Proceedings of the Quadrennial Ozone Symposium, l'Aquila, Italy, September, 1996

A Canadian Middle Atmosphere Initiative

David W. Tarasick
Environment Canada, 4905 Dufferin Street, Downsview, ON, M3H 5T4 Canada

Gilbert Brunet
Environment Canada, 2121 Voie de Service nord, porte 514, Route Trans-canadiene, Dorval, PQ, H9P 1J3 Canada

Roger Daley
Naval Research Laboratory, Monterey, California, USA

Pierre Gauthier
Environment Canada, 2121 Voie de Service nord, porte 514, Route Trans-canadiene, Dorval, PQ, H9P 1J3 Canada

William E. Ward
Institute for Space and Terrestrial Studies, York University, 4700 Keele Street, North York, ON, M3J 1P3 Canada

Abstract. Environment Canada's Middle Atmosphere Initiative (MAI) was begun in 1995 with the object of developing an integrated Canadian middle atmosphere modeling, data assimilation and (space and ground-based) monitoring capability. Middle atmosphere modeling capability (for the purpose of data assimilation) will be enhanced both through modifications to the existing middle atmosphere model and the Canadian Meteorological Centre global forecast model. In the longer term this initiative is expected to have significant impact on the future development of the Canadian middle atmosphere observation system.

The assimilation of satellite observations into a middle atmosphere model is a powerful technique that derives maximum value from satellite data by combining and reconciling them with other observations and with prior information on atmospheric structure and fundamental dynamics. The value added to very expensive satellite data, compared to using them alone or in individual comparison with models, can be very significant. The result is both an improved model and an enhanced data product. The data assimilation system can also be used in direct support of the design and optimization of middle atmosphere instruments (through observation system simulation experiments (OSSE)) and post-launch calibration and validation.

For both of these reasons the assimilation of satellite data with middle atmosphere models should be viewed, in the future, as an essential component of the observation program. For full value to be realized from data assimilation techniques, collaboration between the data assimilation team and the instrument designers should begin at the instrument design phase. For this reason, funding agencies such as the Canadian Space Agency (CSA) should recognize the appropriateness of funding the development of the instrument forward model (IFM) at the same time as the Phase "A" hardware design study. It is our view that in the future, an OSSE will be regarded as a necessary part of the proof-of-concept study for any proposed atmospheric sounding instrument.

We report here on our progress to date in development of a middle atmosphere data assimilation system in Canada. Initial results of the assimilation of retrieved total ozone from TOVS are very encouraging.

1. Introduction

Environment Canada has important and long standing interests in middle atmosphere phenomena. The study of stratospheric ozone, of the causes and effects of climate change and of methods to improve long-range forecasting are each key components of its research mandate. Stratospheric ozone has been monitored in Canada since the late 1950s, and Environment Canada operates one of the largest and most complete ground-based ozone measurement networks in the world, with twelve Brewer ozone spectrophotometer and six ozonesonde sites, as well as a high-Arctic observatory that operates two lidars and other instruments that measure ozone, NO_2 and other atmospheric constituents important to ozone chemistry. Data from the Brewer network is delivered in quasi-real time to the operational forecast centre for use in producing the daily ozone and UV Index forecast. Environment Canada is also already engaged in modeling efforts in this region, with the Middle Atmosphere Model (MAM), a collaboration with Canadian universities, as well as the operational global forecast model (SEF). Recent improvements to this model have raised its lid to the stratopause.

Better knowledge of middle atmosphere dynamics is essential to progress in each of the three key issues referred to above. The global distribution of ozone and its annual cycle at a given location are both products of transport, as are short-term variations, and apparently interannual variability as well. It seems likely that transport also has a role to play in explaining long-term changes in total ozone over Canadian and other mid-latitude sites, either via the transport to lower latitudes of ozone-depleted air from the Arctic winter stratosphere ("polar processing"), or through changes in the stratospheric meridional circulation, and hence the rate at which ozone is transported from the tropical regions where it is primarily formed. Improved knowledge of middle atmosphere dynamics will lead to better understanding of sudden warmings, of vortex interchange with midlatitudes and of the effects of volcanic aerosol injections. Stratospheric parcel trajectory analysis from numerical weather prediction (NWP) model output will become much more reliable. A middle atmosphere modeling and data assimilation system will provide a powerful tool for the study of global ozone transport.

Improved knowledge of the middle atmosphere circulation should also lead to significant improvements in climate modeling for global change issues. When combined with improved initialization for forecast models, this is expected to lead to improvements in long-range forecast skill. Proper modeling of winds and gravity waves even as high as the mesopause or higher appears to be essential to balancing the upward flux of momentum and energy through the stratosphere [*Haynes et al.*, 1991; *Holton et al.*, 1995]. Of course, problems with spurious wave reflection from model lids have been appreciated for some time [e.g. *Lindzen et al.*, 1968]. Modeling studies [*Boville and Baumhefner*, 1990] have in fact shown that long-range forecast skill is apparently improved in models with higher lids.

The importance of the middle atmosphere to environmental issues affected by longer-term atmospheric motions is becoming increasingly recognized. Research projects similar to the one we describe here are either planned or already underway at the UK Met Office, the European Centre for Medium-Range Weather Forecasting (ECMWF), and the Data Assimilation Office of NASA Goddard.

2. Data Assimilation

Data assimilation is conceptually quite simple. The task is to optimally combine observations from different measurement systems with prior knowledge of atmospheric structure and fundamental dynamics, expressed in an atmospheric model. In the three-dimensional problem, successive and adjacent measurements, as well as predicted variables on adjacent grid points, will have errors that are correlated with each other. The observations are therefore weighted inversely by their estimated error covariances, and the *background* (predicted + observations from other sources) variables by their estimated error covariances. It can be shown [Daley, 1991] that imposing the condition that the resulting estimate of the atmospheric state variables, $\mathbf{x}$, be a maximum likelihood estimate leads to a minimization problem of the form:

$$J(\mathbf{x}) = (\mathbf{H}(\mathbf{x}) - \mathbf{z})^{\mathrm{T}}\mathbf{O}^{-1}(\mathbf{H}(\mathbf{x}) - \mathbf{z}) + (\mathbf{x} - \mathbf{x_b})^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x} - \mathbf{x_b}) \quad (1)$$

where $\mathbf{z}$ is the vector of observations, $\mathbf{x_b}$ is the vector of background values of the atmospheric state variables, $\mathbf{O}$ and $\mathbf{B}$ are the observational and background error covariance matrices respectively, and the $\mathbf{H}$ are the *instrument forward models* (IFM). The IFM is an operator that takes as input state variables (u, v, w, T, etc.) generated by the assimilating model and produces as output an equivalent of the observational data (e.g. line-of-sight integrated wind or radiance). Equation (1) will be recognized as having the form of a least-squares problem. Since $\mathbf{x_b}$ and $\mathbf{B}$ will in general involve both the model forecast and information from other correlated observations, equation (1) must be solved iteratively for each observation type.

This process of constraining the model to "reality" produces a final representation of the atmosphere (the *objective analysis* or state estimate) that is a better estimate than the initial forecast of the actual state of the atmosphere. The objective analysis is then used as the initial conditions for the next forecast cycle. The assimilation also propagates information into areas where there are no observations, in a way that is consistent with the (known) physics of the atmosphere, and, via the model, imposes a constraint of physical consistency between observation data that are physically related, such as wind, pressure and temperature. This will highlight inconsistencies between measurement types, or deficiencies in model processes or parameterizations.

While for the meteorologist the primary goal of this is an improved initial state estimate for long-range forecasts, the observational scientist will note that the objective analysis is a better representation of the state of the atmosphere than that from either measurements or modeling alone. The goal here is a better understanding of processes, both in modeling and measurement. Moreover, the value added to very expensive satellite data, compared to using them alone or in individual comparison with models, can be very significant. The result of data assimilation is therefore *both* an improved model and an enhanced data product.

The data assimilation system can also be used to perform Observation System Simulation Experiments (OSSE) to evaluate quantitatively the value (i.e. the *new* information content) of potential new atmospheric data *before* the instruments are built and deployed. An OSSE assimilates simulated observational data, sampled in the manner of the proposed instrument from a model arbitrarily designated as "truth", and examines their effect on the resulting analysis, i.e. their impact on our knowledge of the atmospheric state. A series of such experiments can also be used to determine the optimal choice of such parameters as orbit height, instrument field-of-view, and CCD integration time (vs coverage, horizontal and vertical resolution, repeat coverage period and temporal resolution), thereby permitting the mission to be designed to obtain maximum scientific value.

By effectively comparing data from an atmospheric sounding instrument with all other observations and with physical consistency between them, data assimilation imposes a powerful constraint on the data from any given instrument. It has for this reason proven very useful in post-launch calibration and validation.

In order to employ the techniques of data assimilation with an existing instrument, or to perform an OSSE with a proposed instrument, an IFM must be developed. The IFM, described in (1) as a mathematical operator, is in practical terms a software routine that interfaces the instrument with the data assimilation system. It takes the place of (and is functionally similar to) the inversion algorithm that would conventionally be developed by the instrument team in order to produce a useful data product (i.e. wind velocity or total ozone) from the actual measured quantity (typically a radiance). Development of the IFM will in general require collaboration between the data assimilation team and the instrument designers, and this effort should begin at the instrument design phase, if OSSE's are to be part of the design process.

Since a typical global atmospheric model has of the order of one million grid points, the direct solution of equation (1), involving matrix inversion, is not practical. Currently most meteorological centres solve a limited version of the problem, where each grid point is assumed to be influenced by only a local subset of the global grid: this is called optimal interpolation (OI). Such inversion methods require that the **H** be linear. More recently variational methods (3DVAR) have been used to solve (1) for the entire globe. These do not require linearity of the forward operators. Perhaps more importantly, the inversion of raw data from an instrument viewing the earth's atmosphere in general requires prior assumptions about the distribution of the absorbers and scatterers in the viewing path: i.e. the problem is underdetermined. The result is therefore not independent of the initial assumptions. As variational methods can deal with such nonlinear forward models, they permit the direct assimilation of radiances, so that no prior assumptions are made, and the optimization problem is solved with the observational constraint being what the instrument actually sees, weighted inversely by its known instrumental error characteristics (expressed by the IFM).

3DVAR algorithms are currently being developed or implemented at most major meteorological centres. More advanced methods, such as the 4DVAR and Kalman filter data assimilation algorithms, which introduce time as an additional dimension in the assimilation, are active areas of current research. These algorithms permit information to be exchanged between fields of wind observations and those of species concentration, as those fields evolve in time.

3. Research Plan and Preliminary Results

The current research plan comprises five major projects. The list of tasks under each should be regarded as preliminary. Other research problems will be identified as each project progresses.

1. 3D Variational assimilation of total ozone and other constituent data and dynamical ozone analyses in the stratosphere:

The goal of this project is the assimilation of total ozone measurements, and subsequently, ozone profile data and other measurements of chemical constituents and aerosols in the stratosphere. This is the first Canadian attempt at middle atmosphere (and constituent) assimilation. The assimilation experiments will be performed with the current operational model, the SEF. This project aims to develop expertise in stratospheric data assimilation of observations from different, already existing instruments. The SEF group has considerable experience with tropospheric data assimilation, and has an active research programme in 3D variational data assimilation (3DVAR), including the direct assimilation of TOVS radiances. The extension of the model into the stratosphere has recently been completed, and the assimilation of (TOVS) ozone data is proceeding.

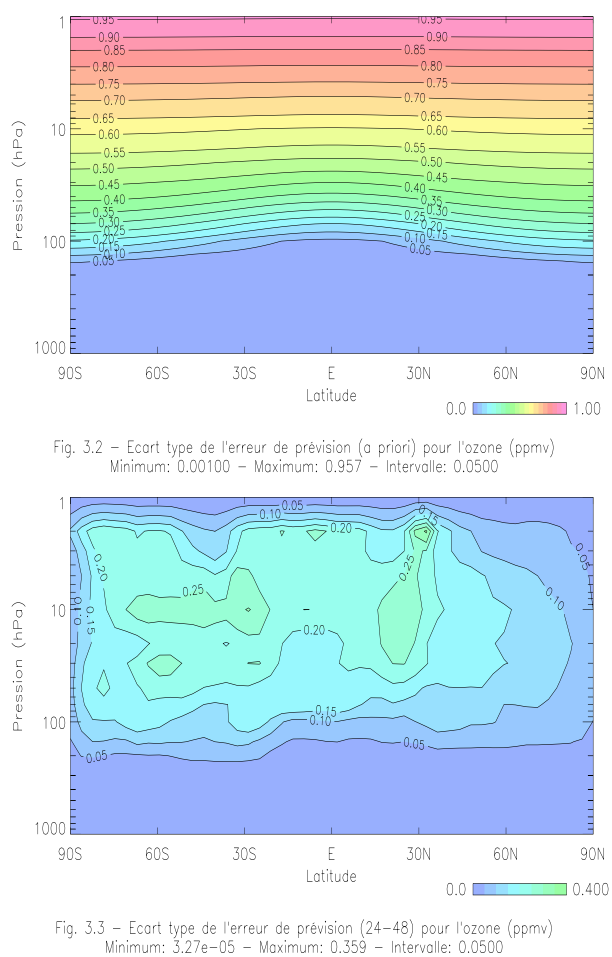

Figure 1. Background error variances: (top) a priori; (bottom) after an assimilation cycle. Figure from Genin and Mereyde, 1996.

Initial results of this experiment have been very encouraging. As a first guess for the background error variances, a field that was a slowly varying function of latitude, virtually zero below the tropopause, but increasing rapidly with altitude (Figure 1a) was used. An assimilation cycle was performed and the results used to produce a better estimate of the variance field (Figure 1b). Vertical correlations and the variation of the horizontal characteristic length were also estimated. These statistics control how a single observation corrects the background field. This is illustrated in the next two figures, for a single observation of ozone concentration (Figure 2) and of total ozone (Figure 3).

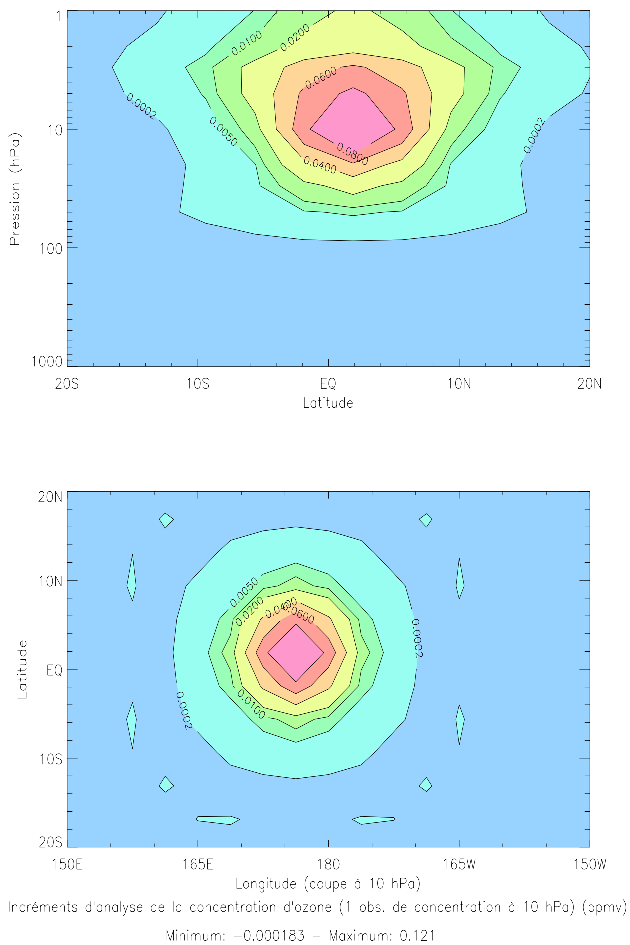

Figure 2. Analysis increments for a single observation of ozone concentration at 10 hPa. Figure from Genin and Mereyde, 1996.

The impact of the improvement in the background error statistics is shown in Figure 4 for the zonal average of the 48-hour forecast error. The reduction in total RMS error over the duration of the assimilation cycle (one month), varies between about 5–40%, over the southern hemisphere and the tropics, although there is an increase in RMS error north of 50°N. Overall it is clear that the change in the background error statistics has improved the results. The results using the new statistics were then compared with those issued by an empirical method due to Riishojgaard [*Riishojgaard et al.*, 1992]. This method assumes a vertical distribution of ozone according to a climatological ozone profile. The 3DVAR results are clearly better (Figure 5) although the climatology for the 3DVAR shows too little variation with latitude (Figures 6a and 6b).

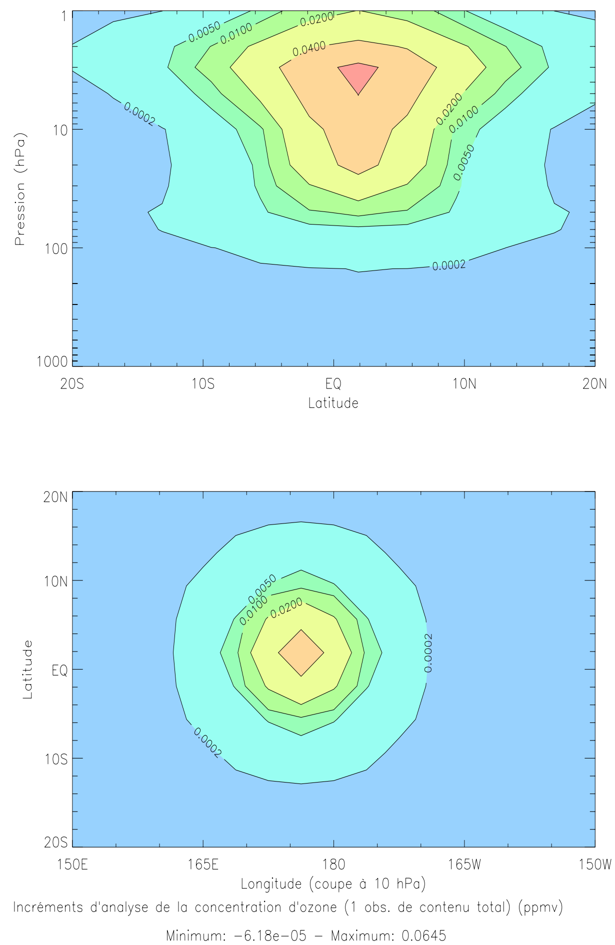

Figure 3. Analysis increments for a single observation of total ozone. Figure from Genin and Mereyde, 1996.

The 3DVAR ozone analysis compares well with the NOAA daily map of retrieved total ozone (Figure 7) even though it has used only 1/4 of the data. The 3DVAR is able to fill in the data gaps by propagating information from other types of observation and from the model. More fine structure is apparent in the 3DVAR analysis as well. Finally, the 48-hour forecast of ozone from the previous analysis can be compared with the NOAA retrieval for the corresponding day (Figure 8). The agreement is remarkably good. Two bright spots over Africa in the NOAA analysis that do not appear in the 3DVAR forecast are caused by a deficiency in the retrieval algorithm over desert areas, involving the breakdown of an assumption regarding surface albedo.

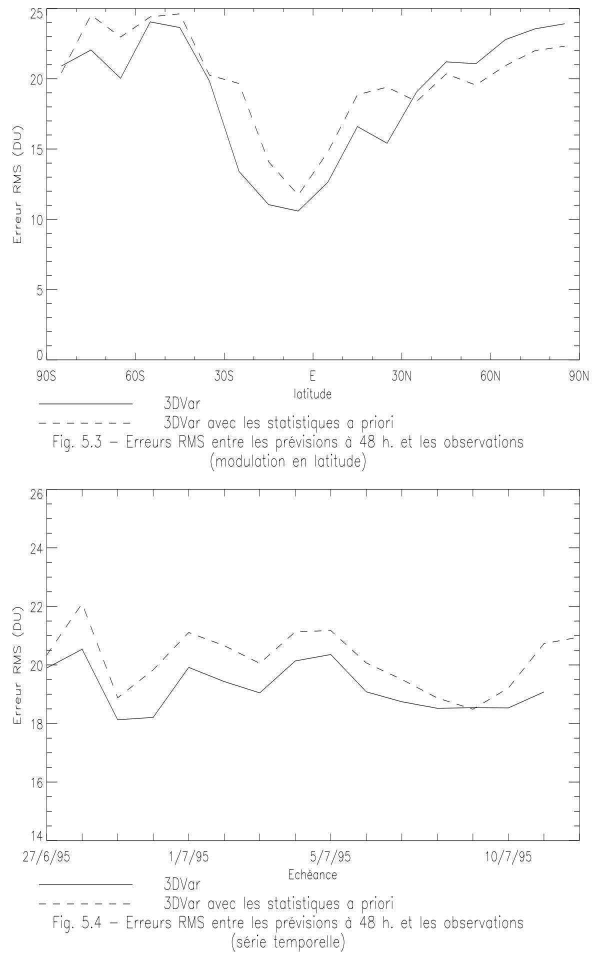

Figure 4. RMS error between 48-hour forecast and observations. Figure from Genin and Mereyde, 1996.

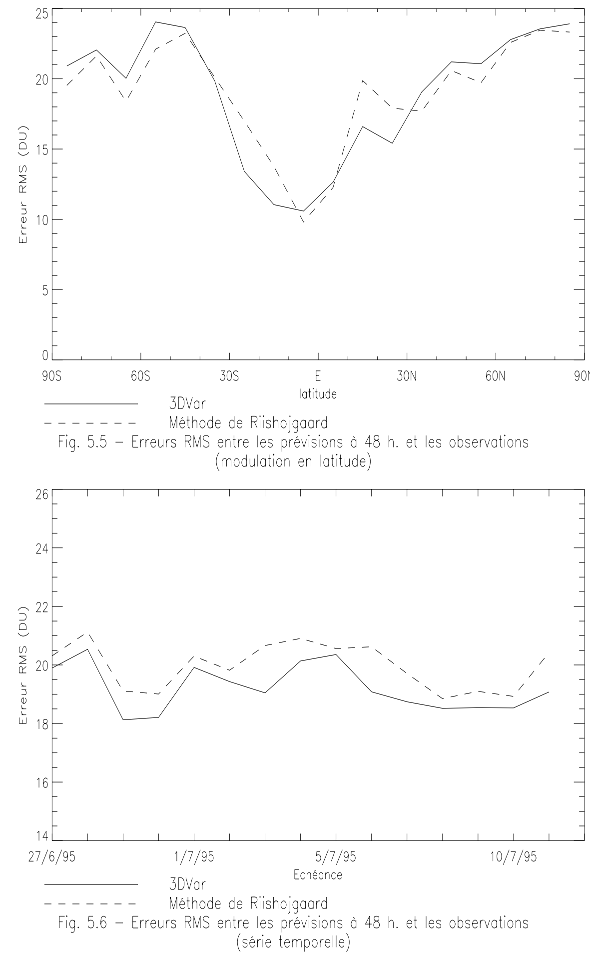

Figure 5. Comparison between 3DVAR and empirical method due to Riishojgaard. Figure from Genin and Mereyde, 1996.

Although these results are very encouraging, improvements can be made in the background error statistics and possibly the model wind fields in the statosphere. The model does not include ozone chemistry or photodissociation, and this could be a deficiency at the highest altitudes. This assimilation was performed on retrieved total ozone: the direct assimilation of the radiance observations made by the instrument should produce significantly better results.

Planned tasks for this project include:

1) 3DVAR assimilation of TOVS radiances at 9.7 μm

2) Multivariate 3DVAR: Currently, the analysis in the stratosphere for the other variables of the model is derived from the operational analysis. Given that the ozone forecasts rely on the quality of the stratospheric winds, it then becomes essential to perform a full analysis including all data and not only ozone-related observations. This can be expected to improve significantly the ozone analyses and forecasts. For example, assimilating data from other TOVS channels should improve our knowledge of stratospheric temperatures, and consequently, of the winds also.

3) Assimilation of GOME data: While TOVS data has been used initially because of its ready availability and the effort that has already gone into assimilating other radiance data from this instrument (for tropospheric temperature analyses), the measurement of ozone via thermal emission at 9.7 μm is a much less reliable way of measuring ozone than UV absorption: in particular the derived ozone amounts are dependent on the vertical distributions of both ozone and temperature. On the ERS-2 satellite, data from the Global Ozone Monitoring Experiment (GOME) are available. A proposal has been submitted and accepted by ESA so that Environment Canada has access to the data to be assimilated.

Proposed future tasks for this project include:

4) Coupling to other variables: Potential vorticity behaves very much as a passive tracer over short periods of time. It can then be expected that its forecast error can be correlated with that of ozone or of any other chemical constituent that also behaves approximately as a passive tracer. If there is a correlation between the forecast er-

rors of ozone and potential vorticity, introducing it in the representation of the background error covariances will imply that the assimilation of measurements of passive tracers will infer information about winds.

5) Implementation of interactive chemistry and improvement of tracer transport interpolation scheme;

6) Aerosol assimilation from LITE instrument observations: The Lidar In-Space Experiment (LITE) flew aboard the space shuttle in September 1994 and data on aerosols were collected over a period of 9 days. The LITE instrument has the capability to make observations of clouds, as well as particulate aerosols in the troposphere and stratosphere. An observing system experiment (OSE) will be performed over the observation period to look at the impact these data have on the analysis.

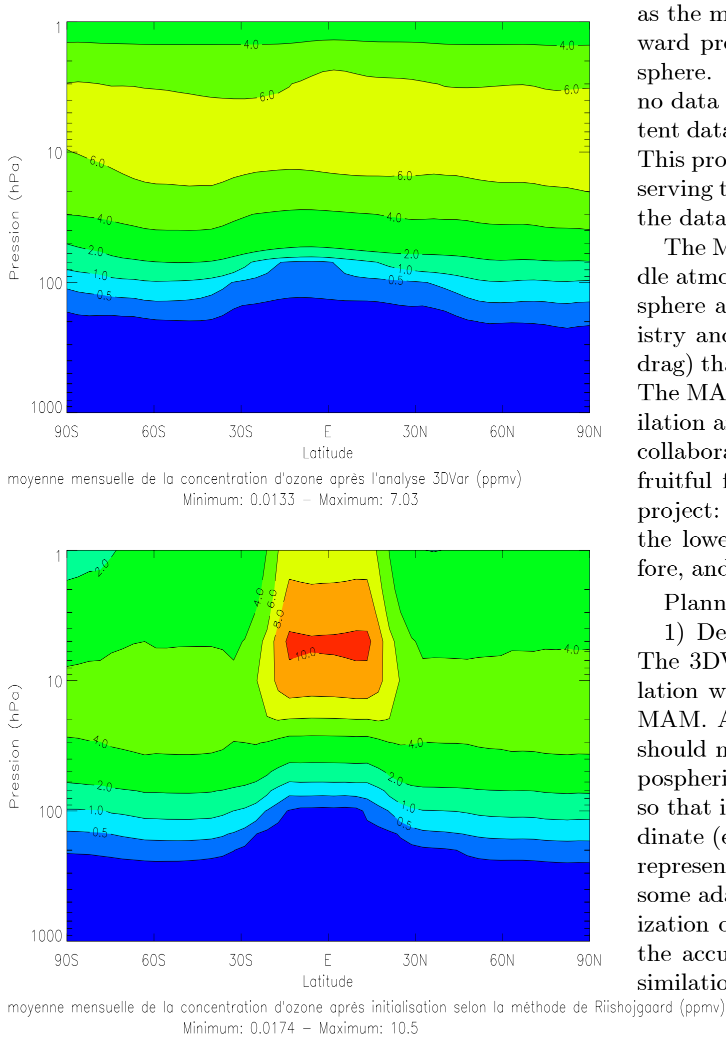

Figure 6. Comparison between 3DVAR and empirical method due to Riishojgaard. Figure from Genin and Mereyde, 1996.

7) Assimilation of ODIN and MOPITT observations: These Canadian instruments are expected to be launched in the relatively near future. The OSIRIS instrument on ODIN will make global measurements of ozone with low to moderate horizontal and vertical resolution. MOPITT will make global measurements of CO with excellent horizontal and vertical resolution, and column measurements of CH4.

2. Assimilation of wind data in the mesosphere:

The goal of this project is to address the problem of assimilating data in the mesosphere. As in the previous project, this one should explore different observing systems, but we will start with the assimilation of real WINDII (retrieved winds) using the MAM and the multivariate (wind/mass coupling) 3DVAR. WINDII winds will be assimilated from 85-105 km. The assimilation from 30-85 km will have to depend heavily on temperature data from MLS, another UARS instrument, as well as the multivariate coupling of the 3DVAR, and the upward propagation by the MAM from the lower stratosphere. Since UARS flips every 30 days, there will be no data poleward of 70 degrees and there will be persistent data voids (every other 30 days) from 40-70 degrees. This problem, however, also offers the opportunity of observing the propagation of measurement information into the data voids by the assimilating model.

The MAM group has developed a state-of-the-art middle atmosphere model that extends to the lower thermosphere and includes an advanced radiation code, chemistry and physical parameterizations (i.e. gravity wave drag) that are needed to properly model the mesosphere. The MAM has, however, never been used for data assimilation and the development of this capability, via direct collaboration with the SEF group is expected to be very fruitful for both groups. This is an ambitious research project: data assimilation from the earth's surface to the lower thermosphere has never been attempted before, and we expect to learn a great deal from this effort.

Planned tasks under this project include:

1) Development of a 3DVAR system for the MAM: The 3DVAR system used for tropospheric data assimilation with the SEF must be adapted for use with the MAM. As the MAM is a spectral model like SEF, this should not pose too many technical problems. The tropospheric 3DVAR has been developed in a general way so that it is not too difficult to modify the vertical coordinate (e.g., pressure, height or s) but rely on a spectral representation in the horizontal. The MAM will need some adaptations (e.g., a nonlinear normal mode initialization or something equivalent) so that it can produce the accurate short-term forecasts needed in a data assimilation cycle,

2) Testing the assimilation and estimation of the MAM short-term forecast error statistics: it will be necessary to characterize the short term forecast error several times as the project evolves to assess the impact of changes brought to the system, whether by the addition of new data or by changes to the model itself. Relatively little data is available at such altitudes, and verification will

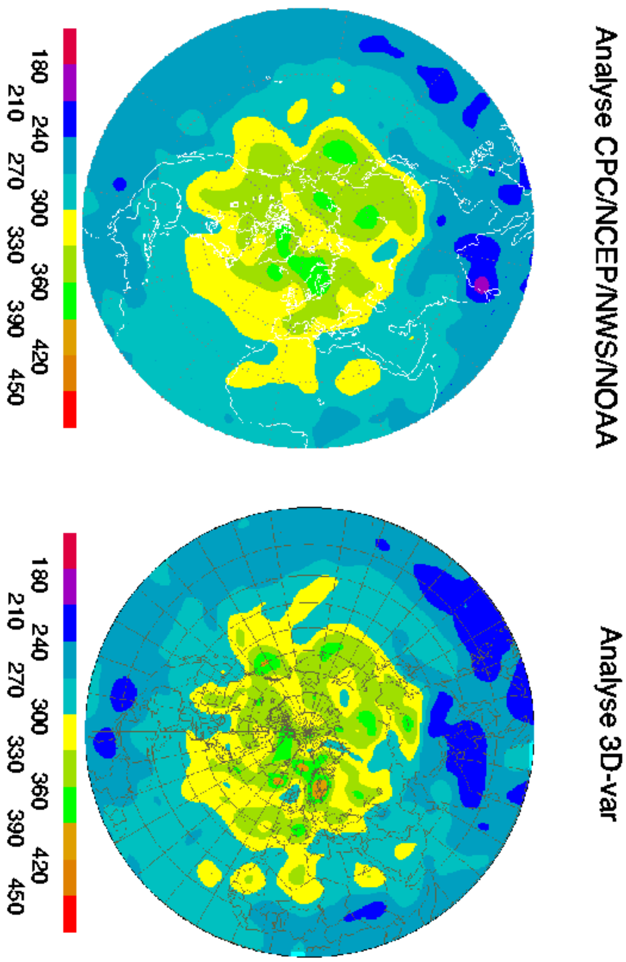

Figure 7. Comparison between 3DVAR assimilation and NOAA daily map of retrieved total ozone. Figure from Genin and Mereyde, 1996.

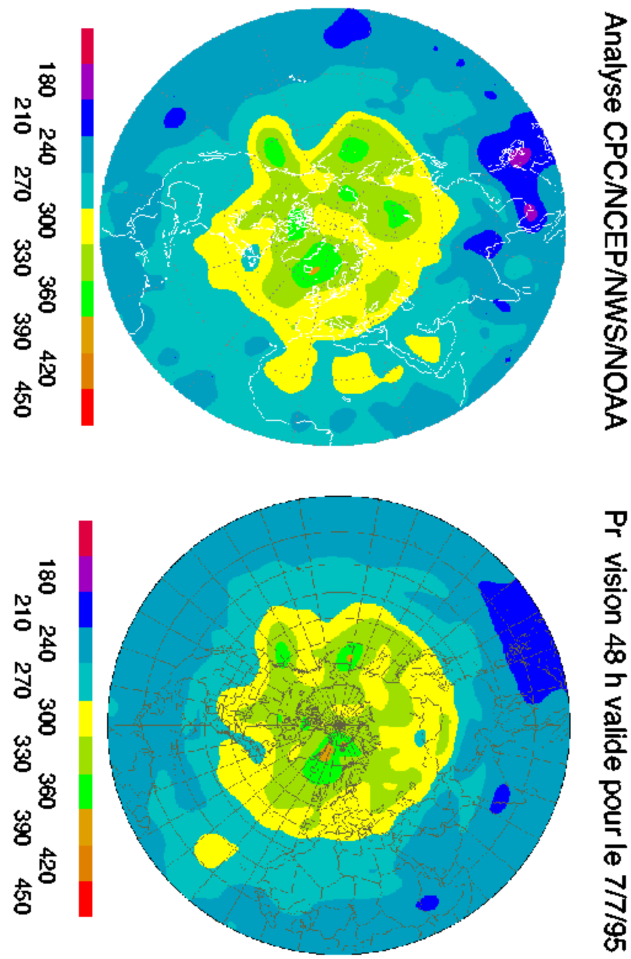

Figure 8. Comparison between 48-hour forecast of ozone using 3DVAR and the NOAA retrieval for the corresponding day. Figure from Genin and Mereyde, 1996.

have to rely primarily on data from various instruments aboard UARS and on GPS-Met data. Forecast error could also be estimated with the NMC method (at least for the correlations). In absence of a data assimilation cycle to alter the initial conditions as is usually done in the NMC method, those could be perturbed by introducing random errors. We propose as a first step to have a first estimate of the prediction error obtained in this manner and to perform an assimilation cycle of two months with UARS observations and compare the generated analyses with the UKMO analyses. This will give us some information about the quality of our assimilation cycle. The second step is to reassess the forecast error statistics using these analyses to produce forecasts. A new assimilation could then be performed over a different period of time and compared to other (e.g. UKMO) analyses.

3) Development of forward and adjoint models for WINDII: This will require collaboration between the instrument scientists and those in the data assimilation group to define precisely what is needed by the assimilation to handle the WINDII data. Forward models of increasing complexity will be tested afterwards in the assimilation to determine if it is indeed necessary to use more complex forward models. From past experience with other types of data, it has been shown that sometimes it is best to do a simple non-ambiguous retrieval (e.g., SSM/I retrieved total precipitable water) that gives a measurement that is more easily assimilated. In other instances, such as for TOVS observations, it is best to use a forward model that produces model equivalents of the radiances.

4) Observational error characteristics: In addition to random and systematic errors intrinsic to the instrument, the correlation between adjacent and successive

observations needs to be estimated, as well as representativeness error (uncertainty due to real, but unresolved (sub-gridscale) fluctuations). The nature of cross errors and quality control need to be examined.

5) Assimilation of WINDII winds: This can proceed in several steps, requiring increasing sophistication of the forward model: (1) inverted winds, assumed located at tangent point of observation, or area-averaged; (2) line-of- sight integrated winds; (3) direct assimilation of radiances. MLS inverted temperature data will also be assimilated to help maintain a realistic upper stratosphere and mesosphere. The question of how the tides and possible aliasing problems due to the predominance of tidal motions at WINDII heights are to be treated will need to be addressed.

Proposed future tasks for this project include:

6) Examination of the dynamical coupling between the winds at WINDII heights and the circulation lower in the middle atmosphere: In order for data assimilated at one level of the atmosphere to influence the analysis at other altitudes, some mechanism must exist to propagate information between levels. In 3DVAR this coupling appears through the forecast error covariances. It will be important to understand the dynamical processes linking the winds in the thermosphere to those below, that are reflected in those error covariances.

3. Development of OSSE and OSE software and its applications:

The principal objective of this project is the development of a suite of software that will permit the middle atmosphere data assimilation system to be used to perform experiments to test the impact on the analysis of various existing data sources, or of proposed instruments. The first OSSE system will be a variant of the 3DVAR system being developed currently for SEF, expected to be available at the end of August, 1996. It will be improved as more advanced techniques such as 4DVAR are introduced into the middle atmosphere data assimilation system. The software tools will be developed so as to be compatible with the different assimilating models, since this project will perform experiments in both the mesosphere and stratosphere. OSSE's will involve considerable interaction with instrument teams, and this effort will be the principal vehicle by which data assimilation expertise is exported to the university community.

Tasks planned under this project include:

1) the development of OSSE software;

2) OSE's with TOVS, GOME and WINDII data;

3) the construction of ISM's for MIMI and SWIFT: these instruments (see *Gault et al.*, 1996; *Buttner et al.*, 1996, this volume, for a description), the first whose performance we expect to analyze via OSSE's, are important experiments for this project, and the initial motivation for the MAI. Some of the forward model development will already have been done in Project 2, for WINDII, and the instrument scientists are already MAI collaborators;

4) OSSE's with MIMI and SWIFT: this could proceed at varying levels of complexity, beginning with a simple ISM, simulating retrieved data for each instrument, and advancing, via collaboration with instrument scientists, to ISM's using simulated raw radiance information;

Proposed future tasks for this project include:

5) OSE's with GO3OS, GPS and other existing middle atmosphere data sources

6) OSSE's with other proposed instruments;

7) the use of more advanced assimilation algorithms.

4. Research into Advanced Methods:

The importance of chemistry to middle atmospheric processes necessitates the assimilation of chemical species observations into middle atmosphere models. The relative sparsity of species data suggests a four-dimensional approach to data assimilation. 4DVAR methods also offer the opportunity of inferring dynamical information from successive observations of species concentration. Such methods are still experimental and have not yet been implemented operationally even for tropospheric data assimilation, although several groups are currently pursuing this goal.

Both horizontal transport using a shallow water model and vertical transport using a vertical 2D model will be examined. Coupling simple chemical models will permit study of the nonlinear transfer of information by 4D data assimilation, and the extraction of windfields from simulated constituent information.

5. Diagnostics and Analysis of Data Sets:

This project groups activities that support and are common to the other projects, including development of diagnostic tools (new tools will be developed for diagnostics of *innovations*, the differences between the model forecast and the observations at the observation locations), archiving of data sets, and comparative diagnostics and analysis of data assimilation output fields. Diagnostic tools for SEF and MAM output files already exist, as well as a translator between standard file types, but translation software for other file types (i.e. UARS, UK Met.Office or NASA Goddard files) may need to be developed.

4. Conclusions

By building on Environment Canada's tropospheric data assimilation research and development, and by exploiting existing expertise in middle atmosphere modeling and measurement, the MAI will enhance Canadian middle atmosphere capability. A middle atmosphere data assimilation system will permit the maximum amount of useful information to be extracted from satellite measurements, as well as providing optimum initialization for models. In addition, the data assimilation system may be used to perform Observation System Simulation Experiments (OSSE) to (1) evaluate the worth (i.e. the *new* information content) of potential new atmospheric data, and (2) determine the optimum choice of orbit and other parameters to maximize that new information content. For both of these reasons it is our opinion that the assimilation of satellite data with middle atmosphere models should be viewed, in the future, as an essential component of the observation program. This will require that instrument designers consider the construction of the IFM during the design phase of the instrument. Like the more familiar inversion algorithm that it replaces, an IFM must be constructed by the instrument designers, since its construction requires intimate knowledge of the instrument design, function, method of operation and especially its error characteristics.

This enhanced middle atmosphere capability is expected to yield improvements in standard meteorological forecasts, particularly on the longer timescale, as well as improved analyses of middle atmosphere phenomena related to ozone variation and depletion, and to climate change. Parcel trajectory analysis from numerical weather prediction model output will become much more reliable. A middle atmosphere modeling and data assimilation system will also provide a powerful tool for the study of global ozone transport.

As Environment Canada moves its interests upward, the CSA, too, is looking downward. The recent document on future directions for Solar-Terrestrial Relations research, the "Magog Manifesto" identifies "Understanding Atmospheric Change" as one of two major themes for future funding. Under that theme, three priorities are specified: middle atmosphere winds, chemistry of trace species, and middle atmosphere gravity waves. As their mandates increasingly come to overlap, CSA and Environment Canada can collaborate to their mutual benefit. Environment Canada is interested in space data, but lacks the resources to carry out even a modest program of space-based observations alone. But it has the (unique in Canada) modeling and data assimilation expertise to lead a coordinated middle atmosphere measurement and modeling program. Collaboration with Canadian universities, research organizations like the Institute for Space and Terrestrial Science and foreign organizations will also be necessary. Such partnerships will benefit research in both modeling and measurement.

A strong interaction between Environment Canada scientists and the Canadian space community will be very useful to both. Investment of Canadian high technology funds in space-based atmospheric instrumentation will be very beneficial to the development of the atmospheric sciences in Canada. Atmospheric observation from space is a practical use of space technology with demonstrable benefits, and Environment Canada expertise could be very helpful to the CSA in instrument planning and design decisions, with ultimate benefit to the Canadian public. Not least of these benefits will be the ability to perform OSSE's: this will provide the CSA with a very valuable tool for the evaluation and optimization of future middle atmosphere remote sounding satellite proposals.

References

Boville, B.A. and D.P. Baumhefner, Simulated forecast error and climate drift resulting from the omission of the upper stratosphere in numerical models, *Mon. Wea. Rev.*, *118*, 1517–1530, 1990.

Daley, R. [1991] *Atmospheric Data Analysis*, Cambridge University Press, Cambridge.

Gault, W.A., G.G. Shepherd, D.W. Tarasick, S. Sargoytchev and W.E. Ward, MIMI: Mesospheric Imaging Michelson Interferometer, *Proc. 9th CASI Conference on Astronautics*, Ottawa, November, 1996.

Genin, Y., and F. Mereyde, Assimilation variationnelle 3D du contenu total d'ozone, Environment Canada internal report, 1996.

Buttner, G., N. Rowlands, A. Raab, G.G. Shepherd, W.A. Gault, M. Cann, S. Dobbie, Y. Rochon, S. Sargoytchev, W.E. Ward, D.W. Tarasick and J. Wimperis, Stratospheric Wind Interferometer for Transport Studies (SWIFT), *Proc. 9th CASI Conference on Astronautics*, Ottawa, November, 1996.

Haynes, P.H., C.J. Marks, M.E. McIntyre, T.G. Shepherd and K.P. Shine, On the "downward control" of extratropical diabatic circulations by eddy-induced mean zonal forces, *J. Atmos. Sci.*, *48*, 651–678, 1991.

Holton, J.R., P.H. Haynes, M.E. McIntyre, A.R. Douglass, R.B. Rood and L. Pfister, Stratosphere-troposphere exchange, *Rev. Geophys.*, *33*, 403–439, 1995.

Lindzen, R.S., E.S. Batten and J.W. Kim, Oscillations in atmospheres with tops, *Mon. Wea. Rev.*, *96*, 133–140, 1968.

Riishojgaard, L.P., F. Lefèvre, D. Cariolle and P. Simon, A GCM Simulation of the northern hemisphere ozone field in early February 1990, using satellite total ozone for model initialization, *Ann. Geophys.*, *10*, 54–74, 1992.