Ozone variability over the southern hemisphere

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The variability of atmospheric ozone over the southern hemisphere is described, being important in understanding the health effects of ozone depletion. A brief summary is provided of the main features and causes of the observed global mean ozone distribution and its seasonal cycle. Next follows a more detailed discussion of ozone fluctuations occurring across the range of time-scales from a day to many years, their variation with latitude and season, and their primary causes. Then the long-term trends are considered; their spatial and seasonal structure, and current understanding of the mechanisms responsible. The paper concludes with a brief discussion of a few of the more pressing scientific issues faced by ozone researchers, and some speculation on the prospects for ozone-layer depletion into the next century.

Introduction

Recent years have seen mounting international concern about the health effects of ozone depletion: the impact on the biosphere of long-term changes in surface UV-B radiation resulting, or expected to result, from ozone-layer depletion. To understand the health risks, it is important not only to quantify the extent of ozone depletion and its impact on surface UV-B, but also to be able to view such changes from within the context of natural variability. This requires an appreciation of the relative influences on surface UV-B levels of solar zenith angle (time of day, latitude, season), scattering of the incoming radiant energy by clouds and aerosols in the atmosphere, and the total amount of ozone along the radiation path. But it is also important to gauge any long-term changes in ozone both from the perspective of long-term mean behaviour and relative to ozone variations occurring at other time-scales.

The long-term mean distribution and seasonal variability of ozone and surface UV-B, and the relative impacts on surface UV-B of atmospheric path length and attenuation are addressed by Karoly (1997) and Rikus (1997). Here the focus is on ozone variability occurring at various time-scales, from the shortest (day-to-day) to the longest (the long-term trends). The long-term mean ozone distribution, and its seasonal variability, is first reviewed briefly, before closer consideration of the spatial distribution and magnitude of ozone variations occurring at other time-scales, and the causes of these variations. The long-term trends in atmospheric ozone, which have been observed over the last few decades, are then examined, followed by a brief discussion of current understanding of the causes of these trends, and what further changes might be expected in the years to come.
The long-term mean global ozone distribution and its seasonal cycle

Figure 1 shows the mean distribution, versus altitude and latitude, of ozone volumetric mixing ratio in the stratosphere. The diagram has been constructed using five years of data from the Microwave Limb Sounder on the Upper Atmosphere Research Satellite (W. Randel, personal communication). Ozone mixing ratio provides a measure of the fractional number of ozone molecules per molecule of air at a particular point in space. The highest mixing ratios (by volume, about 10 parts of ozone per million parts of air, or 10 ppmv) are found in the ozone photochemical source region: the tropical middle to upper stratosphere (at about 35 km, or 10 hPa). Ozone concentrations tend to decrease poleward and downward from the source region, but in Fig. 1 an important downward bulge in the mixing ratio isopleths is visible in the mid to high latitude lower stratosphere (at about 20 km), and is the result of poleward and downward advection from the tropical source region by a slowly overturning global circulation (Brewer 1949; WMO 1985; Andrews et al. 1987), which is variously termed the Dobson-Brewer, diabatic or residual circulation (hereinafter the Dobson-Brewer circulation).

Figure 2 shows the long-term mean seasonal evolution of total ozone versus equivalent latitude (a latitude-like coordinate (Randel and Wu 1995)), obtained using data from the Total Ozone Mapping Spectrometer on the Nimbus 7 satellite. Total ozone is usually measured in Dobson Units (DU). It is proportional to the pressure-weighted vertical integral of the ozone mixing ratio pro-

file, providing a measure of the total number of ozone molecules in a vertical column above the earth's surface, and so controlling, to first order, the atmospheric attenuation of incoming UV-B.

Despite the occurrence of the highest ozone mixing ratios in the tropical source region, Fig. 2 shows that tropical total ozone values are relatively low. This stems from the exponential decrease of atmospheric pressure with altitude, which results in ozone concentrations at high altitudes contributing little to the total ozone column. It is the ozone concentrations in the lower stratosphere that provide the major contribution, and Fig. 1 shows these to be small in the tropics. Similarly, Fig. 2 shows the tendency, irrespective of the time of year, for the highest total ozone values to occur in the sub-polar region of each hemisphere, this being due to the local maxima in lower stratospheric mixing ratio (the aforementioned downward bulges) evident in Fig. 1 at these latitudes.

Turning from the ubiquitous features of the global ozone distribution to its seasonal evolution, Fig. 2 shows little seasonal variation in the tropics other than a weak latitudinal meander in the tropical total ozone minimum and a small minimum in southern summer, these weak features reflecting the seasonal march of the sun and the seasonal cycle in the strength of the Dobson-Brewer circulation. However, a marked springtime peak is clearly evident in the extratropical total ozone collar in each hemisphere, which results from a dynamically and radiatively driven peak in the strength of the Dobson-
Brewer circulation at this time. A last feature of note in Fig. 2 is the Antarctic total ozone minimum. While a weak minimum is understood always to have existed at high southern latitudes (Dobson 1966), the springtime extremum is accentuated in Fig. 2 by the appearance in recent years of the Antarctic ozone hole phenomenon (Farman et al. 1985; WMO 1995).

For the southern hemisphere, Fig. 2 suggests a zonally and seasonally averaged latitudinal variation in total ozone of about 30 per cent, from a value of around 260 DU in the tropics and at the south pole, to around 340 DU at subpolar latitudes. It also shows substantial variation with latitude in the amplitude of the seasonal cycle, which is less than 10 per cent in the tropics, increasing to about 20 per cent at subpolar latitudes, and, due largely to the onset of significant springtime Antarctic ozone depletion during the 1980s, about 40 per cent near the pole. (Before the ozone hole appeared, this latter figure was closer to 20 per cent.)

Short-period ozone variability

While there is a significant diurnal cycle in ozone mixing ratio in the upper stratosphere and mesosphere, where ozone photochemical time-scales can be shorter than a day, the overall effect of these variations on the total ozone column is small, again because upper stratospheric concentrations do not greatly influence the total ozone column. Across the spectrum of time-scales from days to months, however, significant total ozone variations do occur.

At the short end of the spectrum, from a day to a few weeks, most variability in total ozone is due, either directly or indirectly, to the passage of tropospheric weather systems. These systems impact on the ozone column by causing large-scale vertical and latitudinal excursions of the stratospheric airstream from its otherwise rather zonally symmetric course. Each component of the motion impacts in its own way on the total ozone column (Atkinson and Plumb 1997), but in the extratropical regions of the hemisphere, the two effects are generally of about the same magnitude (Reed 1949; Kurzega 1984). (It is the domination of short-period extratropical total ozone variability by these dynamical disturbances, and our ability to forecast them using numerical weather prediction models, which make it feasible to attempt deterministic prediction of ozone over the populated middle latitudes.)

To illustrate short-period variability in total ozone at different locations, Fig. 3 shows the daily total ozone time series from July 1995 to June 1996 for each of the five ozone-monitoring stations currently operated by the Bureau of Meteorology. (The July to June time series are shown to highlight the summer period, of most interest from a UV-B perspective.) The five stations extend from Darwin, deep in the tropics at 12°S, through Brisbane (27°S), Perth (32°S) and Melbourne (38°S), to Macquarie Island, at 55°S and under the subpolar peak in total ozone shown in Fig. 2.

In the tropical stratosphere, the abovementioned large-scale vertical excursions tend to be small, and horizontal ozone gradients are weak, so the day-to-day variability in total ozone evident in Fig. 3 is seldom greater than about 10 per cent. This is also the case for tropical variations occurring at other subseasonal time-scales.

Comparison of the time series for the four extratropical stations shown in Fig. 3 reveals a number of common features. In particular, the amplitudes of the day-to-day variations in total ozone tend to be smaller from the start of summer to midwinter when total ozone is relatively low at each station, and larger in springtime when the total ozone is high. Also, the amplitude of the variations tends to increase with latitude, just as does mean total ozone. This overall behaviour is consistent with the dynamical mechanism primarily responsible for the observed distribution. Outside the tropics, day-to-day variability in total ozone tends to be largest in spring, and to increase with latitude, because this is when, and where, the amplitudes of the large-scale dynamical disturbances tend to be largest. Since it is the dissipation of the stratospheric extensions of these
dynamical disturbances which helps to drive the Dobson-Brewer circulation, and hence the mean ozone distribution, day-to-day variability in total ozone tends to be greatest when total ozone itself is at its maximum, in the springtime.

Figure 3 provides a picture of the temporal variability of ozone at different locations, but it lends no direct insight into the dominant spatial scales involved. A direct impression of these spatial scales can instead be gained from inspection of Fig. 4, which shows snapshots of the total ozone distribution over the southern hemisphere on four consecutive days during mid-October 1994. In this case, the data originate from the TOMS instrument on the Meteor 3 satellite. The four snapshots show both the small degree of temporal and spatial variability in tropical total ozone, and the large-scale, large amplitude variations that dominate the mid-latitudes at this time of year, which is close to the seasonal peak in both mean values and day-to-day variability.

The ozone variations discussed so far are what might be termed ‘natural’ variations, but since the onset of springtime Antarctic ozone depletion an additional component of short-period mid-latitude ozone variability has become evident (Atkinson et al. 1989; Atkinson and Plumb 1997). Throughout spring the ozone hole phenomenon remains confined within an intensely cold and rapidly rotating mass of air over Antarctica, the so-called polar vortex. Because the air is isolated, the ozone hole does not impact directly on mid-latitudes while the polar vortex remains steady and pole-centred. But the same large-scale dynamical disturbances that perturb the mid-latitude ozone column in spring cause the polar vortex to wobble about the pole, and the edge of the ozone hole region sometimes passes over populated areas. An example of this is depicted in Fig. 4: during the four days shown an initially small-amplitude vortex perturbation amplifies rapidly, and eventually forces the edge of the ozone hole region over the southern tip of South America. For essentially topographical reasons (James 1988) these wobbles tend only to impact on South America, causing temporary local total ozone reductions there of as much as thirty per cent, while the Australia – New Zealand region remains unaffected. Later though, in the few weeks immediately following the annual dynamical breakup of the polar vortex/ozone hole (typically in early December), there can be several brief occasions when ozone-depleted air is carried northward over the populated mid-latitudes. Unlike their springtime South American counterparts, these events can be subtle, and difficult to attribute with certainty to the ozone hole. Based on an examination of the ozone hole breakup in each year from 1979 to 1989 (Atkinson 1993), it seems likely that a location such as Hobart, for example, experiences a few such events during a typical December. Each event is unlikely to last more than a day or so, or cause total ozone to decrease by more than several per cent, but they occur at the time of year when the population tends to be coming out into the sunshine, when ozone levels are in any case quite low, and when the sun is near its zenith.

**Longer period ozone variability**

As well as the total ozone fluctuations occurring at timescales of a day to a few weeks, Fig. 3 suggests variability at longer time-scales. A good example of this is seen in the ozone records from the three mid-latitude stations (Brisbane, Perth, Melbourne) during August 1995, the negative ozone deviation coinciding with a period of anomalously high surface pressure (T. Skinner, National Meteorological Centre, Melbourne, personal communication). In periods of high surface pressure, the tropopause is lifted and the ozone column consequently decreases. Figure 3 is not ideal for examining these longer period fluctuations, though, because they are heavily masked by the day-to-day and seasonal variations. A better picture is provided by Fig. 5, which shows the full time series of (deseasonalised) monthly mean total ozone anomalies for Melbourne. It shows
significant variations occurring at a range of time-scales, from months to years. At the shorter of these time-scales the fluctuations can be as large as several per cent, due to similar period fluctuations in dynamical activity or in the structure and strength of the Dobson-Brewer circulation. At longer time-scales, weak evidence can be seen in Fig. 5 (see 1956-1962) of a quasi-biennial variation (Oltmans and London 1982; Garcia and Solomon 1987). Although not evident in Fig. 5, an El Niño/Southern Oscillation component to ozone variability has also been suggested (Kodera and Yamazaki 1990), and total ozone is known to vary by a per cent or so with the eleven-year solar cycle (WMO 1985).

So there are substantial variations in extratropical total ozone at all time-scales from a day to a season or so, and smaller ones at longer periods (up to 10 or so years). In the populated middle latitudes of the southern hemisphere, the seasonal peak-to-peak amplitude amounts to as much as 25 per cent of the annual mean total ozone, and day-to-day variations can be almost as large as this. In the tropics, on the other hand, both seasonal and day-to-day variability are much lower, amounting to less than ten per cent.

The long-term trends in ozone

The most obvious feature in Fig. 5 is the relatively steady downward decline of about eight per cent in total ozone at Melbourne between 1956 and 1995. To provide a more global perspective, Fig. 6 shows the distribution with equivalent latitude and season of the overall trends in total ozone observed by Nimbus 7 TOMS during the 1980s. It highlights three main features in the observed decadal trends. The most obvious of these is the lack of a significant trend in the tropics. The second is the large negative trend focussed over springtime Antarctica, and its smaller but still significant boreal counterpart (the average location of the edge of the polar vortex in each hemisphere is shown by the bracketed xs in Fig. 6). The third main feature is the sizeable trend at mid-latitudes, particularly in the southern hemisphere, where it is present in all months.

To understand the mechanisms behind the observed trends, it is important to know not only the pattern of total ozone changes, but also how the ozone changes are distributed in the vertical. Such information is available from a recent analysis of the latitudinal and vertical distribution of the changes in ozone mixing ratio during the 1980s, as observed by the Stratospheric Aerosol and Gas Experiment (SAGE) instruments (see Fig. 1-13 of WMO 1995). That analysis revealed significant ozone losses to have occurred in two distinct regions. The first is the upper stratosphere, where the SAGE instruments show decreases of up to 10 per cent at all latitudes examined (i.e., from 60 degrees South to 60 degrees North). The second region is the lowermost stratosphere, below 20 kilometres, where strikingly large trends were found, with a peak in the tropics. The magnitude and latitudinal structure of these latter trends are at odds with most other sources of data. Large tropical lower stratospher-
ic decreases are not consistent with the (insignificant) total ozone trends shown by TOMS, and ozonesonde data, which are typically more accurate at these altitudes than the satellite data, show SAGE overestimates the depletion at mid-latitudes (WMO 1995). Nonetheless, the extratropical lower stratospheric SAGE trends provide a useful qualitative guide.

Overall, the observed ozone trends are now quite well understood. Significant total ozone trends in the tropics are not expected, nor have they been observed. Model results suggest that the observed upper stratospheric losses are the result of anthropogenic emissions of chlorine-containing substances, but the same models fail to replicate the observed upper stratospheric ozone distribution so there are still gaps in our understanding (WMO 1995). The large springtime ozone losses over Antarctica, and their smaller but significant Arctic counterpart, have now been definitely attributed to chlorine/bromine chemistry (Anderson et al. 1991; WMO 1995). In this case, though, rather than homogeneous gaseous phase reactions, the springtime polar depletion mechanism stems from heterogeneous chemical reactions occurring on the surfaces of polar stratospheric cloud particles which form during the cold polar winter.

The causes of the mid-latitude lower stratospheric ozone trends have not yet been completely resolved, but the observed depletion appears to be due to a combination of \textit{in situ} chemical loss and a polar ozone depletion influence. Modelling studies (e.g. Rodriguez et al. 1988; Prather et al. 1990; Grose et al. 1990; Pitari et al. 1992) have previously suggested that the annual breakup of the ozone hole, and the subsequent mixing out into the hemisphere of the substantial polar ozone deficit, might be responsible for an overall downward trend in mid-latitude ozone during the 1980s, but it is unlikely that this mechanism is able to explain fully the observed trends, and their temporal and spatial structure. It has been argued that the southern hemisphere summertime mid-latitude trends are consistent with this mechanism (Atkinson 1993), but the pronounced trends in the mid-latitudes of each hemisphere in early winter (see Fig. 6) are suggestive of a different cause, since the polar ozone depletion process has scarcely commenced by this time of year. It now seems likely that the wintertime trends are primarily due to heterogeneous chemical reactions of a type similar to those involved in the polar ozone depletion mechanism but occurring on the surfaces of mid-latitude stratospheric sulphate aerosols. It is also conceivable that a contribution to the midwinter losses comes from the transport of chemically perturbed polar air into mid-latitudes at altitudes between the tropopause and the base of the polar vortex, with subsequent \textit{in situ} mid-latitude ozone depletion (WMO 1995).

So we understand much, but not all, of the ozone trends observed over the last few decades. Although not as large as the day-to-day fluctuations or the seasonal cycle, the trends are still significant, and although the overall trends at mid-latitudes are considerably smaller than the shorter term variations, the superposition of these variations at different time-scales implies, in the absence of other effects such as accompanying increases in cloudiness, increased surface UV-B in recent years, both in the average and extreme.

\section*{Expectations and issues for the future}

The observed variability of ozone has been discussed, with emphasis on the southern hemisphere. But what are the prospects for the future? As noted above, most of the long-term ozone changes are understood to be due to anthropogenically induced changes in the global stratospheric chlorine loading. A recent slowing (and, in at least one case, a cessation) has been noted in the tropospheric accumulation rates of some of the more critical ozone-depleting substances (Fraser 1997), and this attests to the positive impact of international agreements to phase out the emissions of these substances. It seems likely that, in the absence of significant dynamical feedbacks of ozone depletion on global climate, the Antarctic ozone hole phenomenon should not worsen significantly in the years to come. This is largely because springtime depletion of ozone is already almost total in the region affected. Given continued compliance with the international agreements, the global chlorine loading is expected to diminish to the late 1970s level (about half of its present value) by about the middle of the next century (Fraser 1997), and this should be accompanied by the recovery of springtime Antarctic ozone to pre-1980 levels. The expected reduction in the halogen loading during this period should also be reflected by substantial recovery of both upper stratospheric ozone and ozone in the mid-latitude lower stratosphere.

There are, of course, additional factors which might influence the rate of ozone-layer recovery, one of which was alluded to above. Ozone, as well as being a strong absorber of UV-B, is also an important greenhouse gas, and its amount and vertical distribution strongly influence both the dynamical structure of the atmosphere and the global radiation balance (Liou 1980; WMO 1995). Perhaps ozone-layer depletion has led (or will lead) to temperature or other dynamical changes which might induce further ozone depletion. An entirely separate issue is the potential impact on stratospheric ozone of the exhaust emissions from planned large fleets of commercial aircraft operating in the lower stratosphere. These are just two examples of the more pressing issues currently being addressed (WMO 1995).

Overall, the future looks bright. Nonetheless, given that we still do not fully understand the causes of the
recent ozone trends, or even their detailed vertical structure, and that there are other issues to be resolved, there is no room for complacency. There remains a strong need both for continued research into the mechanisms controlling atmospheric ozone, and for improved monitoring of ozone and the atmospheric chemical species influencing it.

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References
