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The ozone layer, ozone depletion and the recovery of the ozone layer

July 2020

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The ozone layer

Ozone is a gas made up of three oxygen atoms (O_3, oxygen is O_2). Ozone is created by the action of sunlight on oxygen high in the stratosphere where the air pressure is very low and sunlight very strong. Lower down in the stratosphere, ozone is naturally destroyed in reactions with other atmospheric gases and the ozone layer is a consequence of the creation and destruction processes. About 300 million tonnes per day of ozone are involved in this cycle [1]. The total mass of ozone in the atmosphere is about 3 billion metric tons but is only about 0.00006 percent of the atmosphere.

Ninety percent of the ozone in the atmosphere is in the stratosphere, the layer of atmosphere between about 10 and 50 kilometres altitude. In the lower atmosphere (the troposphere) near the Earth's surface, ozone is created by chemical reactions between air pollutants. At ground level, high concentrations of ozone are toxic to people and plants. [2]

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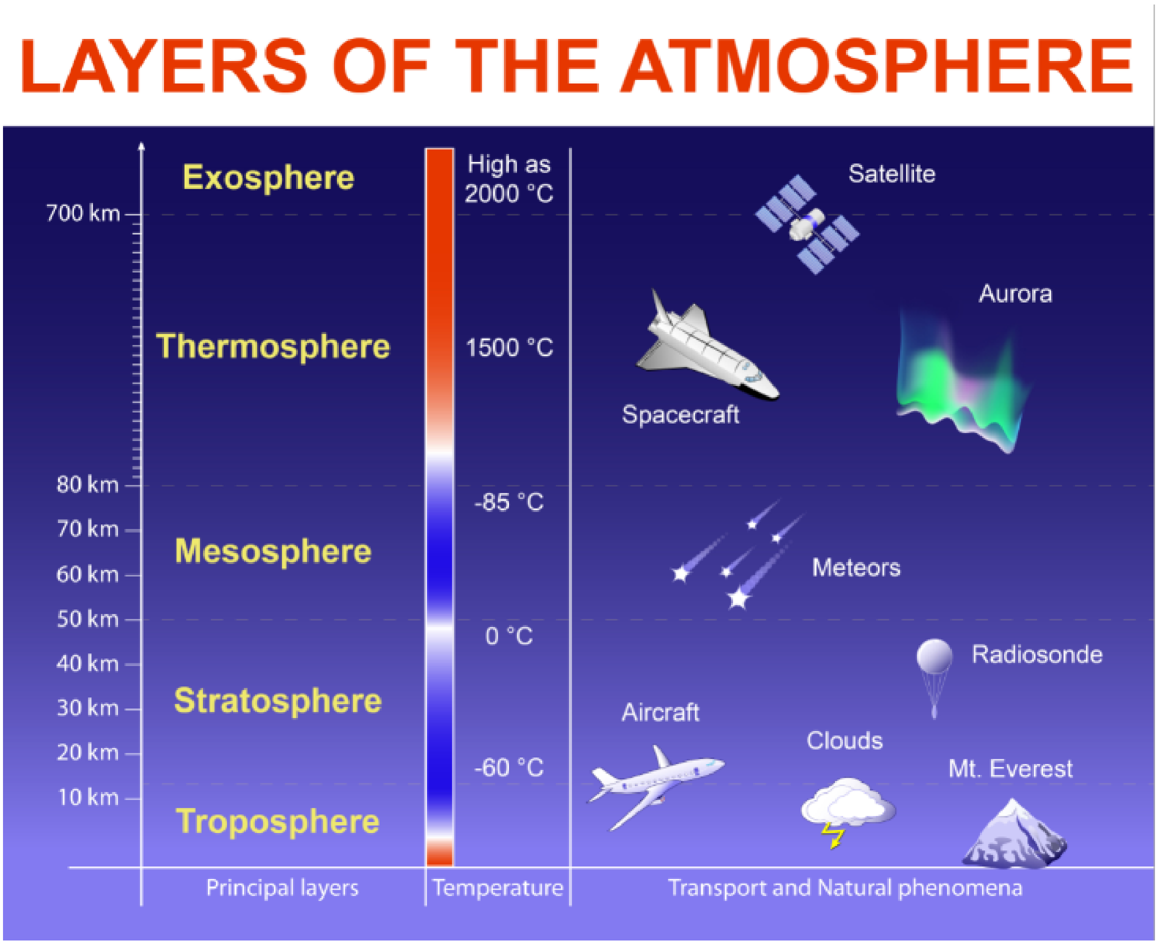

The ozone layer exerts two important influences on the atmosphere:

- the processes that create and destroy ozone generate heat, so that the ozone layer controls the temperature of the stratosphere; consequently, the stratosphere is warmer than the atmospheric layer immediately below it (the upper troposphere), and
- ozone absorbs the higher energy parts of the ultra-violet (UV) irradiation coming from the Sun (all of the UV-C and most of the UV-B).

Formation of ozone is controlled by sunlight; this means that most ozone is formed over the Equator and almost none over the Poles. The ozone in the stratosphere at the Poles is transported there on stratospheric winds.

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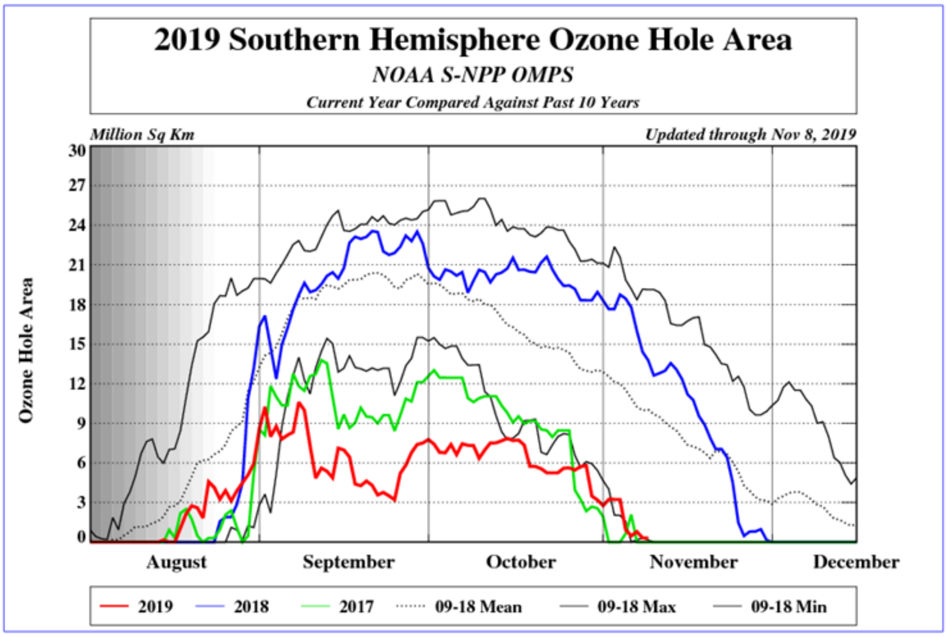
Ozone depletion

Ozone depletion occurs if the processes that destroy ozone are augmented, so that the balance between its formation and removal is disturbed. This makes the Polar stratosphere particularly vulnerable (because ozone is not formed there).

A large number of chemical species are involved in the natural ozone removal processes: water, hydrogen peroxide, hypochlorous acid, nitric acid, methane, carbon monoxide, nitric oxide, nitrogen dioxide, nitrous oxide, chlorine, chlorine monoxide, hydrochloric acid and bromine monoxide all play a part. The removal process is also augmented by reactions that occur on the surface of particles; in turn these are influenced by stratospheric temperatures [3]

The most important parameters now are the increased chlorine and bromine concentrations (from ozone depleting substances) and the existence of stratospheric particles (such as ice clouds). Because it is a consequence of an upset to the balance between formation and removal, ozone depletion is temporary. In the short term, the lower ozone levels that result are regional and seasonal (like the Antarctic ozone hole) and, in the long term, ozone depletion should cease when the balance is restored.

Contrasting the 2019 arctic and Antarctic ozone levels



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The Antarctic 2019 ozone "hole" was one of the smallest since the early 1980s. In contrast the ozone "depletion" over the Arctic this spring reached a record low in March. While such low levels are rare, they are not unprecedented. Similar low ozone levels occurred in the upper atmosphere, or stratosphere, in 1997 and 2011. The lowest March ozone value observed in the Arctic is usually around 240 Dobson units, but this year it reached 205 Dobson units. The 2019 Antarctic ozone hole reached a minimum ozone value of 167 Dobson units, higher than the lowest minimum ozone value of 92 Dobson units measured in 1994. [4,5]

Year to year variations are driven by atmospheric conditions

While, levels of chlorofluorocarbons and other man-made ozone-depleting substances have measurably decreased in the atmosphere and continue to do so and there are signs that the ozone layer is beginning to recover, year to year variations are driven by atmospheric conditions. The stratospheric temperature and the amount of sunlight reaching the south polar region control the depth and size of the Antarctic ozone hole, and in 2019 the stratosphere over Antarctica was warmer than the previous few years, so the ozone hole was smaller. The March Arctic ozone depletion was caused by a combination of factors that arose due to unusually weak upper atmospheric "wave" events that drive movements of air through the upper atmosphere. In a typical year, these waves travel upward from the mid-latitude lower atmosphere to disrupt the circumpolar winds that swirl around the Arctic. When they disrupt the polar winds, they do two things. First, they bring with them ozone from other parts of the stratosphere, replenishing the reservoir over the Arctic and second, the mixing warms the Arctic air. The warmer temperatures then make conditions unfavourable for the formation of polar stratospheric clouds. These clouds enable the release of chlorine for ozone-depleting reactions. [6,7]

The recovery of the ozone layer

"*For the first time, there are emerging indications that the Antarctic ozone hole has diminished in size and depth since the year 2000, with the clearest changes occurring during early spring. Although accounting for natural variability is challenging, the weight of evidence suggests that the decline in ODSs made a substantial contribution to the observed trends*."

"Model simulations show that implementation of the Montreal Protocol has prevented much more severe ozone depletion than has been observed in the polar regions of both hemispheres"

"No statistically significant trend has been detected in global (60°S–60°N) total column ozone over the 1997–2016 period. Average global total column ozone remains roughly 2.2% below the 1964–1980

*average. These findings are expected given our understanding of the processes that control ozone. In the mid-latitudes, the increase in ozone expected to arise from the 15% decline in EESC [*Equivalent Effective Stratospheric Chlorine -EESC see definition below] *since 1997 is small (1% per decade) relative to the year-to-year variability (about 5%).”*

“The Antarctic ozone hole is expected to gradually close, with springtime total column ozone returning to 1980 values shortly after mid-century (about 2060);

“Arctic springtime total ozone is expected to return to 1980 values before mid-century (about 2030s). Substantial Arctic ozone loss will remain possible in cold winters as long as ODS concentrations are well above natural levels. In contrast to the Antarctic, the timing of the recovery of Arctic total ozone in spring will be strongly affected by anthropogenic climate change;”

“Northern-Hemisphere, mid-latitude column ozone is expected to return to 1980 abundances before mid-century (2030s), and Southern Hemisphere, mid-latitude ozone is expected to return around mid-century.” [7]

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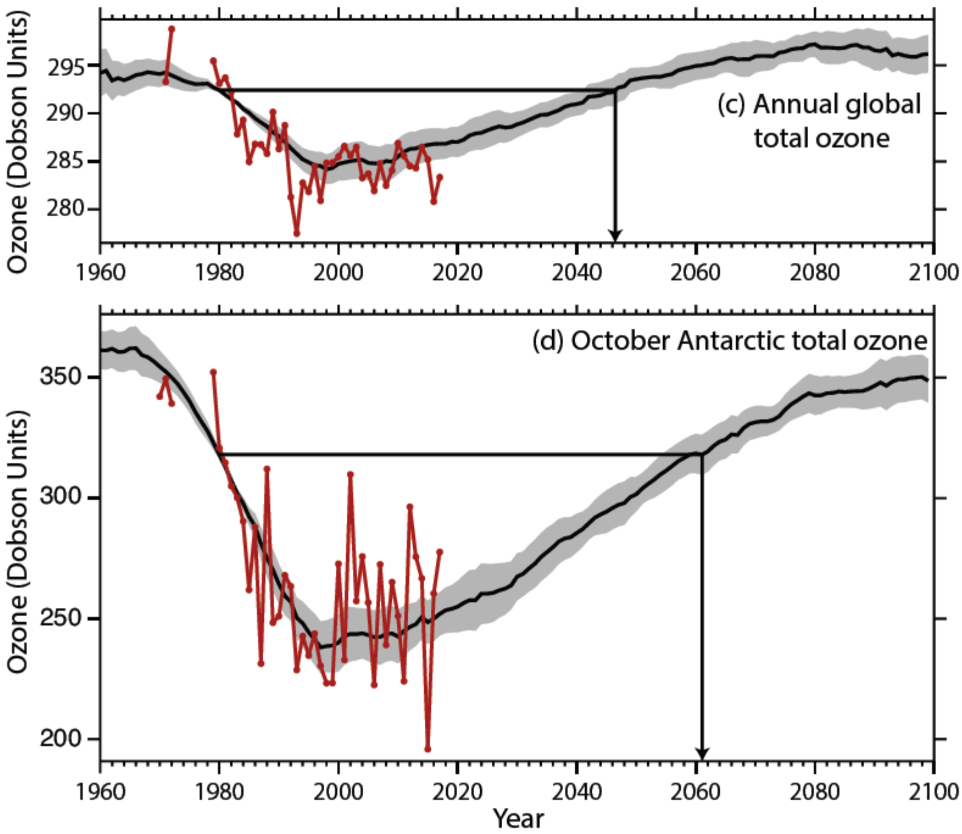
Timeline of ozone [7]



Parameters important for recovery of the ozone layer

The key parameters that determine depletion of the stratospheric ozone layer and so are important for its recovery are:

- The chlorine and bromine concentrations in the layer now and in the future;
- The existence of particles in the stratosphere; and
- Stratospheric temperature

Chlorine and bromine concentrations: The Montreal Protocol is reducing these and has been successful in limiting the maximum Equivalent Effective Stratospheric Chlorine (EESC) to 3.6 ppb in 1993. It has now fallen to about 3.2 ppb (in 2016). It is expected to fall below 2 ppb by the middle of the 21st century in response to much reduced emissions of Ozone Depleting Substances.

Equivalent effective stratospheric chlorine (EESC): *EESC is a metric for representing ODS levels in the stratosphere. It is calculated based upon three factors: surface atmospheric concentrations of individual ODSs and their number of chlorine and bromine atoms, the relative efficiency of chlorine and bromine for ozone depletion, and the time required for the substances to reach different stratospheric regions and break down to release their chlorine and bromine atoms.*

Stratospheric particles: Most ozone depletion occurs because particles in the stratosphere provide reactive surfaces that regenerate chlorine that has been released from CFCs but is held in the stratosphere in forms that are inactive (such as hydrogen chloride). Thus, volcanoes that inject sulphuric acid mist into the stratosphere can profoundly affect ozone for a few years until the sulphuric acid falls out into the troposphere.

Stratospheric temperature: If the stratospheric temperature falls low enough, ice crystals will form, even in this comparatively dry region of the atmosphere. This is the reason that Polar Stratospheric Clouds can form during the winter over both Poles but particularly Antarctica. Ice crystal surfaces act in the same way as sulphuric acid mist to regenerate chlorine. Stratospheric temperatures have been observed to have fallen over the past decades; this is in part because of the lower ozone levels. Furthermore, if the surface temperature of the earth and the temperature of the lower atmosphere rise in the future due to greenhouse gases, the temperature of the stratosphere will fall.

Climate change and ozone layer recovery

Although it may appear to contradict the intuitive view of the greenhouse effect, when the atmospheric concentration of CO_2 increases, the stratosphere actually cools. This favours the formation of Polar Stratospheric Clouds (PSCs) which strongly accelerate polar ozone depletion by catalytic effects that are now well understood [8].

Outside the Antarctic, CO_2, CH_4, and N_2O will be the main drivers of stratospheric ozone changes in the second half of the 21st century, assuming full compliance with the Montreal Protocol. These gases impact both chemical cycles and the stratospheric overturning circulation, with a larger response in stratospheric ozone associated with stronger climate forcing. The wide range of possible future levels of CO_2, CH_4, and N_2O represents an important limitation to making accurate projections of the ozone layer. [7]

Nevertheless, chlorine loading is the most important factor for the recovery of the ozone layer and is controlled under the Montreal Protocol.

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