# Three-Dimensional Constituent Transport Models and the Study of Interannual Variability

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An approach to using three-dimensional (3D) models to simulate realistic ozone variability is described. The technique represents planetary and tropospheric cyclonic scales accurately. Therefore, it is possible to define the origins of the dynamical variability of ozone. Then smaller effects, such as solar variability, can be evaluated against this realistic dynamical background.

## 1. Introduction

Middle atmospheric data sets have long been examined for evidence of solar signals. Because of its longer data record and known dependence on ultraviolet radiation, ozone has been most extensively studied. In order to extract either a solar signal or an anthropogenically induced trend, the dominant variability due to dynamical processes must be quantitatively accounted for.

The possibility that solar activity can profoundly affect atmospheric dynamics (e.g. LABITZKE and VAN LOON, 1989; BALDWIN and DUNKERTON, 1989) further confounds the effort to extract a definitive solar signal from constituent measurements. While there is good theoretical foundation to expect ozone to respond to changes in solar ultraviolet flux and temperature, the mechanisms that could cause large scale modulation of the dynamics are much less clear. No attempt will be made to address variability of the sort discussed by Labitzke and van Loon in this paper.

The search for solar signals in ozone and other constituent measurements is active on several fronts. JACKMAN *et al.* (1990, and the references therein) showed definitively the effect that solar proton events (SPE's) have on ozone (see also JACKMAN, this issue). Furthermore, it has been suggested that solar induced nitrate variability is visible in Antarctic ice cores (ZELLER *et al.*, 1981). CALLIS and NATARAJAN (1986) incorrectly speculated prior to polar aircraft expeditions to study the Antarctic Ozone Hole (SOLOMON, 1988), that the ozone hole could be an extreme response to solar driven changes in reactive nitrogen compounds. HOOD (1987), CHANDRA (1986), KEATING *et al.* (1985), and their coworkers have expended considerable effort trying to understand 27 day variability in ozone and temperature data.

In general solar signals are expected to be small compared to dynamical variability. The expected variability of total ozone between solar maximum and solar minimum is approximately 2% (C. Jackman, personal communication). This signal must be extracted from a much larger annual variability. At high northern latitudes, for instance, the amplitude of the the annual cycle of total ozone is on the order of 50% (LONDON *et al.*, 1976). This

variability is strongly dependent on planetary wave transport, which varies widely from year to year.

Once the annual cycle is removed, the predominate systematic signal that remains in the total ozone record is the quasi biennial oscillation (QBO) (Fig. 1). The QBO variability is on the order of 3–5% of the total column, and it is a complicated function of time and space. After accounting for the QBO, such episodic events as SPE's and volcanic eruptions and fluctuations due to long term dynamical processes (e.g. El Nino) remain in the signal.

The problem of extracting solar signals is made even more difficult because of possible pollutant impact on ozone. Figure 2 shows global annual average ozone change as predicted by the 2-D model from 1950–1990. The 11 year solar cycle is clearly superimposed on ozone decrease caused by the reactive chlorine increase. The expected ozone decrease is such that the magnitude of the solar cycle maximum in one decade is significantly reduced in the following
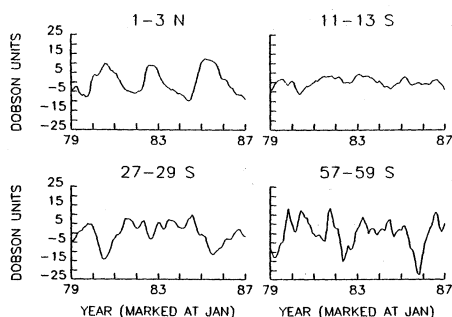


Fig. 1.   Zonal mean TOMS total ozone data detrended and deseasonalized to reveal the quasibiennial oscillation (SCHUSTER et al., 1989). The tropical QBO is evident at 1–3 N, and it weakens rapidly south of the equator. South of 20 S the amplitude increases, the phase shifts, and the QBO becomes much more erratic.
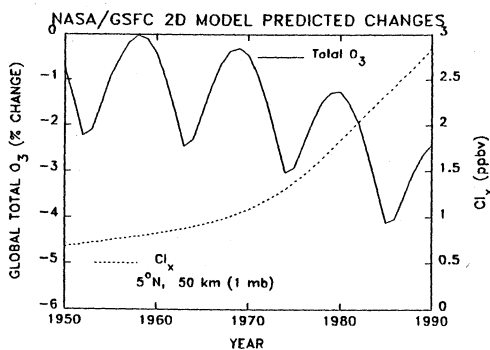


Fig. 2.   Global total ozone as a function of time in an atmosphere with increasing chlorine. The dashed line is the increase in total inorganic chlorine as a function of time. These are 2D model calculations courtesy of C. Jackman.

decade. Finally, one must deal with limited data records, limited data types (e.g., total ozone rather than long records of vertical profiles), and, very importantly, instrument variability associated with instrument degradation and instrument type changes.

If atmospheric models could realistically represent dynamical variability, then they could potentially be a very useful tool for extracting solar signals and trends. However, tropospheric and stratospheric models both are notorious for their lack of interannual variability. In stratospheric models this is most explicitly stated by MAHLMAN and UMSCHEID (1984) and GELLER (1984) in their enumerations of model short comings. In particular, stratospheric general circulation models (GCM's) have a cold pole problem that indicates radiative domination of the model. Since models are dominated by radiative processes, and since radiative processes are cyclical from year to year, the interannual variability is too small. Also the QBO is not adequately simulated.

MAHLMAN and UMSCHEID (1987) have shown that increasing model resolution yields results that are more realistic because they are further removed from radiative equilibrium. RIND et al. (1988) show that the inclusion of gravity wave drag increases interannual variability in coarse resolution models. These results both suggest that interannual variability is dependent on small scale, essentially stochastic, processes.

Given the biases that remain in even the best stratospheric GCM's, and the expense of performing constituent transport and chemistry, straightforward GCM modeling has only limited application to problems of seasonal and interannual variability. However, another strategy is available that allows for applications of 3D models to problems that address dynamical constituent variability.

In this approach the dynamical GCM is used as an analysis tool to generate global wind and temperature fields by standard techniques of meteorological data assimilation (e.g. BAKER et al., 1987). A chemistry transport model (CTM) is then operated with winds from the data assimilation (see ROOD et al., 1989, 1990a, 1990b). The model configuration is parallel to the "off-line" transport experiments described by MAHLMAN and MOXIM (1978). The major difference from MAHLMAN and MOXIM (1978) is that the dynamical GCM has been used as an analysis tool to process meteorological data.

As will be shown, this wind analysis has enough information to represent the basic observable properties of the constituent field for seasonal time scales. However, the CTM is a necessary ingredient in the system because it provides a physical mechanism to represent subscale transient processes that are essential to transport and mixing (ROOD et al., 1990b). The assessment of whether or not the assimilation approach represents the transport properties of the general circulation that are related to diabatic processes can only be proven in multiyear integrations.

Since ozone has been studied most extensively, dynamic variability of ozone will be the focus of this paper. The response of ozone to dynamically forced temperature perturbations (e.g. DOUGLASS and ROOD, 1986) will not be discussed here. The purpose of the paper is to show that the combination of a CTM with data assimilation winds can accurately represent ozone variability due to planetary scale waves in the stratosphere and cyclone scales in the troposphere. Furthermore, with proper quantification of diabatic processes the data assimilation winds should provide a mechanism for defining the dynamically driven interannual ozone variability. With such a model other sources of variability (e.g., solar, volcanic) can ultimately be more precisely extracted.

## 2. Results

A major component of the variability of ozone and total ozone comes from planetary wave activity in the stratosphere. Total ozone is also profoundly influenced by tropospheric disturbances. Therefore, the ability to represent planetary wave and baroclinic wave activity (tropospheric cyclones) accurately is central to ozone transport calculations.

Figure 3 shows ozone at 30 mb on January 26, 1979 from a model calculation initialized on 1 January. Also shown are LIMS (limb infrared monitor of the stratosphere) data. January 26 is at the height of a wave 1 minor warming and the comma shaped area of low ozone values is coincident with the cyclonic polar vortex that has been longitudinally
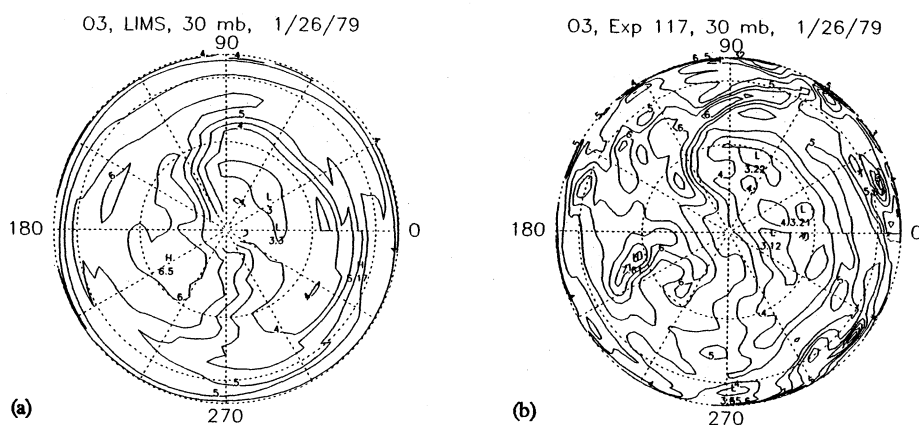


Fig. 3.  LIMS data (a) and model simulation (b) of ozone on the 30 mb surface for 26 January 1979 during a wave 1 warming (ppmv).
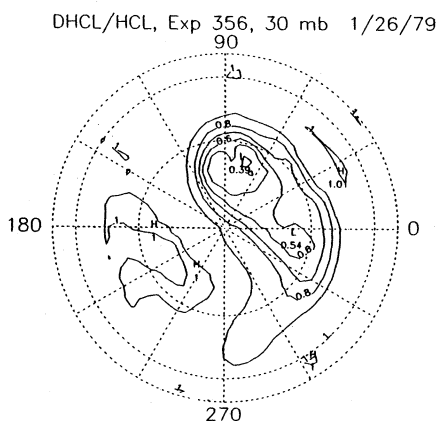


Fig. 4.  The ratio of model calculated HCl with heterogeneous chemistry (DHCl) to model calculated HCl without heterogeneous chemistry. The DHCl experiments represent the effects that polar stratospheric clouds are expected to have on the chlorine budget. This chemically perturbed air remains primarily confined to the polar vortex during the winter.

distorted during the warming.

The model shows more structure than the LIMS data. If the model is "observed" by a limb scanning satellite and the resultant observations Kalman filtered in the same manner as the LIMS data (REMSBERG et al., 1986) then the agreement between observations and model improves significantly. Hence the model reproduces the behavior observed during stratospheric warmings. Further discussion of the impact of satellite observation systems and more detailed comparisons to the LIMS data are given in ROOD et al. (1990b).

The model calculations show the polar vortex to be largely isolated from the rest of the hemisphere (see also JUCKES and MCINTYRE, 1987). It has been definitively shown (e.g. TURCO et al., 1990) that reactive chlorine is present in high concentration in the polar vortex. Figure 4 shows the ratio of HCI from an experiment that simulates heterogeneous chemistry to HCI from an experiment that only has homogeneous chemistry. The HCI has been depleted within the polar vortex.

This demonstrates another feature that a model must reproduce if interannual variability is to be properly accounted for. The amount of time that the reactive Cl remains in the vortex, and where and when the polar vortex is mixed with the rest of the hemisphere, could significantly impact the interannual variability of ozone. Because the data assimilation represents real stratospheric states, the longevity of the polar vortex is accurately represented.

Similarly the duration, frequency, and location of baroclinic waves in the troposphere are properly represented in the data assimilation. These waves are an important feature of total ozone variability, and changes in storm tracks from year to year can lead to a significant interannual signal. Figure 5 shows traces of model and TOMS (Total Ozone Mapping Spectrometer) total ozone from January 1 to March 31, 1989. The model captures day-to-day variability with accurate frequency and amplitudes. The major jump in the time series in the middle of February is due to a stratospheric warming. During the warming stratospheric transport is large enough to dominate the effect of baroclinic scales.

The larger amplitude tropospheric events are specifically captured by the model. Figure 6 shows a short trace of TOMS and model data during the minihole of late January of 1989. Miniholes are transient depressions of total ozone that are associated with tropospheric
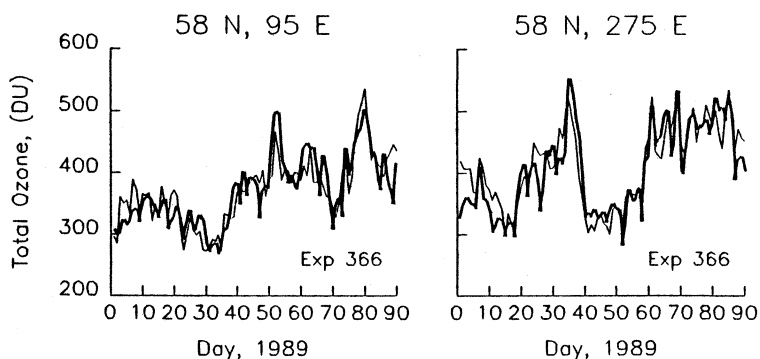


Fig. 5.  Model and TOMS total ozone at 95 E and 275 E and 58 N. Note the jump in middle February as the stratospheric vortex stretches over the United States (275 E).

Total O3, 10 E, 58 N
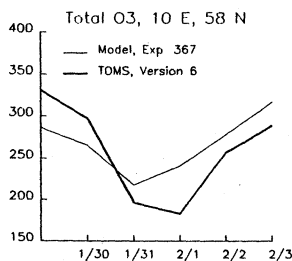
—— Model, Exp 367
—— TOMS, Version 6

Fig. 6.   TOMS and model total ozone from January 29 through February 3, 1989 at 58 N and 10 E. This figure shows the passage of an ozone minimum associated with a tropospheric anticyclone. These minima are sometimes called miniholes, and the ozone reduction is a reversible dynamical event.

anticyclones (NEWMAN *et al.*, 1988). These events are frequent, and because they can cause the formation of clouds in the stratosphere, they can lead to perturbations of stratospheric chemistry.

## 3.  Conclusions

The chemistry transport model driven by winds from the data assimilation has been shown to represent realistically both tropospheric cyclonic scale and planetary scale ozone variability. Because the data assimilation represents real stratospheric states, there is a potential to represent interannual constituent variability quantitatively. This offers an advantage over free running GCM's because the GCM's underestimate interannual variability.

The technique should be helpful for extracting solar and anthropogenic influences on constituents. Multiyear control runs can be made with a standard chemical formulation. Then by changing the chemical parameters (e.g., add a solar cycle) and then observing the 3D model analogously to the real observation systems, it will be possible to assess the signal of perturbed chemistry on a realistic background of dynamic variability.

REFERENCES

BAKER, W. E., S. C. BLOOM, J. S. WOOLLEN, M. S. NESTLER, E. BRIN, T. W. SCHLATTER, and G. W. BRANTSTATOR, Experiments with a three-dimensional statistical objective analysis scheme using FGGE data, *Mon. Wea. Rev.*, **115**, 272–296, 1987.

BALDWIN, M. P. and T. J. DUNKERTON, Observations and statistical simulations of a proposed solar cycle/QBO/weather relationship, *Geophys. Res. Lett.*, **8**, 863–866, 1989.

CHANDRA, S., The solar and dynamically induced oscillations in the stratosphere, *J. Geophys. Res.*, **91**, 2719–2734, 1986.

CALLIS, L. B. and M. NATARAJAN, The Antarctic ozone minimum: Relationship to odd nitrogen, odd chlorine, the final warming, and the 11-year solar cycle, *J. Geophys. Res.*, **91**, 10771–10796, 1986.

DOUGLASS, A. R. and R. B. ROOD, Derivation of photochemical information near 1 mb from ozone and temperature data, *J. Geophys. Res.*, **91**, 13153–13166, 1986.

GELLER, M. A., Modeling the middle atmosphere circulation, in *Dynamics of the Middle Atmosphere*, edited by J. R. Holton and T. Matsuno, pp. 467–500, Reidel, Dordrecht, 1984.

HOOD, L. L., Solar ultraviolet radiation induced variations in the stratosphere and mesosphere, *J. Geophys. Res.*, **92**, 876–888, 1987.

JACKMAN, C. H., A. R. DOUGLASS, R. B. ROOD, R. D. McPETERS, and P. E. MEADE, Effect of solar proton events on the middle atmospheres during the past two solar cycles as computed using a two-dimensional model, *J. Geophys. Res.*, **95**, 7417–7428, 1990.

JUCKES, M. and M. E. McINTYRE, A high resolution one-layer model of breaking planetary waves in the stratosphere, *Nature*, **328**, 590–596, 1987.

KEATING, G. M., G. B. BRASSEUR, J. Y. NICHOLSEN, III, and A. DE RUDDERS, Detection of the response of ozone in the middle atmosphere to short-term solar ultraviolet variations, *Geophys. Res. Lett.*, **12**, 449–452, 1985.

LABITZKE, K. and H. VAN LOON, Association between the 11-year solar cycle, the QBO, and the atmosphere. Part III: Aspects of the association, *J. Climate.*, 554–565, 1989.

LONDON, J., R. BOJKOV, S. OLTMANS, and J. KELLY, Atlas of the global distribution of total ozone, July 1957–June 1967, NCAR Technical Note, TNI 13, Boulder, CO, 276 pp., 1976.

MAHLMAN, J. D. and W. J. MOXIM, Tracer simulation using a global general circulation model: results from a midlatitude instantaneous source experiment, *J. Atmos. Sci.*, **35**, 1340–1374, 1978.

MAHLMAN, J. D. and L. UMSCHEID, Dynamics of middle atmosphere: successes and problems of the GFDL SKYHI general circulation model, in *Dynamics of the Middle Atmosphere*, edited by J. R. Holton and T. Matsuno, pp. 501–525, Reidel, Dordrecht, 1984.

MAHLMAN, J. D. and L. UMSCHEID, Comprehensive modeling of the middle atmosphere: the influence of horizontal resolution, in *Transport Processes in the Middle Atmosphere*, edited by G. Visconti and R. Garcia, pp. 251–266, Reidel, Dordrecht, 1987.

NEWMAN, P. A., L. R. LAIT, and M. R. SCHOEBERL, The morphology and meteorology of southern hemisphere spring total ozone mini-holes, *Geophys. Res. Lett.*, **15**, 923–926, 1988.

REMSBERG, E. E., R. J. KURZEJA, K. V. HAGGARD, J. M. RUSSELL, III, and L. L. GORDLEY, Description of data on the Nimbus 7 LIMS map archive tape, NASA Technical Paper 2625, 1986.

RIND, D., R. SUOZZO, and N. K. BALACHANDRAN, The GISS global climate-middle atmosphere model. Part II: Model variability due to interactions between planetary waves, the mean circulation, and gravity wave drag, *J. Atmos. Sci.*, **45**, 371–386, 1988.

ROOD, R. B., D. ALLEN, W. BAKER, D. LAMICH, and J. KAYE, The use of assimilated stratospheric data in constituent transport calculations, *J. Atmos. Sci.*, **46**, 687–701, 1989.

ROOD, R. B., J. A. KAYE, A. R. DOUGLASS, D. J. ALLEN, S. D. STEENROD, and E. M. LARSON, Wintertime nitric acid chemistry: implications from three-dimensional model calculations, to appear in *J. Atmos. Sci.*, **15**, November, 1990a.

ROOD, R. B., A. R. DOUGLASS, J. A. KAYE, M. A. GELLER, C. YUE-CHEN, D. J. ALLEN, E. M. LARSON, E. R. NASH, and J. E. NIELSEN, Three-dimensional simulations of winter time ozone variability in the lower stratosphere, to appear *J. Geophys. Res.*, 1990b.

SCHUSTER, G. S., R. B. ROOD, and M. R. SCHOEBERL, Quasi-biennial and interannual variability in high resolution total ozone data (TOMS), in *Ozone in the Atmosphere*, edited by R. Bojkov and P. Fabian, pp. 260–264, Deepak, Hampton, 1989.

SOLOMON, S., The mystery of the Antarctic ozone "hole", *Rev. Geophys.*, **26**, 131–148, 1988.

TURCO, R., A. PLUMB, and E. CONDON, The Airborne Arctic Stratosphere Expedition Prologue, *Geophys. Res. Lett.*, **17**, 313–316, 1990.

ZELLER, E. J. and B. C. PARKER, Nitrate ion in Antarctic firn as a marker for solar activity, *Geophys. Res. Lett.*, **8**, 895–898, 1981.