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Recovery of the Ozone Layer: The Ozone Depleting Gas Index

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The stratospheric ozone layer, through absorption of solar ultraviolet radiation, protects all biological systems on Earth. In response to concerns over the depletion of the global ozone layer, the U.S. Clean Air Act as amended in 1990 mandates that NASA and NOAA monitor stratospheric ozone and ozone-depleting substances. This information is critical for assessing whether the Montreal Protocol on Substances That Deplete the Ozone Layer, an international treaty that entered into force in 1989 to protect the ozone layer, is having its intended effect of mitigating increases in harmful ultraviolet radiation.

To provide the information necessary to satisfy this congressional mandate, both NASA and NOAA have instituted and maintained global monitoring programs to keep track of ozone-depleting gases as well as ozone itself. While data collected for the past 30 years have been used extensively in international assessments of ozone layer depletion science, the language of scientists often eludes the average citizen who has a considerable interest in the health of Earth's protective ultraviolet radiation shield. Are the ozone-destroying chemicals declining in the atmosphere? When will these chemicals decline to pre–ozone hole levels so that the Antarctic ozone hole might disappear? Will this timing be different in the stratosphere above midlatitudes?

To make the answers to these questions easier to understand, NOAA has developed the Ozone Depleting Gas Index (ODGI). This index is derived from atmospheric measurements of chemicals that contain chlorine and bromine at multiple surface sites across the globe. The index has two components, one relevant for ozone-depleting chemicals and the ozone hole over Antarctica (the ODGI-A), and one relevant for midlatitudes (the ODGI-ML). While both indices are derived from NOAA measurements of ozone-depleting chemicals at Earth's surface, separate indices for these different stratospheric regions are necessary to account for the unique nature of the Antarctic stratosphere compared with the stratosphere at midlatitudes in both hemispheres.

The situation in the Arctic is somewhat different. Air parcels from midlatitudes at times easily penetrate into the Arctic polar stratosphere, thus preventing it from becoming the isolated chemical reaction vessel that the Antarctic vortex represents. Thus, ozone-depleting gases will enter the Arctic stratosphere in a poorly definable manner that cannot be simply modeled, as it varies dramatically from year to year. Though an index for ozone-depleting chemicals in the Arctic stratosphere is not described here, it is likely that its value would lie between the midlatitude and Antarctic ODGI in any given year.

Observations of Ozone-Depleting Gases

The ODGI is estimated directly from observations of the most abundant, long-lived, chlorine- and bromine-containing gases regulated by the Montreal Protocol (15 individual chemicals). These ongoing observations provide a measure of the total number of chlorine and bromine atoms in the troposphere that are likely to reach the stratosphere and contribute to ozone depletion. Because stratospheric air reaching the Antarctic on its journey from the Northern Hemisphere to the south polar regions has been isolated from the troposphere for a long period (~6 years on average), nearly all of the ozone-depleting chemicals reaching the Antarctic stratosphere have degraded to inorganic forms that are potential ozone-depleting agents. When the enhanced

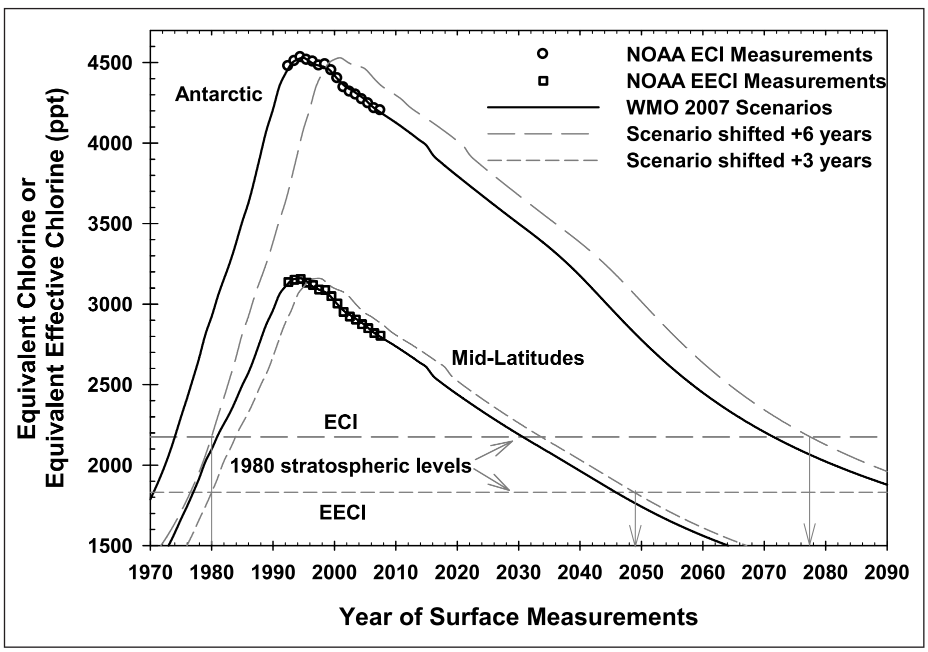

Fig. 1. The equivalent chlorine (ECl; upper curves) and equivalent effective chlorine (EECl; lower curves) content of the atmosphere, including both chlorine and bromine compounds, as a function of time. The plots show NOAA measurements (circles and squares) and projections for the future provided by WMO/UNEP *[2007] scenarios (solid curves), which assume that regulations of the Montreal Protocol will be followed in the future. Approximate stratospheric changes, based upon lagged tropospheric observations and scenario projections, are shown for midlatitudes and Antarctica (dashed curves). The two horizontal dashed lines represent levels of ECl (top) and EECl (bottom) from 1980 and are used as target levels for this study. The vertical arrows pointing downward represent the estimated dates that ECl and EECl in the stratosphere return to levels present in 1980, before large ozone depletion was observed.*

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efficiency of bromine to destroy ozone compared with chlorine is also considered, this total halogen amount is called the equivalent chlorine (ECl) burden of the atmosphere [*Montzka et al.,* 1996].

The calculation for midlatitudes of both hemispheres is different than for Antarctica primarily because air in the midlatitude stratosphere has a younger mean "stratospheric age" (~3 years) compared with air above Antarctica. As a result, ozone-depleting substances in the midlatitude stratosphere have had less time to become degraded by high-energy solar radiation. By accounting for compound-dependent degradation rates in the stratosphere, a younger mean stratospheric air age, and the enhanced efficiency for bromine to destroy ozone compared with chlorine, a quantity known as equivalent effective chlorine (EECl) can be derived to represent how the burden of ozone-depleting halogenated gases is changing in the midlatitude stratosphere [*Daniel et al.,* 1995; *Montzka et al.,* 1996].

Figure 1 shows ECl (for Antarctica) and EECl (for midlatitudes) versus time calculated primarily from NOAA's surface-based measurements and compares them with future projections provided by the *World Meteorological Organization/United Nations Environment Programme (WMO/UNEP)* [2007] Scientific Assessment of Ozone Depletion baseline scenario. Different lag times have been applied to observed and projected tropospheric changes (indicated as solid curves, circles, and squares) to approximate stratospheric changes in different regions (dashed curves). While a lag time of 6 years is used here to account for the time it takes for gases at Earth's surface to reach the Antarctic stratosphere, a mean lag of about 3 years is more appropriate when considering air transport to the stratosphere at midlatitudes.

Ozone Depleting Gas Index

The ODGI is defined here as being 100 at the time that NOAA's surface-based observations indicated a maximum in ECl or EECl in the troposphere (1994). For Antarctica, the zero point of the scale is defined as the ECl level that existed when the Antarctic ozone hole first became easily detectable, about 2170 parts per trillion ECl in about 1980, which is the ECl level when full recovery of the ozone hole is expected, all other factors being constant. On this scale, the current value of ODGI-A is about 86, indicating that observations show that the tropospheric abundance of ozone-depleting chemicals has declined by about 14% (100 – 86) of the way toward a halogen level that should allow an ozone hole–free Antarctic stratosphere (Figure 2). The latter has been projected to occur sometime in the 2080 range, as indicated by the 2006 WMO/UNEP Scientific Assessment of Ozone Depletion scenarios and as indicated in Figure 1.

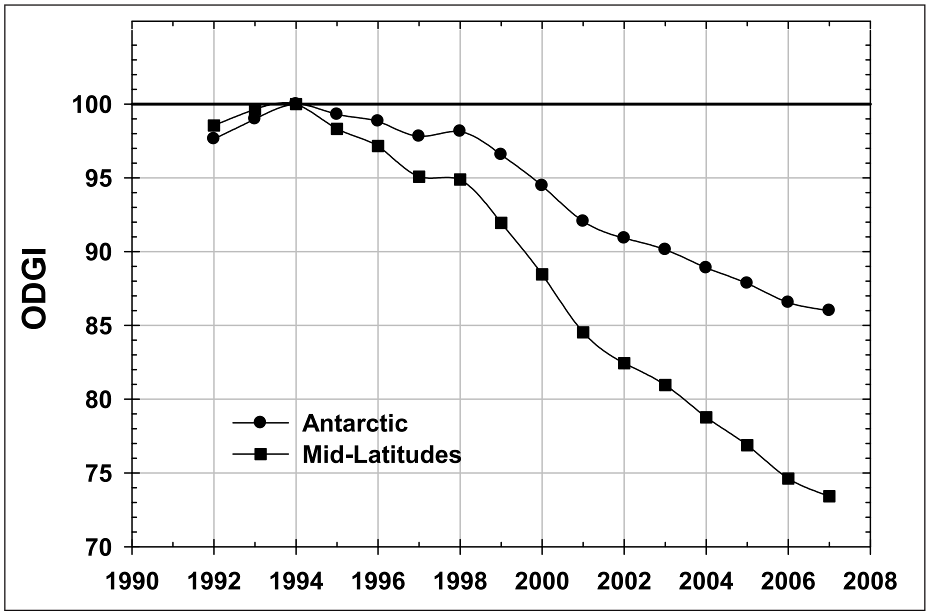

Fig. 2. The Ozone Depleting Gas Index (ODGI) versus time relevant for Antarctica and midlatitudes. While the ODGI represents changes in the troposphere, actual stratospheric changes lag those shown here by 3 years in midlatitudes and by 6 years above Antarctica, on average.

Similar to ODGI-A, the ODGI-ML is defined as 100 at the peak in EECl, and zero at the halogen level corresponding to when ozone recovery might be expected in the midlatitude stratosphere. On the basis of ozone-depleting chemical abundances inferred for the midlatitude stratosphere in 1980, we expect this recovery level to be approximately 1825 parts per trillion EECl, or somewhat less than required for full recovery in Antarctica. On this scale, the current value of the ODGI-ML is about 73, indicating that observations show that the tropospheric abundance of ozone-depleting chemicals has declined by about 27% of the way toward a halogen level that should allow a normal ozone layer in midlatitudes, all other factors being constant (Figure 2). The latter has been projected to occur in midlatitudes sometime around the 2050 range (see Figure 1).

Of the ozone-depleting gases restricted by the Montreal Protocol, the NOAA results show that nearly all were decreasing in the atmosphere by 2006. The notable exceptions include some halons (bromine-containing compounds used mainly in fire extinguishers) and hydrochlorofluorocarbons (HCFCs), which are used as replacements for chlorofluorocarbons (CFCs) in many applications. Most of the decline in ECl has been due to the relatively rapid phaseout and atmospheric decline of short-lived chemicals such as methyl chloroform (CH_3CCl_3) and methyl bromide. The decline related to CFC-11 and CFC-12, the two major ECl components, has been less dramatic. Though emissions of these two CFCs have declined substantially over the past 15 years, their atmospheric decay has been slow because their lifetimes are very long (50–100 years).

Further, methyl bromide and methyl chloride (CH_3Br and CH_3Cl) are unique among ozone-depleting gases because they have substantial natural sources. Despite the large natural source of CH_3Br, its mixing ratio has declined each year since 1998, when human industrial production was reduced. Some halons continue to increase slowly in the atmosphere because of large banks or reserves that are slowly being emitted to the atmosphere. Though HCFCs continue to increase and production is not scheduled for a complete phaseout until 2040, they currently contribute relatively little (~5% or less) to the atmospheric burden of ECl and EECl.

The ODGI is updated yearly at http://www.esrl.noaa.gov/gmd/odgi.

Future of the Ozone Layer

While the Montreal Protocol must be considered a huge success and a model for future efforts to stem climate change, ozone layer recovery is expected only with continued adherence to the production and consumption restrictions outlined in the Protocol and sustained declines in atmospheric chlorine and bromine in future years. Recovery of the ozone layer is expected as the ODGI approaches zero, though the timing of complete ozone layer recovery is difficult to determine exactly because other chemical and physical factors such as climate change also influence stratospheric ozone abundances, alter projected changes in ozone-depleting chemical abundances, and alter the efficiency of chlorine and bromine to destroy stratospheric ozone.

The ODGI-A and ODGI-ML represent important components of NOAA's effort to guide the recovery of the ozone hole over Antarctica and the midlatitude ozone layer. These indices provide a means by which adherence to international protocols can be assessed, and they allow the public and policy makers to discern if policy measures are having their desired effects. Because ozone depletion is still near its peak, continued monitoring of ozone and ozone-depleting gases is critical to ensuring that the recovery proceeds as expected through the 21st century.

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References

Daniel, J. S., S. Solomon, and D. L. Albritton (1995), On the evaluation of halocarbon radiative forcing and global warming potentials, *J. Geophys. Res., 100*(D1), 1271–1285.

Montzka, S. A., J. H. Butler, R. C. Myers, T. M. Thompson, T. H. Swanson, A. D. Clarke, L. T. Lock, and J. W. Elkins (1996), Decline in the tropospheric abundance of halogen from halocarbons: Implications for stratospheric ozone depletion, *Science, 272*(5266), 1318–1322.

World Meteorological Organization/United Nations Environment Programme (WMO/UNEP) (2007), Scientific assessment of ozone depletion: 2006, *Rep. 50,* Global Ozone Res. and Monit. Proj., Geneva, Switzerland.

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Online Access to Western North American Igneous Rock Geochemical Data

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The Western North American Volcanic and Intrusive Rock Database (NAVDAT) is a free, Web-accessible, and searchable repository of age, chemical, and isotopic data for Late Cretaceous and younger (~85 million years ago to present) igneous rocks from western North America, principally from the western conterminous United States and northern Mexico. The database (http://navdat.org) provides the Earth science community and the general public with ready access to information regarding the locations, compositions, and ages of igneous rocks throughout the region.

The database was established by the authors to better define space-time-composition patterns in igneous activity, which are key to plate tectonic reconstructions of western North America throughout the Cenozoic (65 million years ago to present) [*Lipman et al.,* 1971]. Prior to NAVDAT, no compilation, whether paper or electronic, of western North American igneous rock age and chemical data had been attempted for at least the past 20 years [*Mutschler et al.,* 1987], even though an impressive amount of new, high-quality geochemical and geochronologic data have been generated during that time. As a result, the implications that these new data have for refining our understanding of regional space-time-composition patterns of igneous activity in western North America had remained largely unexplored. Because no searchable electronic database of igneous rock ages, locations, and compositions existed for western North America prior to the advent of NAVDAT, anyone interested in investigating space-time-composition patterns in magmatic activity on the basis of both new and preexisting data was faced with a long and tedious data compilation exercise undertaken by all earlier researchers. Thus, there has been a need for a permanent and searchable online repository of age and chemical data from western North American igneous rocks.

Construction of NAVDAT

The construction of NAVDAT began in 2002, with support from grants by the U.S. National Science Foundation and the Geothermal Program Office, China Lake Naval Air Weapons Station. The NAVDAT database schema [*Walker et al.,* 2006] was developed in cooperation with representatives of the two other large, Web-based igneous rock databases currently available worldwide, Petrological Database of the Ocean Floor (PetDB) and Geochemistry of Rocks of the Oceans and Continents (GEOROC). All three databases are now jointly accessible through EARTHCHEM (http://www.earthchem.org/).

The NAVDAT data portal, along with its embedded data visualization and mapping tools, was developed and is currently maintained by the University of Kansas and the Kansas Geological Survey, both located in Lawrence. Data entry has involved the efforts of numerous senior scientists (including the authors) and undergraduate and graduate students at University of North Carolina; University of Colorado; Universidad Nacional Autónoma de México (Campus Juriquilla and Instituto de Geología, Hermosillo); Carnegie Institution for Science, Washington, D. C.; and University of Arizona.

NAVDAT Capabilities

As of December 2008, NAVDAT was populated with data from approximately 60,000 individual rock samples (~1,000,000 discrete chemical values) culled from a variety of sources, including peer-reviewed literature, the U.S. Geological Survey, M.S. and Ph.D. theses, and unpublished data donated by individual scientists. For all rock samples, locations and ages are included, along with whatever chemical and isotopic data were obtained by the original investigators. Also, for each sample, extensive metadata are available, including information regarding the methods used for obtaining the compositional data. Most of the uploaded data are searchable using criteria such as location, age, chemistry, rock type, or literature reference (Figure 1a). The data extracted from the database can be viewed as html, or they can be downloaded as .xls or .txt files that can be easily imported into other applications, including geographic information system software.

A particular strength of NAVDAT is the array of data representation and mapping tools that can be accessed by database users solely from their Web browsers. For example, interfaces allow users to quickly plot rock sample locations on satellite images via Google Maps™ and Google Earth™ (Figure 1b). Clicking on sample markers in such a map view opens a panel that provides quick links to a rock sample's age and compositional information. Database users also can generate on-demand an array of *x-y* and *x-y-z* geochemical plots for extracted data, including Harker diagrams (major element oxide weight percents plotted versus the weight percent of silicon dioxide) and total alkali versus silica diagrams (Figure 1c). Users can even create and view animations of *x-y* plots, a useful method for visualizing changes in igneous rock compositions through time.

Populating NAVDAT and refining the user-interface are ongoing activities. Already, though, the database represents a significant new tool for investigations into the origin and evolution of North American igneous rocks, and into the significance of these igneous rocks for models of the evolution of the continental lithosphere and the underlying mantle in western North America. NAVDAT provides easy access to a significant portion of the data that have been generated for Mesozoic and younger igneous rocks in the western United States and northern Mexico, and thus it provides an unprecedented opportunity to assess regional space-time-composition patterns in igneous activity. We encourage the community to take advantage of this new capability.