Ozone: Past, Present and Future

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Abstract. Over the past 50 years the global ozone layer has been depleted by anthropogenic emissions of ozone depleting substances. This paper presents an overview of the changes observed in global ozone to date, addresses the effectiveness of the Montreal Protocol in reversing the decline in ozone, and describes projections in future ozone and their dependence on changes in climate. While the primary focus of the paper is on ozone, potential avenues for future UV research, and the likely importance of future UV changes in the tropics, are also discussed. The paper concludes with an outlook on potential future threats to the ozone layer; in particular geoengineering.

Global ozone mass

Daily global total column ozone fields from the NIWA combined total column ozone database have been used to calculate daily global ozone mass values (Figure 1). A clear annual cycle in global ozone mass is apparent. Global ozone mass increases during the first 4 months of the year as ozone is transported to Arctic latitudes where its lifetime is long. As the sun returns to the Arctic and the northern hemisphere meridional transport weakens, global ozone mass falls. The Antarctic polar vortex, which is significantly stronger than the Arctic vortex, creates a stronger barrier to meridional transport so that ozone is not transported efficiently to Antarctic latitudes. This, together with the effects of the Antarctic ozone hole, suppresses a second peak in global ozone mass during the southern hemisphere winter and spring.

Figure 1 also shows anomalies in global ozone mass which approximately mirror the changes in stratospheric halogen loading (not shown). Global ozone decreases from the beginning of the record, showing significant declines after the two largest volcanic eruptions in the period (orange arrows in lower panel), and reaching a minimum in 1993, two years after the eruption of Mt. Pinatubo. Thereafter, ozone shows a steady increase with a rapid rise to
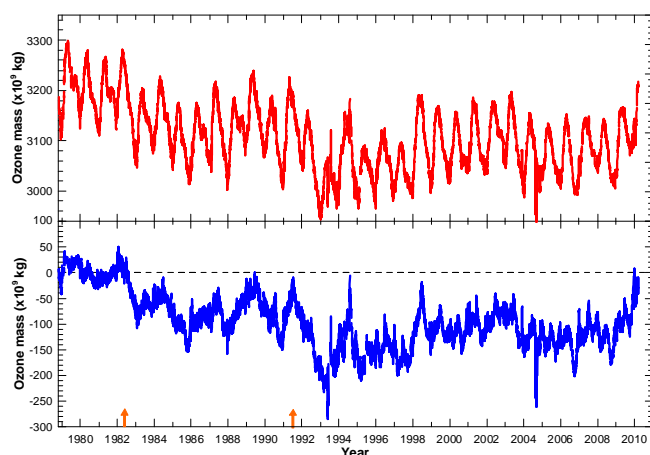

Figure 1: Upper panel: daily global ozone mass from November 1978 to March 2010. Lower panel: global ozone mass anomalies with respect to the 1979-1981 mean annual cycle. The two orange arrows denote the timing of the El Chichón (April 1982) and Mt. Pinatubo (June 1991) volcanic eruptions.
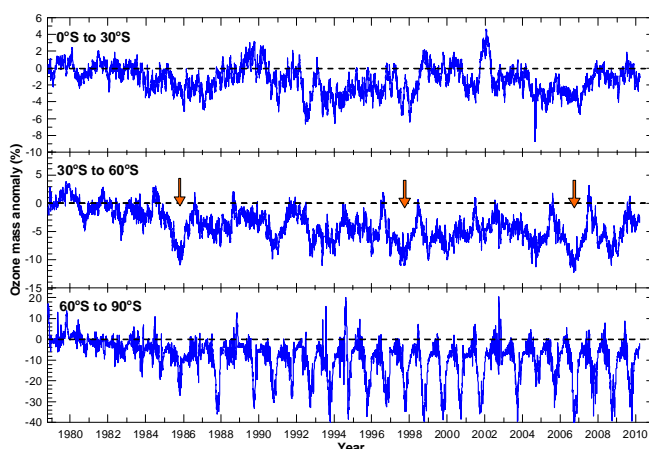

Figure 2: Daily ozone mass percentage anomalies (with respect to 1979-1981) for 30° latitude zones in the Southern Hemisphere. The orange arrows indicate periods of excessively low southern midlatitude ozone (see text for details).

levels close to what was observed from 1979 to 1981 by the end of the period. Whether this recent increase is sustained will require a few additional years of measurements.

Ozone mass percentage anomaly time series in 30° latitudes zones for the Southern Hemisphere are shown in Figure 2. The low latitudes of the Southern Hemisphere show only small reductions in ozone. Mid-latitudes show a more pronounced decline punctuated by periods of excessively low ozone (orange arrows in Figure 2). These events result from a combination of (i) an anomaly in the meridional circulation resulting from the westerly phase of the equatorial quasi-biennial oscillation (QBO), (ii) weaker transport of ozone from its tropical mid-stratosphere source across the sub-tropical barrier to mid-latitudes related to the particular phasing of the QBO with respect to the annual cycle, and (iii) a solar cycle induced reduction in ozone (Bodeker *et al.*, 2007). These events highlight the importance of tropical processes for ozone over southern mid-latitudes and in particular indicate that any future changes in the tropical source of ozone could affect southern mid-latitude ozone. Figure 2 also shows the development of the Antarctic ozone hole with large negative ozone anomalies appearing in late winter and early spring from the mid-1980s onwards.

The Effectiveness of the Montreal Protocol

In 1985 the *Vienna Convention for the Protection of the Ozone Layer* was signed by 20 nations who agreed to take appropriate measures to protect the ozone layer from human activities. In 1987, in response to growing concern, the *Montreal Protocol on Substances that Deplete the Ozone Layer* was signed and entered into force in 1989. As scientific advances led to deeper understanding of the chemical processes affecting ozone, and the implications of those changes, a number of Amendments and Adjustments were enacted to provide further protection of the ozone layer (Figure 3).
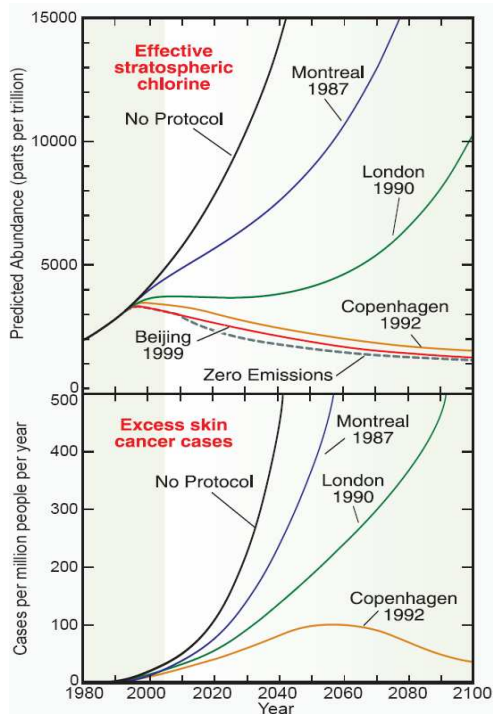
Figure 3: Projections of future abundances of effective stratospheric chlorine (a combination of the effects of chlorine and bromine on stratospheric ozone) are shown in the top panel assuming (1) no Protocol regulations, (2) only the regulations in the original 1987 Montreal Protocol, and (3) additional regulations from the subsequent Amendments and Adjustments. The lower panel shows how excess skin cancer cases might increase with no regulation and how they might be reduced under the Protocol.

In response to the provisions of the Protocol, ozone through much of the atmosphere is no longer declining and in some regions ozone is increasing. In some cases the increase has been driven by changes in dynamics possibly brought about by changes in climate. To assess the success of the Montreal Protocol, it is therefore important to correctly attribute the causes of observed changes in ozone. Chemistry-climate model projections indicate that were it not for the Protocol, 17% of the global ozone mass would be destroyed by 2020, and 67% destroyed by 2065 compared to 1980 values. Ozone in the tropical lower stratosphere would collapse to near zero around the middle of
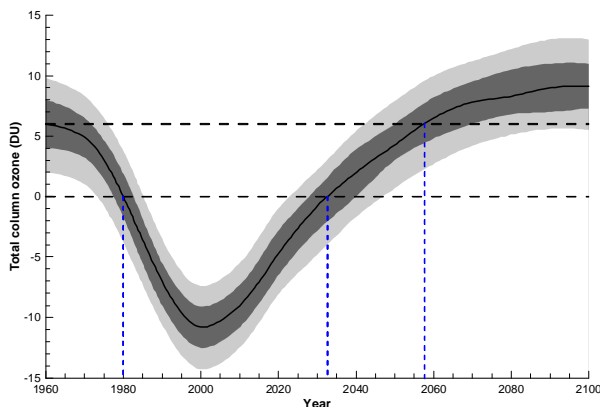

Figure 4: Annual mean global total column ozone chemistry-climate model simulations. The thick black line shows the multi-model mean and the dark- and light grey shaded regions show the 95% confidence and 95% prediction intervals, respectively. The horizontal dashed lines show 1960 and 1980 levels while the vertical dashed lines indicate dates of return to those levels.

the century as a result of heterogeneous chemical processes (as currently observed in the Antarctic ozone hole, see paper by Wood *et al.*). The summer-time UV index would exceed 25 over midlatitudes during the latter half of the century.

Future projections and interactions with climate

Projections of global ozone changes through the 21st century from a suite of chemistry-climate models are shown in Figure 4. Global mean ozone is projected to return to 1980 values sometime during the 2030s and to 1960 values in the 2050s. Later in the century global mean ozone is projected to be higher than 1960 levels. This results from greenhouse gas induced cooling of the upper stratosphere which slows gas phase ozone destruction chemistry. However, the same increase in greenhouse gases induces changes in stratospheric transport. In the tropics this decreases ozone in the lower stratosphere so that during the latter half of the 21st century, tropical total column ozone is projected to be in decline.

There are other potential future threats to tropical ozone. Proposals for large scale kelp farms as a means of CO_2 sequestration would increase marine biogenic emissions of bromocarbons. This, together with increases in sea-surface temperatures (which also increase bromocarbon emissions) and increasing strength and ubiquity of tropical deep convection, would increase the flux of bromine to the tropical lower stratosphere. This would induce additional ozone depletion in the tropical and extra-tropical lower stratosphere which would in turn increase surface UV irradiance. Higher UV stresses kelp and induces higher bromocarbon emissions. The potential effects of this positive feedback biogeochemical cycle have not yet been quantified.

Geoengineering

As a means of mitigating the effects of increases in greenhouse gases on surface temperatures, serious consideration is being given to combating climate change through geoengineering. The most technically feasible approach would be continuous emissions of sulphate to the stratosphere at ~2 Mt/year. In the stratosphere the sulphate is oxidized to form sulphuric acid aerosols which reflect incoming solar radiation. This would be equivalent to 'perpetual post-Pinatubo' conditions; the Mt. Pinatubo volcanic eruption cooled global surface mean temperatures for a few years after the eruption. However, it is clear from Figure 1 that large enhancements in stratospheric sulphate aerosol loading significantly reduce ozone. Under such a scenario, the recovery of the Antarctic ozone hole could be delayed by between 30 and 70 years depending on the assumed geoengineered aerosol size distribution. Therefore, during the period when stratospheric halogen levels remain elevated, implications of sulphate geoengineering on stratospheric ozone need to be carefully considered as part of climate change mitigation policy employing this approach.

References

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