

# Three-dimensional simulations of springtime dissipation of the Antarctic ozone hole\*

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**A three-dimensional offline transport model is used to study the evolution of the Antarctic ozone hole in spring 1994. The modelled ozone profiles generated using winds from the UK Meteorological Office (UKMO), including the whole stratosphere, are closer to observations than simulations driven by operational weather analyses from the Global Assimilation and Prediction system (GASP), with highest level at 10 hPa. Model simulations are also fairly insensitive to horizontal or temporal resolution of the input driving fields, particularly at middle and high latitudes. While the large-scale synoptic variations in simulated total ozone are in good agreement with satellite observations, the model underpredicts total ozone at high latitudes during the ozone hole recovery phase. Further analysis suggests that the polar stratospheric clouds (PSC) chemical parametrisation is not appropriate for the specific spring of 1994. In addition, our results also suggest that dynamics are partially responsible for the slower than observed recovery of column ozone.**

## Introduction

The substantial springtime loss in ozone amount in the lower Antarctic polar stratosphere has prompted extensive studies of ozone depletion over the last two decades (World Meteorological Organization (WMO) 1992, 1995, 1999). Due to the important role ozone plays in absorbing harmful ultraviolet radiation, the ozone decline in mid-latitudes and dramatic ozone depletion over Antarctica may have potentially

important impacts on human life and the Earth's climate. As a result, the state of the ozone layer and its changes has become a topic of great concern for the public and governments.

In general, the spatial distribution and evolution of ozone are determined by transport and chemical processes. Therefore, knowledge of stratospheric transport and chemistry is important for understanding the distribution of ozone and the causes of stratospheric ozone depletion. As an increasingly important tool to study atmospheric transport and chemistry, global chemical transport models (CTMs) have been developed and used to investigate stratospheric trace gases and their variability. In recent years there have been a number of CTM studies dealing with stratospheric ozone, its annual cycle (e.g., Douglass et al. 1996; Waugh et al. 1997), and the three-dimensional (3D) nature of ozone depletion (Lefevre et al. 1994; Chipperfield et al. 1996; Chipperfield 1999). In this study we examine CTM simulations of stratospheric

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ozone in the southern hemisphere, and their utility in modelling the dissipation of the Antarctic ozone hole.

This paper uses a 3D offline CTM, using winds from GASP (Bureau of Meteorology, Australia, (Seaman et al. 1995)) and UKMO (United Kingdom Meteorological Office) assimilated data. To incorporate the contribution of chemical evolution on ozone distributions, we use simple parametrised chemistry schemes for ozone production/loss derived from two-dimensional (2D) photochemical models.

The model and datasets are described in the next section, followed by a comparison of ozone fields between model simulations and ozone analysis. In order to study the sensitivity of ozone simulations to differing resolution, some additional experiments driven by GASP winds at different spatial and temporal resolutions are also performed. A comparison between simulated total ozone and satellite observations is then presented, and the dissipation of the Antarctic ozone hole in 1994 is investigated.

## Model and datasets

The 3D offline CTM is based on the CTM developed at the National Center for Atmospheric Research (NCAR) by Rasch and Williamson (Rasch and Williamson 1990; Rasch et al. 1994). More details of the model are provided in Li et al. (2002). This model has been used for many CTM studies to simulate stratospheric aerosols (Boville et al. 1991), radioactive isotopes (Rasch et al. 1994), CFCs in the troposphere (Hartley et al. 1994), stratospheric species (Rasch et al. 1995), long-lived stratospheric constituents (Vaughn et al. 1997), and transport out of the Antarctic polar vortex (Li et al. 2002). This model uses a semi-Lagrangian advection scheme (Rasch and Williamson 1990) for both the horizontal and vertical directions, while the spatial resolution depends directly on the resolution of the driving fields.

Two sets of assimilated data are used to drive the model transport. The first dataset is from GASP, an operational weather analysis system which gives special attention to the southern hemisphere (Bourke et al. 1995; Seaman et al. 1995). The original GASP data for 1994 have a spectral rhomboidal truncation of R53 (equivalent to 162 longitudes x 134 latitudes) with 19  $\sigma$  levels in the vertical (approximately pressures 991 hPa to 10 hPa). The data are available every six hours, at 0500, 1100, 1700 and 2300 UTC respectively. For ease of use, the CTM simulations presented in this study use GASP winds and temperature truncated to R21 (64 longitudes x 56 latitudes). Model comparisons have shown good agreement between simulations run at R53 and R21, as described later in this paper.

The second set of assimilation data is from UARS (Upper Atmosphere Research Satellite) UKMO global analyses (Swinbank and O'Neill 1994), which are available once a day, at 1200 UTC. The data are distributed at 22 pressure levels equally spaced in pressure-altitude (from 1000 to 0.32 hPa) and converted horizontally from a regular 3.75° longitude by 2.5° latitude resolution to R31 (96 longitudes x 80 latitudes). As the UKMO data cover the entire stratosphere and troposphere, they enable examination of transport up to the upper stratosphere and thus better predict the total column ozone in the atmosphere.

A global 3D ozone analysis field, determined using statistical interpolation from combined satellite observations (Grainger 1998), is used for both model initialisation and model evaluation. The ozone analysis has a horizontal resolution of 2.5° x 2.5° on 19 pressure levels between 1000 and 0.3 hPa. Total column ozone is obtained from National Aeronautics and Space Administration's (NASA) Total Ozone Mapping Spectrometer (TOMS) data, which are widely used for study of ozone trends and evolution of the Antarctic ozone hole (WMO 1995, 1999).

Model simulations are initialised with the 3D ozone analysis from 1 October 1994, using a one-hour time step. The boundary conditions restrict vertical motions to zero at the model lid.

## Model simulations of ozone

### Ozone simulation: transport and chemistry

For periods of up to several weeks, ozone in the lower stratosphere can be treated as a 'passive tracer' (Andrews et al. 1987). For longer periods, the ozone distribution is controlled by transport and chemical evolution. Although it is difficult to explicitly separate the relative contribution of these two processes (because of their feedback and interactions), the contribution of chemistry may be assessed using an offline CTM. In this study, a parametrised chemistry scheme is applied in the CTM simulations. To model the chemical evolution of tracers, 'look-up' tables of coefficients of production ( $P$ ), linear loss ( $L$ ) and quadratic loss ( $Q$ ) are incorporated in model simulations. These coefficients are functions of latitude, height and month of year, and were previously computed by explicit solution of multi-species photochemical (2D) models. At each CTM time step, the tracer change due to chemical evolution is determined by the equation

$$\frac{\partial \chi}{\partial t} = P - L\chi - Q\chi^2 \quad \dots 1$$

where  $\chi$  is the tracer mixing ratio.

The CTM simulations are performed with/without chemical consideration, so as to study the relative importance of chemistry. The coefficients  $P$ ,  $L$  and  $Q$  are obtained from two sources, the NASA Goddard 2D model (Douglass et al. 1989) and the CSIRO Telecommunications and Industrial Physics (CTIP) 2D model (Randeniya et al. 1997; Vohralik et al. 1998). The parametrised chemistry in both the NASA and CTIP 2D model considers homogeneous gas phase reactions for ozone production and loss. In addition, the NASA chemistry also contains a parametrisation of heterogeneous reactions on polar stratospheric clouds (PSC), using an observed PSC climatology (Consideine et al. 1994). Therefore, the NASA rates contain a simplified representation of the mechanisms responsible for the Antarctic ozone hole.

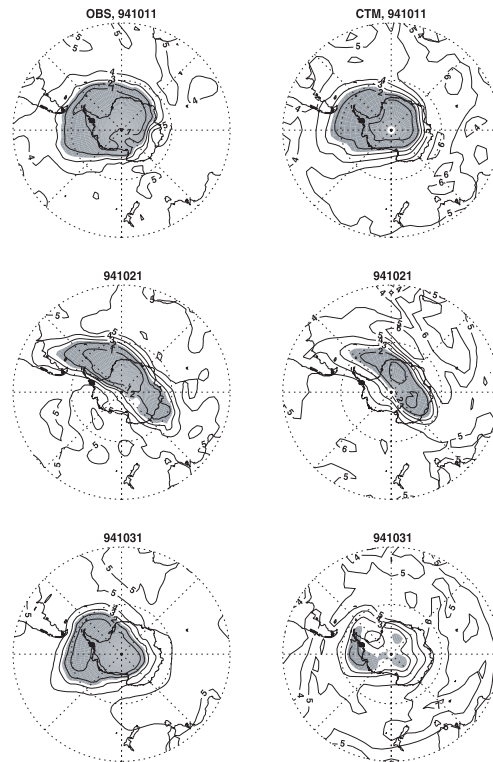
#### Ozone simulations driven by GASP winds

The GASP data only extend to 10 hPa in altitude, thus missing the mid-upper stratosphere, an important component in the control of ozone distributions, particularly in the polar region. Indeed, this is an important limitation for model runs with the GASP fields of more than several weeks. However, the GASP data provide different rhomboidal truncation as well as six-hour intervals of analysed fields, and thus are useful in sensitivity studies to differing spatial/temporal resolution.

Figure 1 shows southern hemisphere (30–90°S) ozone mixing ratio at 24 km both from observations (ozone analysis) and the model. The model simulation was driven by R21 GASP winds, initialised on 1 October, and contains no chemical processes. In general, the gross features of the observed ozone distribution are reproduced by the CTM simulation without chemistry. These include the relatively low mixing ratio in the polar region, high ozone concentration at mid-latitudes, and the elongated vortex-like low ozone over Antarctica on 21 October. However, the CTM seems to overestimate ozone mixing ratio in the polar region after 2–3 weeks, resulting in weaker gradients between the mid-latitudes and polar region. As a whole, the simulation overestimates ozone mixing ratio in most of the domain and the discrepancy appears to increase with time.

To investigate the relative contribution of chemistry, a simplified look-up table of production ( $P$ ) and linear loss ( $L$ ) coefficients from the NASA 2D model is incorporated in the CTM simulation. At 24 km, the ozone mixing ratio with chemical consideration is different from the simulation without chemistry in some regions (not shown). The impact of the NASA PSC chemistry appears to be more significant at high latitudes due to the relatively large polar chemical loss in October. It is clear that relatively lower ozone concentrations are produced in the polar region compared with the simulation without chemistry.

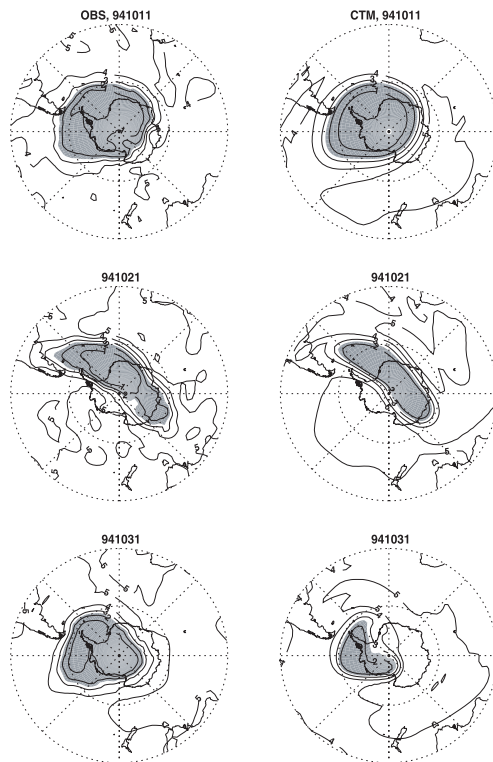
**Fig. 1** Ozone mixing ratio on 11, 21 and 31 October 1994 at 24 km for the southern hemisphere, with left panels taken from observations and right panels from CTM simulations driven by GASP winds (initialised on 1 October). The Greenwich meridian points upward, and the region with values less than 2.5 ppmv is shaded.



#### Ozone simulations driven by UKMO winds

The UKMO data cover the entire stratosphere and thus make it possible to examine the performance of the 3D CTM in simulating ozone distributions in the upper stratosphere. For a comparison with the above discussion based on GASP winds as driving fields, the ozone simulation in October driven by UKMO winds is shown in Fig. 2 at the 24 km level. Within 2–3 weeks, the simulated ozone field shows good correspondence with the observations. Particularly, the elongated vortex-like low ozone on 21 October is well captured by the CTM. Although the discrepancy between the modelled and observed ozone also tends to increase with time, the UKMO-based simulations are closer to the observed ozone than the simulations completed with the GASP winds. In fact, comparisons with descent rates derived from observations

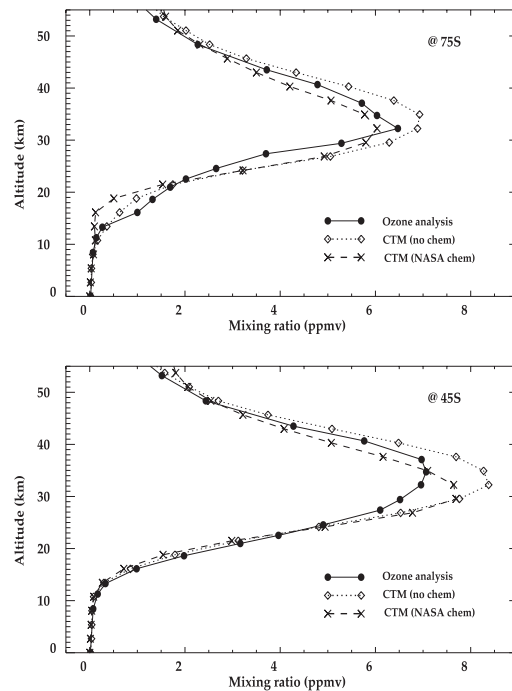
**Fig. 2** Ozone mixing ratio on 11, 21 and 31 October 1994 at 24 km for the southern hemisphere, with left panels taken from observations and right panels from CTM simulations driven by UKMO winds (initialised on 1 October). The Greenwich meridian points upward, and the region with values less than 2.5 ppmv is shaded.



(e.g., Godin et al. 2001) in the high-latitude lower stratosphere indicate that the descent rates from UKMO data appear to be more realistic than those from GASP data (Li et al. 2002).

The vertical distribution of the zonal-mean ozone mixing ratio at 75°S and 45°S on 21 October 1994 is depicted in Fig. 3. In the mid-latitudes, there is good correspondence between the model simulations (with or without chemistry) and the analysed profile except for a layer in the middle stratosphere (30–40 km) where the simulated ozone concentration is obviously higher than the observation if no chemistry is taken into account. After chemical evolution is included, the simulated ozone profile is closer to that from ozone analysis, suggesting that chemical contribution is important in the middle stratosphere for integrations

**Fig. 3** Zonal-mean ozone mixing ratio at two latitudes 75°S and 45°S on 21 October 1994, taken from global ozone analysis and CTM simulations initialised on 1 October. The model is driven by UKMO winds.



of up to three weeks. However, differences at the ozone peak also suggest systematic biases in global transport. For example, excessive tropical/midlatitude transport would produce higher than normal ozone levels near 30 km in altitude.

At 75°S, significant differences between the model simulation and ozone analysis exist in the lowermost and middle levels of the stratosphere. The simulated ozone with/without chemistry underestimates the observation at lower levels (15–20 km); while at middle levels (30–40 km) the simulation with chemistry shows better performance than that without chemistry. It is clear that the PSC chemistry scheme, which acts only in the lower stratosphere, causes the sharp underprediction of ozone between 15–20 km.

Overall, the simulated ozone using UKMO data as driving fields appears closer to the observations than GASP-based simulations. This is due in part to the higher vertical domain and higher vertical resolution of UKMO data.

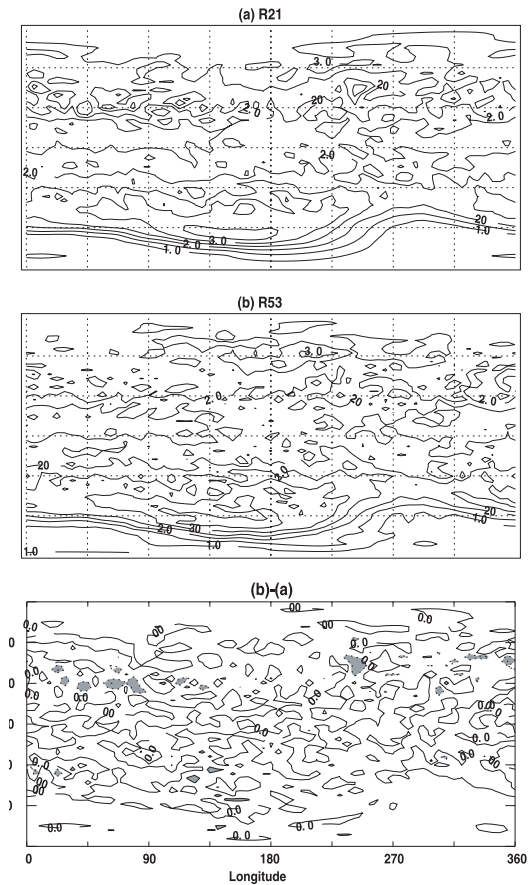
### Sensitivity of ozone simulation to resolution

The sensitivity of transport to horizontal or temporal resolution of the input winds has been documented recently in a number of studies (e.g., Waugh and Plumb 1994; Edouard et al. 1996; Wauben et al. 1997). In investigating fine-scale structure of tracer transport using the contour advection technique, Waugh and Plumb (1994) found that the transport details are relatively insensitive to spatial resolution of the advecting wind field, but sensitive to the temporal resolution. Wauben et al. (1997) examined sensitivity of transport out of the vortex to model resolution. They concluded that the net loss of the vortex tracer mass is insensitive to changes in spatial resolution. We investigate here the sensitivity of ozone simulation to differing resolution using GASP winds. This serves as an independent check on the conclusions of the previously mentioned studies. The model simulation, initialised on 1 October 1994, is driven by GASP data at R21 and R53 resolution covering the same 19  $\sigma$  levels. In addition, the GASP winds at R21 with the time interval of six hours and 24 hours are used to examine the sensitivity to temporal resolution.

Figure 4 shows the simulated ozone mixing ratio averaged over 11–20 October 1994 at the 20 km level, using GASP winds at R21 and R53 resolution as driving fields. The results from high-resolution (R53) input data are similar to those from lower-resolution (R21) data, not only in the spatial distribution but also in the magnitude of the ozone mixing ratio. Indeed, the differences between the two simulations are very small (see the bottom panel of Fig. 4). From a variety of other model simulations, it appears that the global ozone distribution from GASP driving fields is insensitive to the spatial resolution of the GASP driving fields.

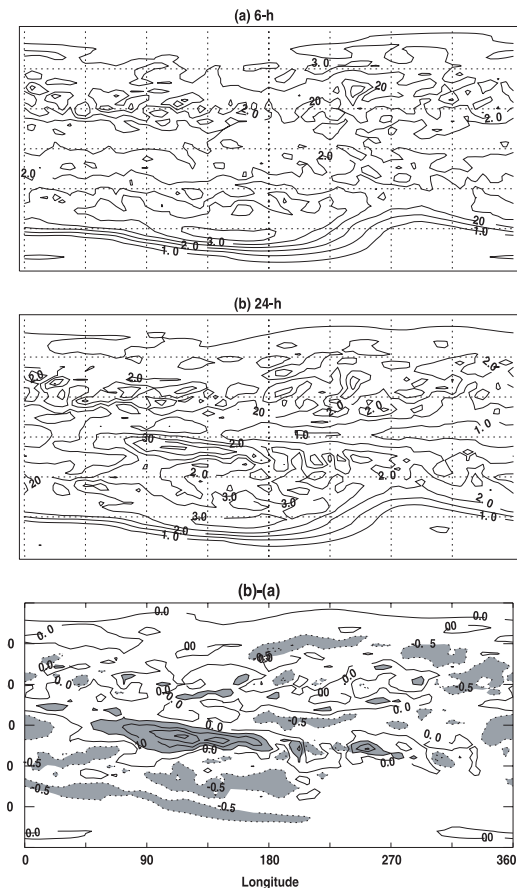
In examining the fine-scale structure of transport, high temporal resolution is often required for accurate calculations if the material contours evolve rapidly. However, Waugh and Plumb (1994) suggested that daily stratospheric analyses will produce reasonably accurate contour advection calculations. The GASP data at R21 with time intervals of six and 24 hours are used here to investigate the sensitivity of the ozone simulation to the time resolution of the input fields. The simulated ozone distributions at 20 km, as shown in Fig. 5, are similar in spatial patterns for the two situations. However, the impact of time resolution seems to be larger compared with the horizontal resolution. As seen from the bottom panel of Fig. 5, the largest difference occurs in the tropical regions. Despite localised differences between the two simulations, the ozone simulation at middle and high latitudes appears to be relatively insensitive to changes in the time interval of the driving fields.

**Fig. 4** Simulated ozone mixing ratio averaged over 11–20 October 1994 at the 20 km level using GASP winds at (a) R21 and (b) R53, and (b)-(a) at the bottom panel. The contour intervals are 0.5 ppmv; solid contours are positive and dotted contours are negative. Differences greater than 0.5 ppmv are shaded.



From the above analysis, the ozone simulation is insensitive to changes in horizontal resolution, suggesting that relatively low resolution, such as R21 or R31, is sufficient to represent large-scale transport. Changing time resolution has a larger impact on ozone simulation in the tropics than at middle and high latitudes. This may arise because of more high-frequency motions in the tropics than in the extratropics. The relative insensitivity to temporal resolution suggests that there is little difference in using input data resolutions of six, twelve or 24 hours in examining transport at middle and high latitudes.

**Fig. 5** Simulated ozone mixing ratio averaged over 11-20 October 1994 at the 20 km level using GASP winds at R21 with the time interval of (a) six hours and (b) 24 hours, and (b)-(a) at the bottom panel. The contour intervals are 0.5 ppmv; solid contours are positive and dotted contours are negative. The difference greater than 0.5 ppmv is shaded.



## The Antarctic ozone hole and its dissipation

The ozone hole refers to a large region where the column ozone is below 220 Dobson units (DU) (WMO 1992; 1995; 1999). The annual appearance of the Antarctic ozone hole observed since the early 1980s is one of the most obvious signs of human impact on the environment. The substantial ozone depletion during the southern springtime leads to a much lower than normal level of total ozone at high latitudes, with up to 70 per cent of ozone amount being destroyed for periods of a month or so (WMO 1999).

## Observed total ozone

TOMS observations provide a measure of total column ozone in the atmosphere and its evolution with time (WMO 1992; 1995; 1999). It has been shown that Antarctic ozone depletion reached its maximum by the end of September 1994. The recorded lowest column ozone in 1994 was 90 DU on 28 September. According to TOMS observations, the well-organised ozone hole persisted for more than two months.

The ozone hole was deeper in October than in November 1994, and although the ozone hole over Antarctica was still evident in the early period of November, its severity weakened and extent reduced as time progressed. From the middle of November, the column ozone substantially recovered. After 24 November the minimum column ozone over Antarctica was above 220 DU and thus the gradients between southern midlatitudes and the polar region were greatly reduced. Although the ozone hole structure displays considerable variability from year to year, its severity and aerial extent experience little change in September and October as indicated by TOMS observations (WMO 1992; 1995; 1999). It has long been recognised that the evolution and deformation of the Antarctic ozone hole is largely controlled by the polar vortex (Schoeberl and Hartmann 1991).

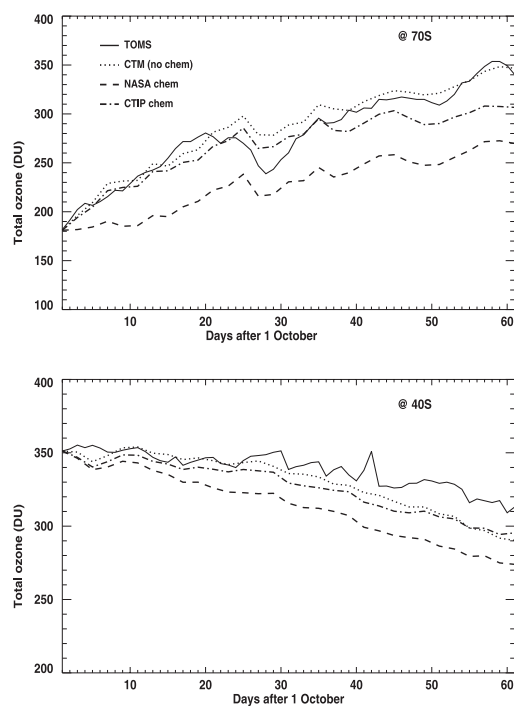
## Total ozone from CTM

Based on CTM simulations of global ozone mixing ratio, driven by UKMO assimilated data at pressure levels, the integral total ozone is calculated between the surface and the top level (about 55 km), which covers more than 95 per cent of the total ozone column. The relative contribution of chemistry can be assessed by comparing total ozone on the basis of CTM simulations with/without chemistry.

On a global view, the total ozone from the CTM simulation without chemistry is lower than observed in southern midlatitudes, but opposite in the polar region. In other words, the modelled gradients in total ozone between mid-latitudes and the polar region are weaker than the observed ozone gradients. This suggests that the horizontal transport in the model at middle-high latitudes is somewhat stronger than that in the atmosphere.

The temporal evolution of column ozone taken from TOMS observations and CTM simulations for October-November 1994 is illustrated in Fig. 6, where the CTM simulations are performed for three cases; no chemistry, parameterised chemistry from the NASA 2D model and the CTIP 2D model. Overall, the model runs simulate the day-to-day variations seen in TOMS observations at southern high latitudes very well. The rises and falls of total ozone are well captured by the model for up to 60 days. However, the magnitude of the

**Fig. 6** Zonal-mean total ozone at 70°S and 40°S during October–November 1994. The CTM simulations are driven by UKMO winds and initialised on 1 October. The simplified chemistry from NASA and CTIP is applied to CTM simulations respectively.



column ozone does differ between cases and observations. The simulation with the NASA chemistry diverges rapidly from TOMS observations during 1–10 October. This is due to the high loss rates of the NASA chemistry in early October. Indeed, there is little or no PSC chemistry after 1 October in 1994, while the normal PSC density based on climatology is still relatively high in early October (Considine et al. 1994). After 10 October, the separation of NASA and CTIP runs is nearly constant, suggesting that their chemical contributions are about the same. Finally, the simulated ozone increase without chemistry is slower than observed in November. Transport is likely important in these differences, as the overall residual circulation and isentropic transport are both important components of the ozone recovery.

At 40°S, the variation of modelled total ozone is generally less than observed. The simulated ozone with the NASA chemistry is still lower than the

CTIP run. This is most likely due to horizontal transport from higher latitudes. The NASA and CTIP chemical rates are nearly identical at 40°S; their only difference is in the polar region, where NASA chemistry has PSC-initiated ozone loss and thus produces lower ozone. The low ozone at the pole is then transported to middle latitudes. Another point is that even without chemistry the simulated total ozone is lower than TOMS observations in November, implying that dynamics is not increasing the ozone column sufficiently.

According to the above discussion, it seems that the NASA polar ozone loss rates are too large for October 1994. Because the NASA rates are calculated from a PSC climatology, natural year to year variability is likely to cause significant deviations. Thus, the NASA 2D chemistry based on climatology may not be appropriate to reflect the specific spring 1994 conditions. The CTIP chemistry does not include PSC, so there is a large difference between these two schemes. In addition, transport biases also look to be at least partially responsible for the slower recovery of ozone at high and middle latitudes.

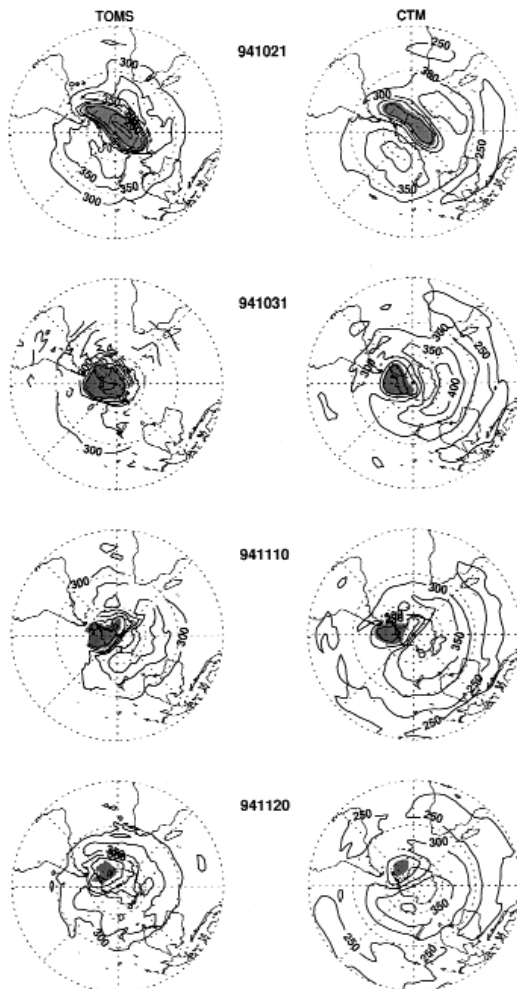
#### Dissipation of the ozone hole

The study of ozone hole dissipation is important in assessing the processes responsible for the evolution and temporal variability of total ozone. The evolution of total ozone in the southern spring of 1994, taken from model simulations initialised on 1 October, is examined for October and November 1994. Figure 7 shows total ozone between 21 October and 20 November at ten-day intervals, from TOMS observations and CTM simulation without chemical consideration. In general, the modelled total ozone is lower than TOMS in the tropics, but slightly higher than the observations at southern high latitudes.

Although the modelled ozone hole is weaker and smaller in extent compared with TOMS observations, the occurrence of the ozone hole dissipation is in good correspondence. Therefore, even if no chemistry is taken into account, the CTM simulation starting from early October (or late September) is able to simulate the dissipation of the Antarctic ozone hole. It is worth noting that the ozone hole dissipation corresponds to the evolution of the south polar vortex. In 1994, the vortex breaks up in late November in the lower stratosphere, coinciding with the dissipation of the Antarctic ozone hole.

By comparison, the total ozone taken from CTM simulations including the NASA chemistry, considerably underestimates the observed total ozone in November 1994 (not shown). Particularly, the ozone hole from the model simulation is much stronger and larger in extent than observed, though the orientation

**Fig. 7** Total ozone for the southern hemisphere in October–November 1994, taken from TOMS observations (left panels) and CTM simulations (right panels). The contour intervals are 50 DU, and the region where total ozone is less than 220 DU has been shaded. The CTM simulations are initialised on 1 October and no chemical evolution is considered.



and general shape of the ozone hole are well reproduced by the CTM simulation. As mentioned above, the P/L rates we use are based on a climatology, and thus we cannot expect exact correspondence between the model and observations. This is simply one of the limitations of our approach.

The CTM has also been used to simulate a dynamical tracer, the potential vorticity (PV), which is often used to depict the structure of the winter polar vortex

(Nash et al. 1996; Randel and Newman 1998). In general, the gross features of the south polar vortex are well represented by the CTM for several weeks. This supports the previous conclusion that the CTM does a good job simulating the large-scale variations. The largest differences between model and observations are thus due to excessive ozone loss due to PSC chemistry, while transport biases seem to play a secondary role. Therefore, CTM simulations would be better initialised from mid-October or early November when PSC chemistry is over.

## Summary and conclusions

This paper has presented simulations of ozone distribution for spring 1994. Although there exist differences between the modelled and observed ozone fields, the simulated ozone distribution shows good correspondence with 3D ozone analysis. Comparing ozone simulations using the two data sets (GASP and UKMO) as driving fields indicates that the modelled ozone profiles using UKMO data are in general closer to those observed than are GASP-based simulations. This is partially attributable to higher vertical domain and higher vertical resolution of the UKMO data.

Based on the CTM simulations of global ozone distribution, the total ozone and its variation during southern spring 1994 have been analysed and compared with TOMS and ozone analysis. Despite systematic bias from the observed ozone amounts (e.g., weaker than observed ozone gradients between southern midlatitudes and the polar region), the modelled total ozone captures the general features of TOMS observations. However, chemistry appears to be responsible for the underestimation of the ozone column in October 1994 near the ozone peak at 30 km. It seems that the ozone production/loss rates obtained from 2D photochemical models do not represent well the 3D nature of ozone and its daily variation during periods when rapid ozone depletion due to PSCs is present. Once PSC chemical loss is over, however, the parameterised chemistry does perform well. This suggests that CTM simulations using this type of parameterised PSC chemistry would be better initialised from mid-October or early November when PSC chemistry is over.

The sensitivity of ozone simulation to spatial/temporal resolution has also been investigated based on the CTM simulations of global ozone in October 1994, using the GASP winds at R21/R53 resolution and 6/24 hours interval as driving fields. Sensitivity results have shown that the ozone simulation is insensitive to horizontal or temporal resolution of the input data at middle and high latitudes, although the tropics does seem sensitive to temporal resolution.



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