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The search for signs of recovery of the ozone layer

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Evidence of mid-latitude ozone depletion and proof that the Antarctic ozone hole was caused by humans spurred policy makers from the late 1980s onwards to ratify the Montreal Protocol and subsequent treaties, legislating for reduced production of ozone-depleting substances. The case of anthropogenic ozone loss has often been cited since as a success story of international agreements in the regulation of environmental pollution. Although recent data suggest that total column ozone abundances have at least not decreased over the past eight years for most of the world, it is still uncertain whether this improvement is actually attributable to the observed decline in the amount of ozone-depleting substances in the Earth's atmosphere. The high natural variability in ozone abundances, due in part to the solar cycle as well as changes in transport and temperature, could override the relatively small changes expected from the recent decrease in ozone-depleting substances. Whatever the benefits of the Montreal agreement, recovery of ozone is likely to occur in a different atmospheric environment, with changes expected in atmospheric transport, temperature and important trace gases. It is therefore unlikely that ozone will stabilize at levels observed before 1980, when a decline in ozone concentrations was first observed.

The ozone layer protects all living organisms from excess ultraviolet radiation. Ozone is continually produced, destroyed and circulated in the Earth's atmosphere by a variety of natural influences[1–4]. In the early 1970s, Molina and Rowland[5] first theorized that chlorine compounds—manufactured as refrigerants and aerosol propellants—could destroy ozone in the Earth's stratosphere, a theory confirmed in 1985 by a measured ozone loss over Antarctica[6,7]. Stratospheric ozone levels significantly declined until the mid-1990s[8] with the largest rates of depletion near the poles and no noticeable depletion near the Equator.

Anthropogenic ozone loss spurred policy makers to ratify a series of international agreements—the Montreal Protocol and its amendments—which, beginning in 1989, led to reduced production and use of ozone-depleting substances[9]. Figure 1a highlights the success of the Protocol by tracing effective equivalent stratospheric chlorine (EESC), a combined measure of stratospheric chlorine and bromine. EESC peaked in the mid- to late-1990s and has started to decline in the past few years[10,11]. Today, controls on ozone-depleting substances often focus on returning EESC to the level that prevailed in 1980. The turnaround in EESC suggests that the early signs of an ozone layer recovery may be detectable in the early part of this century[12,13].

Although previous work has examined changes in ozone trends at 40 km altitude[14,15], ozone amounts at this altitude contribute very little to total column amounts, thus the observed changes at 40 km have little effect on ultraviolet radiation levels and their associated human health and environmental effects. The first studies examining total column ozone are now emerging[16]. In light of the importance of the ozone layer to the biosphere, we need to verify our understanding of ozone loss and confirm the effectiveness of the Montreal Protocol. We ask whether the observed changes in ozone abundances are consistent with our current understanding of atmospheric processes. It is vital to ask not only whether ozone concentrations are levelling off or increasing, but whether these changes are occurring where and when we are expecting them.

The recovery of the ozone layer is a process beginning with a lessening in the rate of decline, followed by a levelling off and an eventual increase in ozone driven by changes in the concentrations of ozone-depleting substances. The analyses of ozone records and conclusions regarding recovery, in the short or long term, are sensitive to many concurrent changes in the atmosphere. Because of high natural variability in ozone levels, total column ozone fluctuates over timescales of a few years. These fluctuations can obscure long-term changes and offer false indications of recovery. The separation of long-term changes in ozone concentrations from natural variability is our current challenge. Even when ozone-depleting substances are significantly diminished, other anthropogenic changes to the atmosphere will further complicate the recovery process and may result in considerably altered ozone levels in the future. The detection of a thickening of the ozone layer can only be evaluated if naturally occurring processes and events are appropriately accounted for.

In this Review, ozone trends are presented as a function of latitude, season and altitude, to determine if the patterns of change indicate recovery. Observed ozone data are compared with a variety of models to help determine if both the magnitude and patterns of change are what can be expected due to declining levels of ozone-depleting substances. To predict future ozone levels, we examine model estimates for ozone in the year 2050, when the levels of chlorine and bromine in the stratosphere should have returned to near pre-1980 values.

Estimating past and future ozone levels

Atmospheric models (Box 1) are used to estimate both past and future ozone levels and they need to take into account atmospheric chemistry, dynamics and temperature, solar inputs and volcanic eruptions, all of which affect ozone amounts. Figure 1b shows 14 two- and three-dimensional (2D and 3D) model estimates of past and future total column ozone levels for 60° S–60° N (refs 17–30). The models show general agreement with respect to ozone depletion and recovery; however, the rates of depletion and recovery can vary

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by a factor of three. The three models that include the effect of the solar cycle in their estimates of future ozone show different estimates of the magnitude of the solar cycle.

The model-calculated abundances of column ozone are normalized to 1980 levels to remove differences between measured and modelled column ozone as high as 30 Dobson units (total column ozone is measured in Dobson units (DU), the number of ozone molecules in a column of atmosphere; at standard pressure and temperature, 330 DU would be 3.3 mm thick). Because of the normalization to 1980, when solar activity was at a peak, this representation overestimates the difference in depletion between measurements and models for 60° N–60° S. However, this bias is removed when trends are derived and presented below. Only about half of the models predict that column ozone will rise above 1980 levels when the abundance of ozone-depleting substances returns to 1980 levels. These differences in recovery rates from the various models result from differences in assumptions about transport, temperature and trace gas concentrations. Examining where and when the models agree with the observed data provides insight about recent changes and whether they can be described as recovery of the ozone layer due to a decline in ozone-depleting substances[17].

Factors affecting ozone levels

Understanding how chemical processes, atmospheric dynamics, temperatures, solar activity and volcanic eruptions affect ozone in the long and short term, and incorporating these factors into models, helps bring model estimates into agreement with observed data. However, many of the effects of these factors are not fully understood, which limits our ability to attribute ozone changes to particular factors. Effects of some of the most important factors and their interactions, together with the limitations in our understanding, are outlined below.

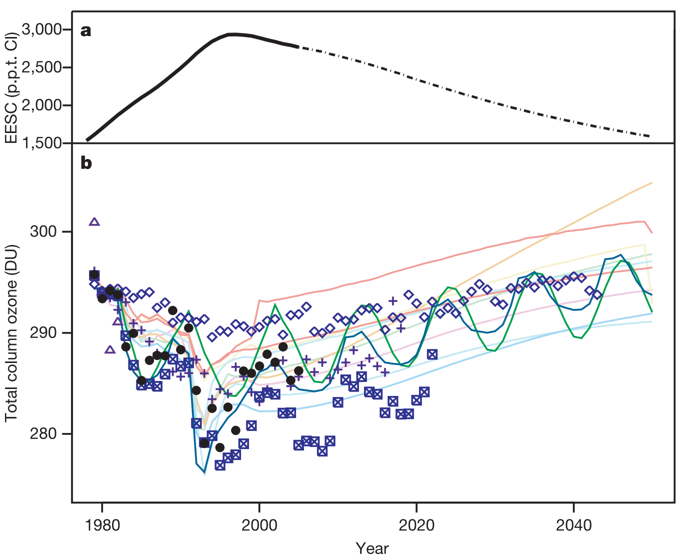

Figure 1 | Reductions in stratospheric chlorine levels compared to total ozone through time. a, Measurements of effective equivalent stratospheric chlorine (EESC, in parts per trillion; solid black line) through to 2005 indicate that the Montreal Protocol and its amendments are succeeding in reducing atmospheric chlorine loading. The dashed line represents projected stratospheric chlorine loading through to 2050 based on compliance with the existing agreements. Highest EESC is estimated to have occurred in 1996–98. **b,** Two-dimensional (solid lines) and three-dimensional (all symbols except filled circles) model estimates of past and future total column ozone levels for 60° S–60° N (Box 1). Filled circles are measured ozone amounts from satellites. The models show general agreement with respect to ozone depletion and recovery when averaged over this large region.

Although much of the chemistry affecting ozone is understood, uncertainties in chemical reaction rates, along with the difficulty in estimating future levels of trace gases in the atmosphere, limit our ability to predict recovery of ozone concentrations. For example, uncertainties in bromine chemistry limit our ability to predict recovery of ozone concentrations[31], and the rates of ozone loss by two key catalytic cycles involving anthropogenic halogens are at present uncertain by about a factor of two[32]. Changes in stratospheric water and methane are difficult to predict yet will affect total ozone levels[33,34], especially if anthropogenic influences alter their concentrations[35–37].

Atmospheric dynamics, especially transport of ozone-rich air

Box 1 | Data analysis

All analyses were carried out using advanced statistical approaches with the assumption of autoregressive components in the noise with time lag one month (AR-1). For details see, for instance, ref. 16. The data were also analysed using the CUSUM approach[13]; results are similar with a high dependence on the impact of the solar cycle. The analyses have been carried out on surface Dobson data, with trend results in notable agreement: small differences in declines between data sets were in agreement with small differences in increases.

To understand ozone trends for near-background aerosol conditions, the 24 consecutive months of data that show the strongest effects due to the Mt Pinatubo eruption have been removed from both model output and the measured data. The exact two years are determined separately for each model or data set. The omitted two-year period differs by location owing to the observed aerosol transport times to high latitudes. For the most part, the results are not highly sensitive to small changes in the starting or ending dates of the omitted data.

Trends reported in Figs 3–5 are based on a contiguous, piecewise linear fit to the data using both quasi-biennial oscillation and solar proxies to estimate the effects of these parameters. Uncertainty estimates were computed for Figs 3 and 5 assuming an AR-1 noise term. The statistical confidence levels are strongest for the decline in ozone. Estimates were calculated for the change in trend from the 1979–95 decline and for indications of a statistically significant upward trend. The results show that the change in trend is outside the 2σ limits for mid-latitudes and high latitudes, but the increase in trends is only significant north of 50° N. Both the derived trends and uncertainty estimates north of 50° N are strongly influenced by the very low ozone values observed in the mid- and late-1990s at these latitude bands. Inclusion of solar proxies, Arctic Oscillation, North Atlantic Oscillation and quasi-biennial oscillation have a little impact on trends but have a substantial impact on the derived error bars on the trends. For additional details, see refs 16 and 17. Data before 1979 are not included in trend analyses presented here.

Ten 2D and four 3D models were used in this analysis. All of the modelling groups were represented in the WMO Ozone Assessment[11], but when more recent runs of the model were available, those were used. The 2D models represented are RIVM, AER, ULAQ, GSFC-INT, GSFC, NOCAR, SUNY, OSLO, UIUC and MPI. The 3D models used are GSFC, UMETRAC, NIES and CMAM. Further details on these models are available elsewhere[11,17].

EESC showed a near linear increase, which began to level off in approximately 1996. For this reason, many studies look for changes in the rate of ozone decline starting at that date[14–16], but changing the date used for the analysis would not significantly affect the results[16]. Although an ozone turnaround could be expected to occur at the same time as the peak in EESC loading, the timing of the start of the turnaround in ozone resulting from decreases in ozone-depleting substances is difficult to identify because a number of other factors influence ozone amounts. Examination of the model output offers an even wider range of dates than assumed in these studies. The models, driven by surface concentrations of halogens, suggest that the date when total column ozone may start increasing is confounded by the effects of the Mt Pinatubo eruption and the turnaround could have started before 1996 or might not begin until after 2010.

poleward and strong polar vortices, have direct influences on ozone levels in the short term[38–41]. Climate change could have long-term effects on atmospheric dynamics throughout the atmosphere. Neither dynamical processes nor dynamical effects on ozone levels are fully understood. For example, recent dynamical activity could be due to natural variability, climate change, or radiative feedbacks resulting from changing concentrations of ozone. Increases in tropopause heights are associated with lower ozone amounts[42–44], whereas changes in both the Arctic and North Atlantic oscillations since the early 1990s are associated with higher levels of ozone[16,45,46]. Climate change may affect dynamical processes by increasing the strength of polar vortices, thereby enhancing polar depletion of ozone[47–49], or it could lead to increases in the magnitude of planetary waves causing slightly higher ozone levels[50].

Ozone levels are directly affected by the temperature of the stratosphere, which is influenced by the stability of the wintertime polar vortex circulation[38,48,51]. Temperature declines of the past two decades in the lower stratosphere are consistent with expectations of rising greenhouse gas concentrations and observed changes in stratospheric water and ozone amounts[11,52,53]. In the upper stratosphere, colder conditions shift the balance of ozone photochemistry towards higher ozone concentrations[54]. At high latitudes, colder conditions in the lower stratosphere promote the formation of polar stratospheric clouds which contribute to severe ozone depletion, a condition that occurred several times in the Arctic in the 1990s[48] and as recently as the spring of 2005. Conversely, in four of the last six years, warmer conditions and less stable Arctic vortices have led to higher levels of ozone in the Arctic[51].

Solar variations directly influence both the destruction and production of ozone[55]. Eleven-year solar cycles can obscure trends, particularly when ozone changes are examined using data over a period of less than two solar cycles. For example, during the 1999–2003 solar maximum, the increases in solar activity may have increased total column ozone levels. However, some short-term solar proton events can cause localized ozone depletions of 30–60% in the upper stratosphere[56], and energetic particles can cause a downward descent and catalytic destruction of ozone, particularly above the middle stratosphere[57–59].

Major volcanic eruptions inject sulphur into the stratosphere, forming sulphate aerosols that react to destroy ozone[60–63]. Major eruptions of El Chichón in 1982 and Mt Pinatubo in 1991 both occurred during solar maxima, yet had their own large effects on ozone for several years following the events[64]. Despite the spread of Mt Pinatubo aerosols in the stratosphere of both hemispheres, the eruption resulted in a sharp decline in Northern Hemisphere ozone levels[60–62,65,66] but not in Southern Hemisphere levels[11].

Signatures of recovery of the ozone layer

Just as with climate change, where fingerprints of changes are helpful for attribution[67], signatures of changes in ozone help ensure that observations can be correctly interpreted in terms of the removal of ozone-depleting substances from the atmosphere. Progress in detecting and attributing ozone recovery is most likely to be realized by looking for expected changes when and where they will be optimally detected. Previous work[11,68] and recent analysis[17] support three signatures as a basis for investigating ozone recovery. These signatures correspond to the latitudinal, seasonal and altitudinal dependences of observed changes. For each of these three identified signatures, we compare the trends derived from the past eight years of data with past depletion rates and model estimates of recovery. Agreement in these three signatures of the magnitude of observed trends will help provide evidence that the ozone layer is recovering. However, analyses on such a short timescale will probably result in large uncertainties because of natural variability. Temperature, winds and other factors have varying effects on stratospheric ozone abundances: the effects can be better understood through detailed analyses of recent atmospheric conditions, which provide further insight into the causes of changes in ozone concentrations[69]. The focus here is to determine if the recent ozone trends are in agreement with what is expected from a levelling off and decrease in atmospheric chlorine and bromine levels, rather than being influenced mainly by natural variability. One strength of this study is the use of a variety of models, which can offer insight into the current range of expected recovery rates. No one test can prove attribution, yet each can offer additional insight and evidence for likely causes of change.

Figure 2 presents a sample of the monthly averaged time series of total column ozone from 1979 through to the end of 2005 from a merged TOMS/SBUV(/2) satellite data set (version 8). In the last eight years of each of the time series a departure from the downward trend observed in the first fifteen years of the data set is apparent at some latitudes, but there is considerable variability that cannot be attributed to concentrations of ozone-depleting substances. Standard statistical techniques are used to remove from the ozone data the effects of variability due to solar inputs and dynamical factors[8,16]. One problem with this approach is that different environmental parameters can behave in a similar manner, making it difficult to separate influences through analytical techniques. Another problem is that, in some cases, ozone levels, stratospheric circulation, and temperatures interact and limit attempts to attribute changes through a purely analytical approach. The scientific difficulty concerns interpretation of the recent data—as a sign of ozone recovery, as simple variability, or as a combination of several parameters that affect ozone. Despite the existing uncertainties, latitudinal, seasonal and altitudinal signatures of recovery stand out as robust in the model projections because they spatially and temporally link current ozone increases to patterns of post-1980 ozone depletion.

Latitudinal signature of recovery. Past ozone depletion, shown in red in Fig. 3, has been near zero at the Equator, while gradually increasing towards the poles. The model projections through to 1995 qualitatively reproduce this feature, although most of the projections do not estimate the magnitude of depletion observed, particularly for high latitudes. Ozone trends derived from data for 1996–2004 are

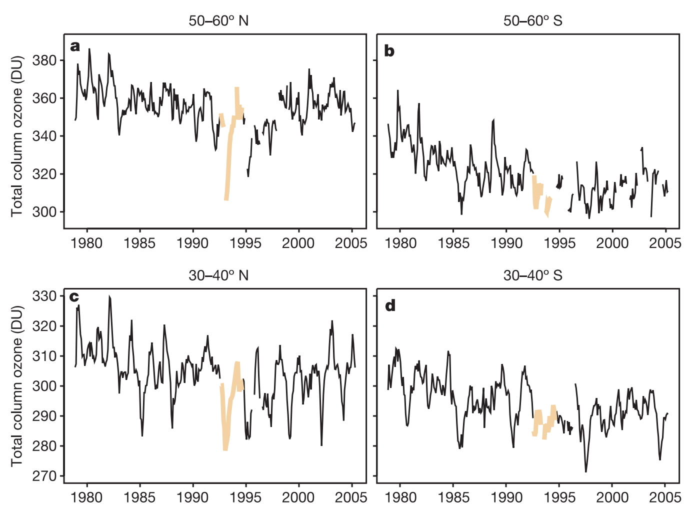

Figure 2 | Deseasonalized ozone data from satellite data at four latitudes. **a**, 50–60° N; **b**, 50–60° S; **c**, 30–40° N; **d**, 30–40° S. The time series illustrate the apparent change in trend that has occurred at mid-latitudes (**c**, **d**). The data removed from the analyses because of possible effects of the Mt Pinatubo eruption are marked in orange. The data contain influences of both the quasi-biennial oscillation and the solar cycle. The changes are most notable in the Northern Hemisphere, particularly for the high latitudes (**a**, **b**), but are not in line with expected changes owing to the current loading of ozone-depleting substances. Data are from version 8 of the TOMS/SBUV(/2) data set.

shown in blue and contrast with the long-term ozone recovery predicted from models. Long-term ozone recovery rates from models are estimated from available time slices for the 3D models and from 1996 to 2050 for 2D models. Again, both the data and models show increases but the amount of the increase observed in the high northern latitudes is considerably larger than what the models predict. This region also exhibits the highest level of natural variability. In the Antarctic, the ozone layer continues to reach severe, low levels in the spring, with some layers in the atmosphere showing nearly complete destruction of ozone[9,68]. In the Arctic, the situation is more irregular because severe ozone depletion occurs during springtime in years when temperatures are low enough to result in conditions conducive to rapid ozone depletion[51,70].

Seasonal signature of recovery. Past ozone depletion has had a distinct seasonal signature in Northern Hemisphere mid-latitudes, with higher rates of ozone depletion observed in the springtime, a feature that the models generally reproduce (Fig. 4). The seasonal aspect of recovery suggested by the recent data is in rough agreement with the modelled patterns, although the recovery is more rapid for most spring and summer months. Similar to the latitudinal signature, the Northern Hemisphere spring is recognized as the season of highest variability, allowing for the possibility of unusual trends being observed from evaluation of short-term data sets. Seasonal trends are not independent, and results have shown that summer ozone levels are strongly linked to spring ozone levels[71]. Polar ozone depletion has been strongest during local spring, with influence to the mid-latitudes dependent on the mixing of air and regeneration of ozone[72].

Altitudinal signature of recovery. Long-term ground-based observations at three stations (Fig. 5) indicate that past ozone depletion has occurred preferentially in the lower stratosphere. The observed altitudinal dependence is consistent with our understanding of stratospheric photochemistry[73]. Depletion above 30 km has been small but significant[74–76]. Ozone concentrations at these higher altitudes, although not contributing significantly to the total column ozone levels, are dominated by changes in chemistry. A turnaround in the decline observed at these layers has been observed[14,15]. For these three locations, trends in total column ozone are a result of the balance between both positive and negative trends at different layers. At both Arosa and Boulder, the changes in total column ozone are dominated by changes in the lower stratosphere that are larger than expected from the models, while data from Tateno are in better agreement with the models. This is the region where the largest recovery rates are expected, but it is also the region of greatest natural variability[77].

Predicting trends in ozone levels

The most severe ozone depletion has been observed in the polar regions, but detecting recovery near the poles will be difficult. In the Antarctic, where conditions are generally conducive to rapid, heterogeneous ozone depletion, ozone at some altitudes can be nearly entirely depleted during the spring. In recent years, total column ozone values have been observed to reach comparably low levels during the Antarctic spring. This apparent levelling off is not attributable to a decline in chlorine loading, but rather is a sign of near-complete depletion at critical layers in the atmosphere. Little improvement is expected for total column ozone in the Antarctic for the next several decades. In contrast, increases in total column ozone in the Arctic will partially depend on possible dynamical and temperature changes in the coming decades, which could result in either an expedited or delayed ozone increase[47,48,50,78]. Changes in ozone concentrations at specific altitudes in both the Arctic and Antarctic will be highly dependent on temperature and resulting

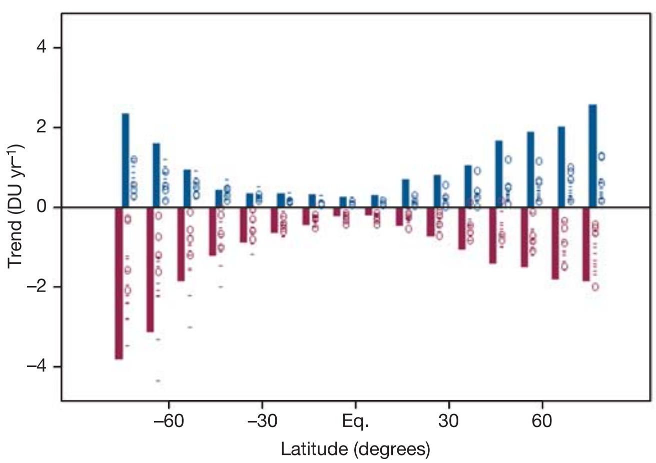

Figure 3 | Measured and modelled ozone trends by latitude for 1979–95 (in red) and 1996–2005 (in blue). Increases in ozone during the past ten years coincide with the regions in which past depletion has occurred. Analyses of the measurements are represented by the solid bars; analyses of 2D models are shown with horizontal dashes, and results of 3D models are shown with circles. The model estimates for 1979–95 are shown in red; projections for long-term recovery are shown in blue. Trends before 1995 are statistically significant (2σ) for mid and high latitudes. Trends after 1995 show a statistically significant change from the observed decline rates, but the positive trends are not, in general, statistically significant—that is, the derived estimates for the last ten years are consistent with level ozone amounts within estimates of statistical uncertainty. Note that the models and measurements agree well in the Southern Hemisphere, and in the Northern Hemisphere show rough agreement for past trends but significant disagreement for the magnitude of emerging trends. The largest natural variability is observed away from the Equator, allowing for potentially spurious trends in these regions. Data are from version 8 of the merged TOMS/SBUV2 data set. Eq., Equator; negative latitudes are °S.

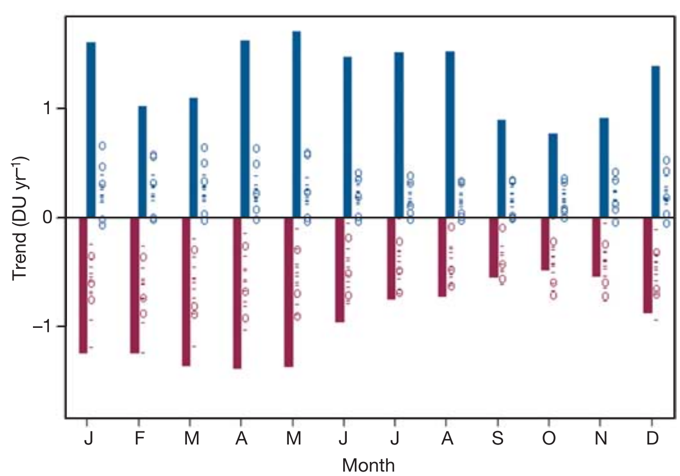

Figure 4 | Measured and modelled seasonal ozone trends at 35° N for 1979–95 (in red) and 1996–2005 (in blue). Recent increases in ozone have occurred at roughly the time of year when past depletion has taken place. The solid bars represent the trends in the data, and the horizontal dashes represent the results from 11 2D models. The open circles represent the five 3D models, each with two years of data removed to avoid the major effects of Mt Pinatubo. The model estimates for 1979–95 are shown in red; long-term projections are shown in blue. Trends before 1995 are statistically significant (2σ) for all seasons. Trends after 1995 show a statistically significant change from the observed decline rates, but the positive trends are not statistically significant for this latitude band—that is, the derived estimates for the last ten years are consistent with level ozone amounts within estimates of statistical uncertainty. Note that the trends over the past ten years show considerably higher rates of increase than expected due to a decrease in EESS. The data are from version 8 of the merged TOMS/SBUV2 data set.

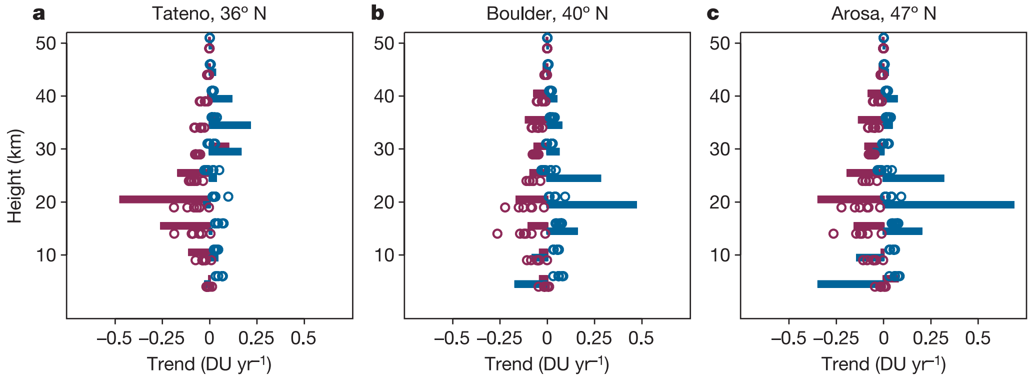

Figure 5 | Measured and modelled ozone trends by altitude at three surface monitoring stations for 1979–95 (in red) and 1996–2005 (in blue). The large positive trends in the most recent data from the lower stratosphere—particularly for Boulder (**b**) and Arosa (**c**), and less so for Tateno (**a**)—are much larger than being predicted by the models for recovery. Trends before 1995 are statistically significant (2σ) for the lower and upper stratosphere, although not for the mid-stratosphere. Trends after 1995 show a statistically significant change from the observed decline rates, with significant positive trends in the upper stratosphere. This is also a region of the atmosphere characterized by high natural variability and strongly influenced by temperature and dynamics. Data are from the revised Umkehr algorithm[77].

polar stratospheric cloud formation, as well as on the amounts of ozone-depleting substances.

Complicating the interpretation of recent ozone data are the effects of natural variability, particularly temperature and dynamical influences as well as solar activity. The most striking data illustrating the effects of temperature on the ozone layer are observations from the northern high latitudes, particularly north of 45° N (Fig. 6). Examination of the latitudinal, seasonal and altitudinal signatures of recovery shows that there is coarse agreement between the models and measurements, except in the north, where the data imply much faster recovery than is indicated by the models. The time series illustrate that the trends are strongly affected by the low ozone levels occurring in the mid- to late-1990s, the timeframe in which we begin to look for signs of recovery. During this time not only was EESC peaking, but the Arctic stratosphere was extremely cold and ozone levels were anomalously low[78]. Most of the subsequent years have been warm (with a notable exception of the winter of 2004/05), and correspond to an apparent change in the ozone trend[51]. These unusually low ozone years in the mid- to late-1990s affect the derived trends before 1996, but also after 1996 because the record for the most recent eight years starts from an unusually depleted level. Thus, the representation of the latest increases in ozone north of 40° N as evidence of a long-term upward trend and recovery due to declining levels of halogens might be misleading. A change to colder conditions in the Arctic stratosphere would probably lead to reversed trends, at least in the short term. Whereas the effects of these cold winters are well studied for the Arctic, data shown in Fig. 6 suggest that the very low ozone values extend to mid-latitudes as well. The short data record combined with the impact of unusually low ozone levels in the mid- to late-1990s make it difficult to estimate the magnitude of the long-term rates of change in ozone.

The solar cycle strongly influences the amount of ozone and complicates the interpretation of data. Figure 1b shows that all three models that include the 11-year solar cycle estimate an increase in ozone for the past eight years. This is a short-term change, not recovery. The magnitude of the effect of the solar cycle differs from model to model, and may be larger than is indicated by the data. Efforts to derive the size of the influence of the solar cycle from past column ozone time series are complicated by the fact that the prior two solar maxima nearly coincided with the last two major volcanic eruptions. These eruptions offset the increase in ozone expected from increases in solar ultraviolet output. Consequently, some of the increase of total column ozone during the past eight years may be due to the recent solar cycle maximum, but the magnitude of this influence is somewhat uncertain. The data collected over the next few years will be important for separating the influence of the solar cycle from the long-term recovery of the ozone layer.

On the basis of the analysis of the trends with respect to the latitudinal, seasonal and altitudinal signatures and with respect to the known mechanisms governing ozone levels, at least some of the observed changes in ozone depletion rates are in agreement with expected ozone recovery rates. The rates of change, particularly the increases north of 45° N, are significantly larger than would be initially expected from the small decrease in the concentrations of ozone-depleting substances in the atmosphere. At least two major parameters have contributed to these higher-than-expected ozone levels: the solar cycle, which peaked in 2000–02; and the combination of cold stratospheric temperatures observed over the past ten years and planetary wave driving observed in the northern polar region. Both of these parameters resulted in lower ozone levels in the mid- to late-1990s and higher ozone levels in most of the subsequent years.

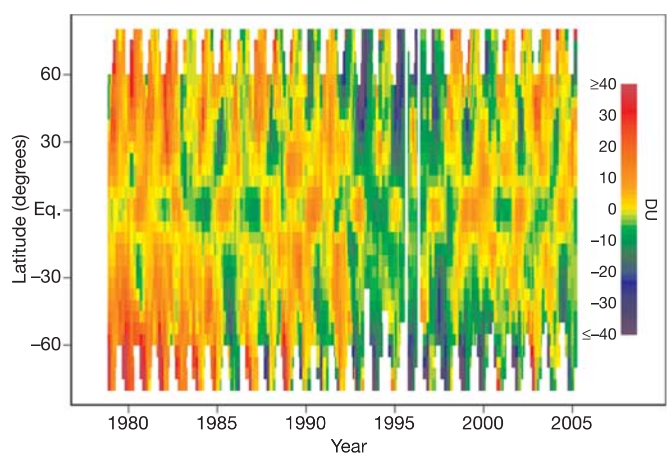

Figure 6 | Deseasonalized total column ozone by latitude. Data are from merged satellite data sets. The very low ozone levels observed in the Arctic in 1996, 1997 and 1998 were well studied and linked to the extremely cold stratospheric temperatures observed in those winters. Because the timing of these very cold winters is close to the turnaround in ozone-depleting substances, the ozone data seem to show a strong change in direction starting in the mid- to late-1990s. It is likely that if the Arctic stratosphere is cold in the near future, ozone will be similarly low. Note that the unusually low ozone conditions appear to extend as far south as 40° N. Colour scale shows deviations of measured total column ozone (in DU) from seasonally expected monthly averages for each latitude band.

Long-term trends are not expected from solar or volcanic activity but variability in ozone as a result of each complicates recovery detection. Ozone data from the very late 1990s and early 2000s coincide with a period of low volcanic activity favouring higher abundances of ozone. Should another major eruption occur in the next few years, ozone levels are likely to be lower, and, depending on the magnitude of the eruption, they could be similar to those observed in the 1990s.

Expectations for ozone levels near the end of this century

A question often asked is 'will ozone return to pre-1980 levels, and if so, when?' Because many of the factors influencing ozone levels are also changing, even if all anthropogenic ozone-depleting substances were removed from the atmosphere, ozone levels might not stabilize at pre-1980 levels[11,34]. Total column ozone, carbon dioxide emissions, stratospheric temperatures and circulation patterns are closely linked, and changes in one of these variables can affect the others[11,79–82]. By the end of the century, provided the concentrations of ozone-depleting substances decrease, ozone levels are expected to be dominated by temperature, atmospheric dynamics and the abundances of trace gases, including water vapour, methane and N_2O. For example, future growth in N_2O, due in part to increased fertilizer production, could lead to decreases in ozone. Some model calculations indicate that ozone could increase to a higher level than that observed before the influences of ozone-depleting substances, while other models indicate that ozone could increase, but reach lower levels. Clarifying the expectations for ozone amounts near the end of this century will require improved estimates of future impacts of the various factors as well as continued improvements in the models to represent the combined effects on ozone of these processes.

Remaining uncertainties

Although many factors affect ozone concentrations and it is difficult to be confident about trend results derived from ten years of data, many of the changes observed in the recent ozone data are qualitatively consistent with what would be expected on the basis of a reduction in the concentrations of ozone-depleting substances in the atmosphere. Over the past ten years, total column ozone values for most of the world have levelled off or show a slight increase. No area shows significant depletion of total ozone, marking the first ten-year period since 1980 (omitting the perturbation following the eruption of Mt Pinatubo) in which ozone has not declined. The observed levelling off of ozone is generally consistent with declines in ozone-depleting substances due to international agreements controlling their production. However, the large increases in column ozone observed in the mid- to high-northern latitudes are probably due to the higher temperatures in the Arctic polar vortex as well as to solar influence and the recent lack of volcanic activity. In contrast, the winter of 2004/05 was extremely cold in the Arctic stratosphere, allowing for severe ozone depletion before the polar vortex broke up. The 11-year solar cycle recently peaked and its influence on ozone is uncertain, but solar variability appears to have contributed to some of the observed levelling off and increases in ozone over the past eight years.

As concentrations of ozone-depleting substances subside, considerable uncertainty about the rate of ozone recovery and future ozone levels exist. In the future, ozone levels will depend on continued compliance with the Montreal Protocol and its amendments and on climate change policies that influence atmospheric changes. Changes in the atmosphere as a result of continued anthropogenic impacts suggest that ozone will recover in an atmosphere much different from that which prevailed before the build-up of ozone-depleting substances. Whether ozone stabilizes at a level higher or lower than pre-1980 levels, the vertical distribution of ozone in the future is almost certain to be different from the pre-depletion period. Because recovery approaching pre-1980 levels could take decades, the amount of ultraviolet radiation reaching the Earth's surface is likely to remain elevated for as long as ozone remains below historically normal values. Data through to the end of this decade are needed to help determine how much of the recent ozone increases are attributable to solar influences, and to establish the extent to which temperatures and concentrations of ozone-depleting substances are affecting current ozone amounts. During the next few years, ozone levels in the Arctic will be strongly influenced by stratospheric temperature, possibly resulting in delayed recovery or record-low ozone observations. Considerably longer data series and improved understanding of atmospheric processes and their effects on ozone are needed to estimate future ozone levels with confidence.

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