONAL MODELING SYMPOSIUM (CONCORDIA UNIVERSITY, MONTREAL, CANADA, 11-12 JANUARY, 2003)			
Ryzhkov, A. and P.A. Ariya: Theoretical studies of carbonyl oxide intermediates.		**ORAL**	

GOA-MAPSCORE-ASSET WORKSHOP ON CHEMICAL DATA ASSIMILATION (KNMI, UTRECHT, THE NETHERLANDS, 15-17 JANUARY 2003)			
Polavarapu, S., Ren, S., Rochon, Y., Sankey, D. and Y. Yang: The impact of dynamic variable assimilation on ozone fields.		**ORAL**	
AHA HULIKOA HAWAIIAN WINTER WORKSHOP (HONOLULU, HAWAII, 21-24 JANUARY, 2003)			
Scinocca, J.: Low-level topographic drag in atmospheric flows.		**ORAL**	
ATMOSPHERIC TIDES WORKSHOP (HONOLULU, HAWAII, 4-7 MARCH, 2003)			
McLandress, C.: Simulations of the migrating diurnal tide in the Canadian Middle Atmosphere Model (CMAM).		**ORAL**	
GRIPS WORKSHOP (WASHINGTON D.C., 4-7 MARCH, 2003)			
de Grandpré: Perturbation scenarios and ozone response in the CMAM.		**ORAL**	
Fomichev V. I.: Radiation code intercomparison: recap of results.		**ORAL**	
Sankey D. and T.G. Shepherd: Correlations of long-lived chemical species in a middle atmosphere general circulation model.		**ORAL**	
AMERICAN CHEMICAL SOCIETY (NEW ORLEANS, 23-28 MARCH, 2003)			
Ryzhkov, A. and P.A. Ariya: Reactions of substituted criegee biradical with water and water dimer.		**ORAL**	
JOINT SPARC-IGAC WORKSHOP ON CLIMATE-CHEMISTRY INTERACTIONS (GIENS, FRANCE, 3-5 APRIL, 2003)			
Lohmann, U.: Water vapour and clouds (INVITED).		**ORAL**	
EGS-AGU-EUG JOINT ASSEMBLY (NICE, FRANCE, 6-11 APRIL, 2003)			
Abbatt, J.P.D. and K. Broekhuizen: Organic Aerosols as Cloud Condensation Nuclei.		**ORAL**	
Lohmann, U.: Impact of Mt. Pinatubo eruption on cirrus clouds formed by homogeneous freezing in the ECHAM GCM.		**ORAL**	
Plummer, D.A., J.C. McConnell, S.R. Beagley and J. de Grandpré: Development of tropospheric chemistry in the Canadian Middle Atmosphere Model.		**ORAL**	
Shepherd, T.G. and V.E. Fioletov: Seasonal persistence of midlatitude total ozone anomalies.		**ORAL**	
Wang, X., D.V. Michelangeli and I. Kletskin: Status of detailed numerical modelling of polar stratospheric clouds and their effect on stratospheric chemistry.		**ORAL**	
SPARC WORKSHOP ON THE ROLE OF THE STRATOSPHERE IN TROPOSPHERIC CLIMATE (WHISTLER, B.C., 29 APRIL-2 MAY, 2003)			
Shepherd, T.G.: Mechanisms for stratospheric influences on tropospheric climate (INVITED).		**ORAL**	
37TH CONGRESS OF THE CANADIAN METEOROLOGICAL AND OCEANOGRAPHIC SOCIETY (OTTAWA, CANADA, 2-6 JUNE, 2003)			
Abbatt, J.P.D.: Interactions of atmospheric trace gases with ice: heterogeneous reactions and scavenging (INVITED).		**ORAL**	
Beagley,. S.R. *et al.*: Development of a Mars spectral general circulation model with chemistry and aerosols in support of future Mars missions.		**ORAL**	
Codoban, S. and T.G. Shepherd: Energetics of a symmetric		**ORAL**	

circulation with momentum constraints.			
de Grandpré, J., A. Jonsson and J.C. McConnell: The Canadian Middle Atmosphere Model: model vs. observation.		**ORAL**	
Lukovich, J., I. McDade, T.G. Shepherd and C.S. Haley: Observational analysis of the containment of Antarctic vortex air following the split ozone hole of 2002.		**ORAL**	
McLandress, C., R. Hallman and T.G. Shepherd: Mesospheric temperature inversions: the role of stationary planetary waves.		**ORAL**	
Neef, L.J., T.G. Shepherd and S.M. Polavarapu: Kalman filter data assimilation and balanced dynamics.		**ORAL**	
Plummer, D.A., J.C. McConnell, S.R. Beagley and J. de Grandpré: Modelling of tropospheric chemistry in the Canadian Middle Atmosphere Model.		**ORAL**	
Polavarapu, S., R. Shuzhan, Y. Rochon and D. Sankey: The Canadian Middle Atmosphere Model (CMAM) Data Assimilation Scheme (INVITED).		**ORAL**	
Russell, J.M., W.E. Ward, R.P. Lowe and R.G. Roble: Multi-year tidal trends in mesospheric atomic oxygen profiles derived from remote sensing of the nightglow.		**ORAL**	
Reszka, M. and T.G. Shepherd: Dynamical balances in the tropical middle atmosphere.		**POSTER**	
Sankey, D. and T.G. Shepherd: Correlations of long-lived chemical species in a middle atmosphere general circulation model.		**ORAL**	
Sankey, D. and T.G. Shepherd: Quantifying the tropopause mixing barrier in the Canadian Middle Atmosphere Model.		**POSTER**	
Sankey, D., Y. Rochon, S. Polavarapu, S. Ren and Y. Yang: The influence of assimilating dynamical variables on ozone in the Canadian Middle Atmosphere Model.		**POSTER**	
Shepherd, T.G.: Modelling of chemical-climate coupling in the middle atmosphere (INVITED).		**ORAL**	
Semeniuk, K.: On the limitations of trajectory-following photochemical box modelling.		**ORAL**	
Wang, X., D.V. Michelangeli and I. Kletskin: A numerical model for polar stratospheric clouds and stratospheric chemistry.		**ORAL**	
Ward, W.E., V.I. Fomichev, S.R. Beagley, and C. McLandress: Non-migrating tides in the extended Canadian Middle Atmosphere Model.		**ORAL**	
SPARC-DA WORKSHOP (FLORENCE, ITALY, 4-6 JUNE 2003)			
Polavarapu, S., D. Sankey, Y. Rochon, S. Ren and Y. Yang: The impact of dynamic variable assimilation on ozone fields.		**ORAL**	
14TH CONFERENCE ON ATMOSPHERIC AND OCEANIC FLUID DYNAMICS (SAN ANTONIO, TEXAS, 9-13 JUNE 2003)			
Campbell, L. and T.G. Shepherd: Constraints on gravity-wave-drag parameterization schemes for simulating the quasi-biennial oscillation.		**ORAL**	
Codoban, S. and T.G. Shepherd: Energetics of a symmetric circulation with momentum constraints.		**ORAL**	
Neef, L.J., T.G. Shepherd and S.M. Polavarapu: Balance dynamics and four-dimensional data assimilation.		**ORAL**	
Scinocca, J.F.: The variability of modelled tropical precipitation.		**ORAL**	
WORKSHOP ON CHEMISTRY-DYNAMICS COUPLING NEAR THE MESOPAUSE (HAMBURG, GERMANY, 10-13 JUNE, 2003)			
Fomichev V.I.: Impact of the CMAM radiative scheme updates on the thermal budget (INVITED).		**ORAL**	

ECMWF WORKSHOP ON THE STRATOSPHERE (READING, U.K., 23-26 JUNE, 2003)			
Ménard, R.: Model error estimation: its application to chemical data assimilation (INVITED).		**ORAL**	
Shepherd, T.G.: Issues for stratospheric modelling and assimilation (INVITED).		**ORAL**	
XXIII IUGG GENERAL ASSEMBLY (SAPPORO, JAPAN, 30 JUNE-11 JULY, 2003)			
Beagley, S.R., J. de Grandpré, V.I. Fomichev, J.C. McConnell and T.G. Shepherd: Simulating Antarctic stratospheric ozone loss in a GCM: variability.		**ORAL**	
Fioletov, V. and T.G. Shepherd: Seasonal persistence of midlatitude total ozone anomalies.		**ORAL**	
Folkins, I: The interface between the tropical troposphere and stratosphere (INVITED).		**ORAL**	
Fomichev V.I.: Model thermal response to minor energy sources and sinks (INVITED).		**ORAL**	
Lohmann, U.: Different aspects of aerosol effects on clouds, climate and the hydrological cycle (INVITED).		**ORAL**	
McLandress, C.: What damps the vertically propagating diurnal tide in the mesosphere and lower thermosphere? (INVITED).		**ORAL**	
McLandress, C., R. Hallmann, and T. G. Shepherd: Mesospheric temperature inversions in middle atmosphere general circulation models: the role of quasi-stationary planetary waves.		**ORAL**	
Neef, L.J., T.G. Shepherd and S.M. Polavarapu: Kalman filter data assimilation and balanced dynamics.		**ORAL**	
Plummer, D.A., J.C. McConnell, S.R. Beagley and J. deGrandpré: Simulation of Rn-222 and Pb-210 in the Canadian Middle Atmosphere Model.		**ORAL**	
Ren, S., S. Polavarapu, Y. Rochon and D. Sankey: Middle atmosphere data assimilation in Canada.		**ORAL**	
Sankey, D. and T.G. Shepherd: Quantifying the tropopause mixing barrier in the Canadian Middle Atmosphere Model.		**ORAL**	
Sankey, D., Y. Rochon, S. Polavarapu, S. Ren and Y. Yang: The influence of assimilating dynamical variables on ozone in the Canadian Middle Atmosphere Model.		**ORAL**	
Shepherd, T.G.: Large-scale transport and mixing in the middle atmosphere (INVITED).		**ORAL**	
Shepherd, T.G.: Dynamical influences on ozone changes (INVITED).		**ORAL**	
Shepherd, T.G.: Some issues in stratosphere-troposphere coupling (INVITED).		**ORAL**	
Ward, W.E.: Dynamical fields in the mesopause region: insights from the extended CMAM (INVITED)		**ORAL**	
Ward, W.E. and J.P. Russell: The effect of dynamical processes on nightglow profiles (INVITED)		**ORAL**	
THE 39TH IUPAC CONGRESS AND 86TH CONFERENCE OF THE CANADIAN SOCIETY FOR CHEMISTRY (OTTAWA, CANADA, 10-15 AUGUST , 2003)			
Ryzhkov, A.B. and P.A. Ariya, Atmospheric reactions of mono- and dimethylsubstituted Criegee intermediate with water.		**ORAL**	
EUROPEAN AEROSOL CONFERENCE (MADRID, SPAIN, 4 SEPT, 2003)			
Lohmann, U.: Global simulations of upper tropospheric aerosols		**ORAL**	

and their effects on clouds and climate (INVITED).			
226TH ACS NATIONAL MEETING (NEW-YORK, USA, 7-11 SEPTEMBER, 2003)			
Ryzhkov, A.B., Bertrand, Revenaz, J. and P.A. Ariya, Ozonolysis of alkenes - impacts on sulfur oxidation in sulfate aerosols during fall and winter.		**ORAL**	
UTLS WORKSHOP (BOULDER, COLORADO, 27-28 OCTOBER, 2003)			
Folkins, I.: Structure and issues in the UT/LS.		**ORAL**	
SPARC WORKSHOP ON UNDERSTANDING SEASONAL TEMPERATURE TRENDS IN THE ATMOSPHERE (SILVER SPRINGS, MARYLAND, 5 NOVEMBER, 2003)			
Shepherd, T.G.: Variability and changes in stratospheric circulation (INVITED).		**ORAL**	
SPARC WORKSHOP ON PROCESS-ORIENTED VALIDATION OF COUPLED CHEMISTRY-CLIMATE MODELS (GARMISCH-PARTENKIRCHEN, GERMANY, 17-19 NOVEMBER, 2003)			
Shepherd, T.G.: Stratospheric dynamics (INVITED).		**ORAL**	
AGU CHAPMAN CONFERENCE ON GRAVITY WAVE PROCESSES AND PARAMETERIZATION (KOHALA COAST, HAWAII, 10-14 JANUARY, 2004)			
McLandress, C. and J. Scinocca: A self-consistent intercomparison of gravity wave drag parameterizations.		**ORAL**	
Shaw, T.A. and T.G. Shepherd: Assessing the importance of momentum conservation in the parameterization of gravity wave drag in atmospheric models.		**ORAL**	
DASP WORKSHOP (LONDON, ONTARIO, CANADA, 19-20 FEBRUARY, 2004)			
McLandress, C. and J. Scinocca: A self-consistent intercomparison of gravity wave drag parameterizations.		**ORAL**	
Sankey, D. and T.G. Shepherd: Correlations of long-lived chemical species in a middle atmosphere general circulation model.		**ORAL**	
Semeniuk, K.: Testing trajectory-based satellite validation methods in a GCM.		**ORAL**	
ANNUAL APS MEETING (MONTREAL, CANADA, 22-26 MARCH, 2004)			
Ryzhkov, A.B. and P.A. Ariya, Structure, stability, and reactions of complexes of Criegee intermediate with water $H_2COO\text{-}(H_2O)_n$, n=1-3: density functional theory investigation.		**ORAL**	
GRIPS WORKSHOP (BOLOGNA, ITALY, 24-26 MARCH, 2004)			
Fomichev, V. I.: Solar heating by the near-IR CO_2 bands in thermosphere.		**ORAL**	
ACE SCIENCE TEAM MEETING. (WATERLOO, ONTARIO, 19-21 APRIL, 2004)			
Polavarapu, S., Y. Rochon, S. Ren, D. Sankey, Y. Yang: Update on CMAM data assimilation. ACE science team meeting.		**ORAL**	
GORDON RESEARCH CONFERENCE ON BIOGENIC HYDROCARBONS AND THE ATMOSPHERE (IL CIOCCO, ITALY, 2-7 MAY, 2004)			
Folberth, G.A., Hauglustaine, D.A. and J. Lathiere: Biogenic emissions and their impact on tropospheric chemical composition in a chemistry-climate model coupled to a terrestrial biosphere model.		**ORAL**	

JOINT AGU/CGU ASSEMBLY (MONTREAL, QUEBEC, CANADA, 17-21 MAY, 2004)			
Du, J. and W.E. Ward: The annual cycle of non-migrating tides in the extended Canadian Middle Atmosphere Model.		**ORAL**	
Fomichev, V.I.: Near-IR CO_2 bands in the mesosphere and their effect for doubled CO_2 conditions.		**ORAL**	
Ward, W.E., V.I. Fomichev, S.R. Beagley, C. McLandress and J.C.R McConnell: Insights from the Extended Canadian Middle Atmosphere Model on the dynamics of the terrestrial mesosphere and lower thermosphere.		**ORAL**	
SIXTH WORKSHOP ON ADJOINT APPLICATIONS IN DYNAMIC METEOROLOGY (ACQUAFREDDA DI MARATEA, ITALY, 23-28 MAY, 2004)			
Neef, L.J. : Balance in the nonlinear Kalman Filter: studies with a simple model.		**ORAL**	
IAGA/ICMA 3RD WORKSHOP "LONG-TERM CHANGES AND TRENDS IN THE ATMOSPHERE" (SOZOPOL, BULGARIA, 9-14 JUNE, 2004)			
Fomichev, V.I. and R.A. Akmaev: Modelling of global change in the middle atmosphere and lower thermosphere (INVITED).		**ORAL**	
35TH COSPAR SCIENTIFIC ASSEMBLY (PARIS, FRANCE, 18 - 25 JULY 2004)			
Russell, J.P., W.E. Ward, R.P. Lowe and R.G. Roble: A climatology of atomic oxygen in the mesopause region using WINDII airglow observations (INVITED).		**ORAL**	
Ward, W.E.: Dynamical influences on the airglow and chemistry of the mesopause region (INVITED).		**ORAL**	
SPARC 3RD GENERAL ASSEMBLY (VICTORIA, BC, CANADA, 1-6 AUGUST, 2004)			
de Grandpre, J., S.R. Beagley,, V.I. Fomichev, J.C. McConnell, N.A. McFarlane and T.G. Shepherd: Middle atmosphere modelling of ozone and climate.		**POSTER**	
Folberth, G.A., Hauglustaine, D.A. and J. Lathiere: Biosphere-troposphere chemical interaction in the LMDz-INCA climate-chemistry model: impact on upper tropospheric HO_X/NO_X and implications for future climate.		**POSTER**	
Fomichev, V.I., A.I. Jonsson, J. de Grandpre, S.R. Beagley, C. McLandress, K. Semeniuk and T.G. Shepherd: Model response to the doubling of CO_2 as simulated by the Canadian Middle Atmosphere Model.		**POSTER**	
Jonsson, A.I., J. de Grandpre, V.I. Fomichev, J.C. McConnell and S.R. Beagley: Greenhouse gases induced cooling and ozone radiative feedback.		**POSTER**	
Polavarapu, S. : Coupled chemical-dynamical data assimilation in the stratosphere: prospects for separating model and measurement bias.		**ORAL**	
Ren, S., S. Polavarapu, Y. Rochon and D. Sankey: Some diagnoses in the stratosphere using CMAM-DA analyses.		**POSTER**	
Reszka, M.K. and T.G. Shepherd: Dynamical balance in the tropical stratosphere?		**POSTER**	
Rochon, Y.J., S. Polavarapu, S. Ren, D. Sankey and Y. Yang: Background error statistics for middle atmosphere data assimilation.		**POSTER**	

Sankey, D., M. Marchand, S. Polavarapu, S. Ren, Y. Rochon and Y. Yang: On the use of data assimilation to help identify model errors in the Canadian Middle Atmosphere Model		**POSTER**	
Scinocca, J.F.: Do current non-orographic GWD parameterizations differ in their application?		**ORAL**	
Ward, W.E., J. Oberheide, A.K. Smith, M Riese, and D. Offermann: Ozone/temperature correlations during the CRISTA 2 flight.		**POSTER**	
Yang, Y., Y. Rochon, S. Polavarapu, S. Ren and D. Sankey: First results of assimilating ozone data into CMAM with CMC's 3DVAR.		**POSTER**	
8TH INTERNATIONAL GLOBAL ATMOSPHERIC CHEMISTRY CONFERENCE (CHRISTCHURCH, NEW ZEALAND, 4-9 SEPTEMBER, 2004)			
Folberth, G.A., Hauglustaine, D.A. and J. Lathiere: A budget analysis of in-situ CO_2 production via CO and BVOC photooxidation.		**ORAL**	
8TH INTERNATIONAL CONFERENCE ON CARBONACEOUS PARTICLES IN THE ATMOSPHERE (VIENNA, AUSTRIA, 14-16 SEPTEMBER, 2004)			
Croft, B., U. Lohmann, and K. von Salzen: Black carbon ageing in CCCma global climate model.		**ORAL**	
FALL AMERICAN GEOPHYSICAL UNION MEETING (SAN FRANCISCO, 13-17 DECEMBER, 2004)			
Ward, W.E. and J.P. Russell, Evidence for a solar cycle variation in nightglow and atomic oxygen in the mesosphere and lower thermosphere.		**ORAL**	
DASP WORKSHOP (EDMONTON, 23-27 FEBRUARY, 2005)			
MacKenzie, D. and W.E. Ward: Hough mode decomposition of CMAM tidal features (Student Prize for Best Oral Presentation).		**ORAL**	
Ward, W.E. and J.P. Russell: Evidence for a solar cycle variation in nightglow and atomic oxygen in the MLT region.		**ORAL**	
WORKSHOP ON REPRESENTING UNRESOLVED DEGREES OF FREEDOM FOR THE ATMOSPHERE AND OCEAN (CRM, U. DE MONTRÉAL, MARCH, 2005)			
Shepherd, T.G.: Gravity-wave parameterization in the middle atmosphere (INVITED).		**ORAL**	
GRIPS WORKSHOP (TORONTO, CANADA, 14-17 MARCH, 2005)			
de Grandpré, J.: Transport processes in the lower stratosphere.		**ORAL**	
Fomichev, V.I.: Carbon dioxide experiments with CMAM.		**ORAL**	
McLandress, C.: The Impact of different gravity wave drag parameterizations on the time- and zonal-average circulation of the middle atmosphere.		**ORAL**	
Scinocca, J.F.: An overview of the Canadian Centre for Climate Modelling and Analysis.		**ORAL**	
Shepherd, T.G.: Inter-annual persistence of total ozone anomalies: a potential diagnostic for CCMs.		**ORAL**	
4TH WMO SYMPOSIUM ON THE ASSIMILATION OF OBSERVATIONS IN METEOROLOGY AND OCEANOGRAPHY (PRAGUE, CZECH REPUBLIC, 18-22 APRIL, 2005)			
Ménard, R., S. Polavarapu and Y. Yang: Estimation of model error bias.		**POSTER**	

Neef, L. J., T. G. Shepherd and S. Polavarapu: Nonlinear balance issues in 4D data assimilation.		**POSTER**	
Polavarapu, S.: The challenges of middle atmosphere data assimilation.		**ORAL**	
Rochon, Y. J. and S. Polavarapu: Generalized innovation operators for the assimilation of integral measurements.		**POSTER**	
Yang, Y., Y. J. Rochon, S. Polavarapu, S. Ren, D. Sankey: Statistical results from the first assimilation of OSIRIS stratospheric ozone measurements.		**POSTER**	
XX EGU GENERAL ASSEMBLY (VIENNA, AUSTRIA, 25-29 APRIL, 2005)			
Codoban S. and T.G. Shepherd: On the energetics of symmetric circulations.		**ORAL**	
Jin, J.-J.: Strato-mesospheric CO measurements from ACE-FTS and Odin/SMR and a comparison with CMAM, a middle atmosphere model.		**ORAL**	
Lohmann, U.: Cirrus, cloud microphysics and aerosols: detailed models versus global climate models (INVITED).		**ORAL**	
Neef, L. J., T. G. Shepherd and S. Polavarapu: Nonlinear balance issues in 4D data assimilation.		**ORAL**	
Semeniuk, K.: Simulation of the October-November 2003 Solar Proton Related Events in the CMAM GCM.		**ORAL**	
Shepherd, T.G.: Summertime total ozone variations over middle and polar latitudes.		**ORAL**	
Shepherd, T.G.: Available potential energy and its relatives (INVITED).		**ORAL**	
5TH CSA WORKSHOP ON ATMOSPHERIC SCIENCE (BANFF, CANADA, 5-7 MAY, 2005)			
Polavarapu, S.: CMAM-Facility for data assimilation and modelling (INVITED).		**ORAL**	
Reszka, M.K. and T.G. Shepherd: Dynamical balance constraints for data assimilation in the tropics.		**POSTER**	
Sankey, D., S. Ren, S. Polavarapu, Y. Rochon and Y. Yang: Comparison of initialisation methods for a climate assimilation run.		**POSTER**	
SPRING AMERICAN GEOPHYSICAL UNION MEETING (NEW ORLEANS, 23-27 MAY, 2005)			
W.E. Ward and J.P. Russell: Atomic oxygen variability in the mesopause region (INVITED).		**ORAL**	
39TH CONGRESS OF THE CANADIAN METEOROLOGICAL AND OCEANOGRAPHIC SOCIETY (VANCOUVER, BC, CANADA, 30 MAY-3 JUNE 2005)			
Beagley, S.R., Semenuik, K., de Grandpre, J., Fomichev, V.I., and J.C. McConnell: Simulating heterogeneous stratospheric ozone loss in a GCM: continuing studies using CMAM.		**ORAL**	
Lohmann, U.: Cirrus, cloud microphysics and aerosols: what can we learn from parcel models for use in global climate models (INVITED).		**ORAL**	
McLandress, C.: The role of small-scale gravity waves in the general circulation of the middle atmosphere (INVITED).		**ORAL**	
Plummer, D.A., S.R. Beagley, J de Grandpré and J.C. McConnell: Simulation of tropospheric chemistry in the Canadian Middle Atmosphere Model.		**ORAL**	
Shepherd, T.G.: Some issues in middle atmosphere climate modelling (INVITED).		**ORAL**	

15TH CONFERENCE ON ATMOSPHERIC AND OCEANIC FLUID DYNAMICS (CAMBRIDGE, MASSACHUSETTS, 13-17 JUNE 2005)			
Codoban S. and T.G. Shepherd: On the available energy of symmetric circulations.		**ORAL**	
Shaw, T.A. and T.G. Shepherd: On the importance of momentum conservation in the parameterization of gravity wave drag in the atmospheric models.		**ORAL**	
Shepherd, T.G.: Issues in stratosphere-troposphere coupling (INVITED).		**ORAL**	
WORKSHOP ON NOVEL APPROACHES TO CLIMATE (ASPEN CENTER FOR PHYSICS, 20 JUNE-1 JULY, 2005)			
Shepherd, T.G.: Statistical uncertainty, attribution, and prediction of stratospheric climate change (INVITED)		**ORAL**	
IAGA SCIENTIFIC ASSEMBLY (TOULOUSE, FRANCE, 18-29 JULY, 2005)			
Fomichev, V.I.: Response of the middle atmosphere to CO_2 doubling: Results from the Canadian Middle Atmosphere Model (INVITED).		**ORAL**	
McLandress, C. and J. Scinocca: Sensitivity of the middle atmosphere to differences in the wave-breaking mechanisms assumed in non-orographic gravity wave drag parameterizations (INVITED).		**ORAL**	
Shepherd, T.G.: The role of the middle atmosphere in climate (INVITED).		**ORAL**	
Ward, W.E., Du, J. and B.D. MacKenzie, Superposition effects between large scale waves in the extended Canadian Middle Atmosphere Model.		**ORAL**	
Ward, W.E., Beagley, S.R., McLandress, C., Semeniuk, K., Fomichev, V. and T.G. Shepherd: The large scale structure and variability in the mesosphere and lower thermosphere of the extended Canadian Middle Atmosphere Model		**ORAL**	
IAMAS GENERAL ASSEMBLY (BEIJING, CHINA, 2-11 AUGUST 2005)			
Du, J. and W.E. Ward: The seasonal cycle of planetary waves in the stratosphere and mesosphere in the extended Canadian Middle Atmosphere Model.		**ORAL**	
Polavarapu, S., S. Ren, Y. Rochon, D. Sankey, Y. Yang, C. McLandress, T. Shepherd: Middle atmosphere data assimilation: The Canadian experience (INVITED).		**ORAL**	
JOINT SPARC WORKSHOPS ON DATA ASSIMILATION AND STRATOSPHERIC WINDS (BANFF, CANADA, 12-15 SEPT. 2005)			
Polavarapu, S. Some issues in middle atmosphere data assimilation.		**ORAL**	
Rochon, Y. and S. Polavarapu: A generalized innovation operator for the assimilation of integral measurements.		**ORAL**	
Rochon, Y., P. Rahnama and A. Scott: Performance model for the SWIFT instrument on Chinook.		**ORAL**	
Sankey, D., S. Polavarapu, B. Bregman, R. Schele, S. Ren and Y. Rochon: Comparison of initialization methods for a climate assimilation run.		**ORAL**	
AGU FALL MEETING (SAN FRANCISCO, 5-9 DECEMBER, 2005)			
Sun, J. and P.A. Ariya, Modeling Studying on Ice Formation by Bacteria in Warm-based Convective Cloud.		**ORAL**	

Ward, W.E., Veselinesovic, D. and J. Du: Mesosphere/lower thermosphere signatures of a sudden stratospheric warming in the Extended Canadian Middle Atmosphere Model.		**ORAL**	
SUBMITTED:			
Bäumer, D., Lohmann, U., Lesins, G., Li, J. and B. Croft, 2006: Parameterizing the optical properties of carbonaceous aerosols in the Canadian Centre for Climate modelling and analysis Atmospheric General Circulation Model with impacts on global radiation and energy fluxes, *J. Geophys. Res.*, submitted.	**YES**		
Folkins I., Bernath, P., Boone, C., Eldering, A., Lesins, G., Martin, R.M., Sinnhuber, B-M., and K. Walker, 2006: Testing convective parameterizations with tropical measurements of HNO3, CO, H2O, and O3: implications for the water vapor budget. *J. Geophys. Res.*, submitted.	**YES**		
Li, J., Scinocca, J.F., McFarlane, N.A., von Salzen, K., Solheim, L. and M. Lazare, 2006: Ocean surface albedo schemes and their impacts on climate modelling. *J. Clim.*, submitted.	**YES**		
TOTALS	**109**	**195**	**11**

As well as the conference presentations listed in the above table, we held an annual workshop in December of 2001, 2002, 2003, 2004 and 2005. The workshops lasted for two days, and incorporated talks from virtually all of the students, postdocs and Research Associates involved in the project. Three internationally renowned speakers were invited each year from outside Canada to give longer talks, which had the dual benefit of informing ourselves about current developments and leading to an increased awareness of the project outside Canada.

4.2 How many of the papers and presentations listed above were co-authored by the partners?

80

4.3 **PATENTS AND LICENCES**

☒ Not Applicable
-or-
☐ None Yet Filed/Granted
-or-

4.4 Identify the tangible results obtained during the research project from the list below (select all that apply) and briefly describe these outcomes in the text box provided:

☐ Prototype/pilot
☐ New product
☐ New process
☒ Improved product
☐ Improved process
☒ Contribution to policy or regulation
☐ Other (specify)________________

4.5 PROSPECTS FOR THE TRANSFER OF THE RESULTS TO THE USER SECTOR

Describe how the results achieved are being transferred to the user sector and the prospects for their commercial/industrial exploitation or their use by other sectors (e.g., revising or formulating policy or regulations).

As a result of the technology transfer of CMAM to MSC, discussed under Task XIV above, CCCma is now in a position to perform its own climate simulations addressing the interaction between ozone depletion and climate change. When coupled with other modules (land-surface, biogenic emission/uptake, ocean), CCCma will have the capability of simulating chemical climate in a fully interactive fashion, thereby helping it to stay at the leading edge of the IPCC assessment activity.

The development of a stratospheric data assimilation capability based on CMAM has led to some spin-off benefits for the operational NWP assimilation activities at MSC, including the development of their "chemical weather" prediction capability. This was achieved in part by the award of a contract from ESA to MSC, which relied in part on capabilities developed at MSCC through the GCC project. The CMAM activities also accelerated the development of a vertically extended domain for the operational NWP model ("stratoGEM").

CMAM output fields are being increasingly used in support of Canadian measurement activities, both to help understand existing data (e.g. representativeness errors, role of variability) and to aid in the design of future instruments. At the same time, this activity helps to validate CMAM. Up to now this activity has used the free-running CMAM, but very soon we expect to be using the analyses produced by CMAM run in data assimilation mode. Because CMAM is being run with stratospheric chemistry, the stratospheric analyses will include chemical as well as dynamical fields. (Unlike with dynamical fields, it is not necessary to assimilate chemical fields in order to produce a useful chemical analysis; this fact underlies the use of Chemical Transport Models.) CMAM chemical analyses should be useful for direct comparison with current Canadian stratospheric chemistry measurement programs such as MANTRA (balloon), OSIRIS, ACE and MAESTRO (satellite), and PEARL (ground-based). The CMAM middle atmosphere data assimilation capability (both dynamical and chemical) will be a unique tool within the international context, which will enable CSA to assess proposed new measurement strategies in a sophisticated fashion.

On this basis, towards the end of the GCC project the CSA established a *Facility for Data Assimilation and Modelling* built around the CMAM, known as the *CMAM-FDAM*. The CMAM-FDAM will ensure that the capability developed by the GCC project will continue to be available for the benefit of the CSA Atmospheric Environment community.

5. PROBLEMS ENCOUNTERED

5.1 Identify the main problems encountered during the research project from the list below (select all that apply):

- ☐ Technical or scientific problems
- ☐ Problems with direction of research or findings
- ☒ Equipment and facilities
- ☐ Staffing issues (including students)
- ☐ Funding problems
- ☐ Partner(s) abandoned project
- ☐ Other (specify): ____________________________

-or-

- ☐ No problems occurred during the research project.

5.2 Briefly describe the main problems identified above and the steps taken to resolve each one:

The main problem encountered during the project was the several changes that took place in the MSC supercomputer system. There was first a series of transitions between different NEC platforms, during each of which we lost significant computing time as fixes were required in each case to reproduce previous results. However the transition in 2004 from the NEC to the IBM platform also involved a change from a vector to a massively parallel system. This meant that CMAM had to be entirely re-coded for the MPI architecture, a task that was undertaken by CCCma following their own re-coding of the GCM. At the time of the machine transition near the end of 2003, even the GCM re-coding was not complete. The CMAM re-coding took additional time and there were a number of bugs to track down. We lost over six months of work because of this transition. Even after CMAM was running, the turnaround was worse than what it had been prior to the transition because of hardware limitations in the new IBM system. Because of these disruptions and set-backs, several goals of the project that relied on significant computing resources had to be abandoned, as described in detail earlier under the specific tasks. We chose to focus instead on process-oriented studies. By the final year of the project, however, CMAM was running efficiently enough that it was possible to perform some long integrations to provide a meaningful Canadian contribution to the 2006 WMO/UNEP Ozone Assessment.

A second problem was the delay in developing an improved radiation scheme for CMAM based on the correlated k-distribution method, as described earlier under the specific tasks. This was due to a delay in the development and freezing of the correlated k-distribution code at CCCma. Progress was being made by the end of the project, but not in time to allow us to perform the planned solar-variability experiments, which depended on the new code. Efforts were directed instead at a detailed analysis of the process-oriented doubled CO_2 experiments.

Finally, a decision was made to not pursue chemical data assimilation within the timeframe of the GCC project. This decision resulted from the award of a contract from the European Space Agency to MSC to perform stratospheric chemical data assimilation with GEM. At that time, we had made the necessary extensions to the data assimilation code and were set to go, but there was no point duplicating the efforts being made for the ESA contract. Our code developments were thus passed to the GEM team to give them a running start, and we focused instead on work on error covariances in the mesosphere (a major issue for middle atmosphere dynamical-variable assimilation). Once the GEM team has developed some experience with stratospheric chemical data assimilation, we can learn from their experience and benefit from their technology development.

6. COLLABORATION WITH PARTNERS

6.1 Who initiated this strategic project?

- ☒ The university researcher
- ☐ The industry partner (if applicable)
- ☐ The government partner (if applicable)
- ☐ Other (specify):__________________

6.2 In what way were the partners directly involved in the project? (Select all that apply.)

- ☐ Partners were not involved in the project apart from their financial and/or in-kind contribution
- ☒ Partners were available for consultation
- ☒ Partners provided facilities
- ☒ Partners participated in the training
- ☒ Partners discussed the project regularly with the university team (List the number of meetings during the grant)
- ☒ Partners were involved in the research

6.3 Describe the partners' involvement and comment on the collaboration:

Our non-academic partners were the Meteorological Service of Canada (MSC) and the Canadian Space Agency (CSA). From the MSC, Drs. Li, McFarlane, Polavarapu and Scinocca were involved as co-Investigators, and Drs. R. Ménard (ARQI), Y. Rochon (ARQX) and K. von Salzen (CCCma) as Collaborators; together they represent four different MSC divisions across all three research branches. MSC provided considerable in-kind support of the GCC project, consisting of the time of its scientists as well as supercomputing time on the MSC computing system. MSC also provided cash support through its Climate Research Network during the first two years of the project. Since the phase-out of the CRN and its replacement by CFCAS funding, NSERC has regarded the CFCAS funding as part of our partner funding.

To supplement the interactions at our thrice-yearly Scientific Steering Committee meetings and annual workshops, the university-based RAs in our project have had the opportunity to spend extended periods of time at the MSC (CCCma) lab in Victoria. RAs C. McLandress, D. Plummer, S.R. Beagley, and V.I. Fomichev all visited Victoria. Toronto-based S. Ren, Y. Yang and D. Sankey spent significant amounts of their time each week at the MSC (ARMA) lab in Toronto, including a biweekly meeting of the CMAM data assimilation subgroup (Task V) attended by Ren, Yang, Sankey from the university side, and by Rochon and Polavarapu from the MSC side. (Yang was replaced by Nezlin in the final year of the project.) This CMAM data assimilation subgroup received guidance from an Advisory Committee consisting of Shepherd and McConnell from the university side, and McFarlane, Ménard, and ARMA Chief D. Steenbergen from the MSC side, which met three times per year.

CSA provided cash support for GCC. It has neither the capacity nor the mandate to conduct a significant amount of its own scientific research. However, CSA represents the key interface between GCC and the Canadian space-based atmospheric measurement community, and supports the Canadian space industry through the development of satellite instruments. Interaction with the CSA occurred on an ongoing basis through the specification of our workplan each year, by which we focused our efforts to most effectively meet the needs of CSA's space science program. We also participated actively in CSA workshops.

6.4 Amount of cash received from the partners during the project (if any):

<u>$3,776,663</u>

6.5 Value of the in-kind contributions received during the project:

<u>$4,017,500</u>

6.6 Describe the in-kind received:

Principally time on the MSC supercomputing system; also the time of MSC scientists involved in the project

6.7 Were all in-kind and/or cash commitments received from the partners?
☒ Yes ☐ No

If not, please provide details.

7. IMPACT ON RESEARCHER

7.1 What impact has the project had on your teaching?

☐ No impact
-or-
☒ Creation of new courses
☒ New content for existing courses
☒ Use of real world examples
☐ Guest lectures from partners
☐ New equipment/materials
☐ Other (specify)

7.2 What impact has the project had on your research?

☐ Influenced the direction to more industrially relevant topics
☒ Opened up new opportunities for research beyond the original objectives
☒ Other (induced a focus on more policy-relevant activity)

8. FINANCIAL INFORMATION

An up-to-date Grants in Aid of Research Statement of Account (Form 300) must be provided for both the NSERC contribution and any partner contributions to this project. These should cover the full period of the project. Please forward them with your report if available, or ask your finance department to forward them directly to NSERC.

In addition, please provide the following financial information.

Budget Item	Total Budget	Actual Expenditures	Balance Remaining
Salaries and Benefits			
a) Students	$600,000	$365,331.99	
b) Postdoctoral fellows	$280,000	$494,287.38	
c) Technical/professional assistants		$14,114.45	
d) Other (Res. Assoc's)	$343,500	$517,999.95	
Equipment or Facility			
a) Purchase or rental	$164,000	$154,188.90	
b) Operation and maintenance costs	$100,000		
c) User fees			
Materials and Supplies			
a) Materials and supplies	$5,000	$109,889.36	
Travel			
a) Conferences	$47,500	$236,937.97	
b) Field work			
c) Collaboration/consultation	$56,250		
Dissemination Costs			
a) Publication costs	$37,500		
b) Other (summer schools)	$30,000		
Other (specify)			
a) Annual workshop	$25,000		
b) Recruitment costs	$4,000		
Totals	$1,892,750	$1,892,750.00	0

Please provide detailed explanations for any deviation from the budget.

9. FUTURE PLANS

9.1 What links are you maintaining with the partners? (Select all that apply.)

- ☐ No contact with the partners
- ☒ Collaborating with the partners on the same research
- ☐ Collaborating with the partners on other research
- ☐ Collaborating with other partners on the same research
- ☐ Continuing the research without partners

9.2 Please describe any follow-up or related work that will be undertaken as a result of this project, and who will be involved in this work (including partners):

The capabilities developed in the GCC project in terms of both chemistry-climate modelling and middle atmosphere data assimilation are being exploited in a new activity, the Canadian SPARC (C-SPARC) programme, which will run from 2006-2010. This is a research network funded jointly by CFCAS and the CSA, together with a contribution from an NSERC Strategic Project as well as very significant in-kind contributions from

Environment Canada. It takes advantage of the Canadian research assets developed during the GCC project to address the goals of the international SPARC programme, though playing to our particular Canadian strengths. As with the GCC project, there is a strong EC-university-CSA collaboration, though it is now focused more strongly on applications with a particular focus on international assessments (WMO/UNEP and IPCC) as well as the generation of ongoing chemical-dynamical analyses. The C-SPARC activity will make a significant Canadian contribution to International Polar Year.