The Antarctic Ozone Hole: An Update

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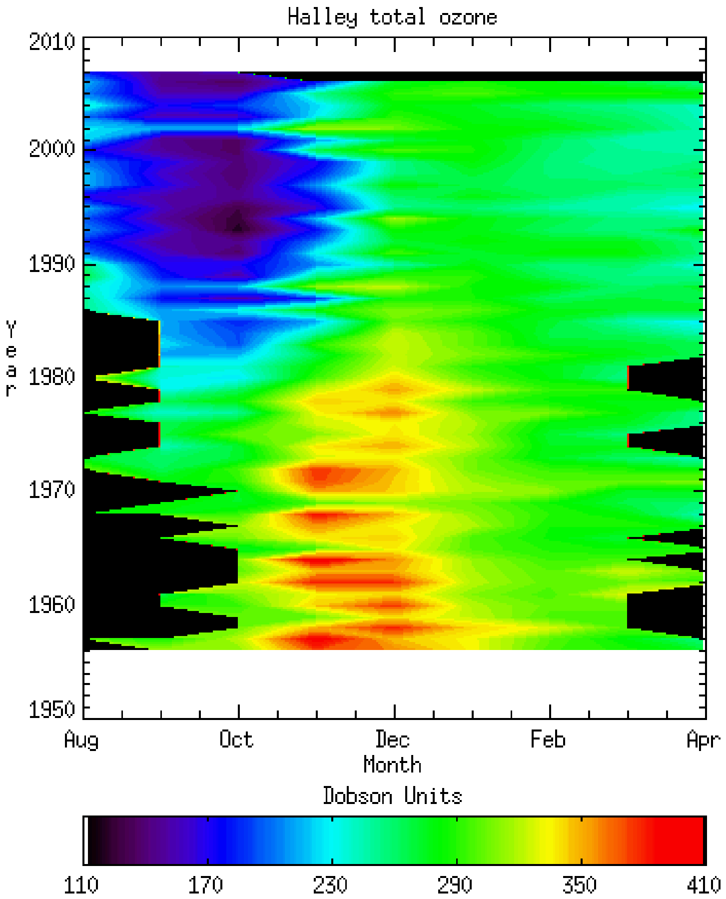
Info sources:
http://www.antarctica.ac.uk/met/jds/ozone/index.html
http://www.antarctica.ac.uk/about_antarctica/geography/ozone.php
http://www.ozone-uv.co.uk/index.php
http://ozonewatch.gsfc.nasa.gov/
http://www.esrl.noaa.gov/csd/assessments/ozone/2010/twentyquestions/
http://www.metlink.org/weather-climate-resources-teachers/useful-links.html#ozone
http://http//www.scienceinschool.org/2010/issue17/ozone

Ozone, O_3, is a naturally occurring gas. Over 90% of the ozone in the atmosphere is found in the stratosphere – between 10km and 50km up in the atmosphere, in the 'ozone layer'. There, it absorbs ultraviolet radiation from the Sun (UV-B, 280-315nm), which would otherwise reach the Earth's surface with harmful effects, including the destruction of chlorophyll in plants and a greater chance of skin cancers and eye cataracts in humans. The remaining 10% of ozone is found in the lower atmosphere, the troposphere, where it is mainly emitted by the combustion of fossil fuels – and isn't relevant to this discussion.

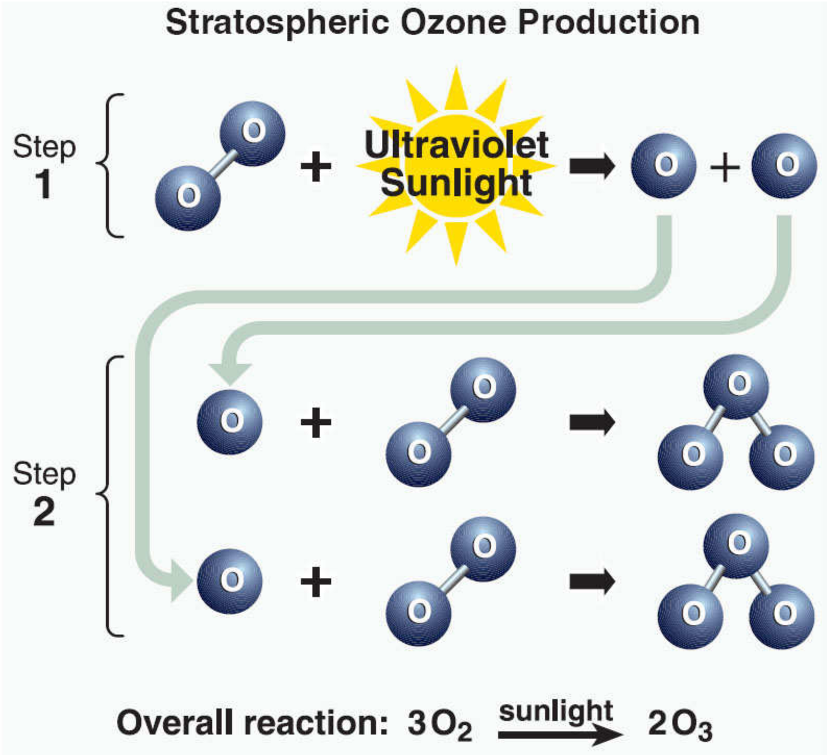
History

In the 1970s, scientists realised that some of the chemicals being used in industrial processes and consumer products were capable of destroying ozone. In 1985, scientists from the British Antarctic survey first reported a startling reduction in the amount of ozone above Antarctica in the Spring. This became known as the 'ozone hole'.
As a result of this, a worldwide agreement called the Montreal protocol was reached in 1987 which governs the production and consumption of all ozone destroying gases.



This figure shows the amount of ozone in the air above a British Antarctic Survey station, Halley, from 1956-2007. There is quite a lot of variation from year to year, due to periodic variations in the large scale circulation of the atmosphere. Total ozone at any location on the globe is found by measuring all the ozone in the atmosphere directly above that location, either using instruments on the ground, weather balloons or satellites, and is measured in Dobson Units. For example, satellites use the absorption of UV sunlight by the atmosphere or the absorption of sunlight reflected from the surface of Earth to measure ozone.

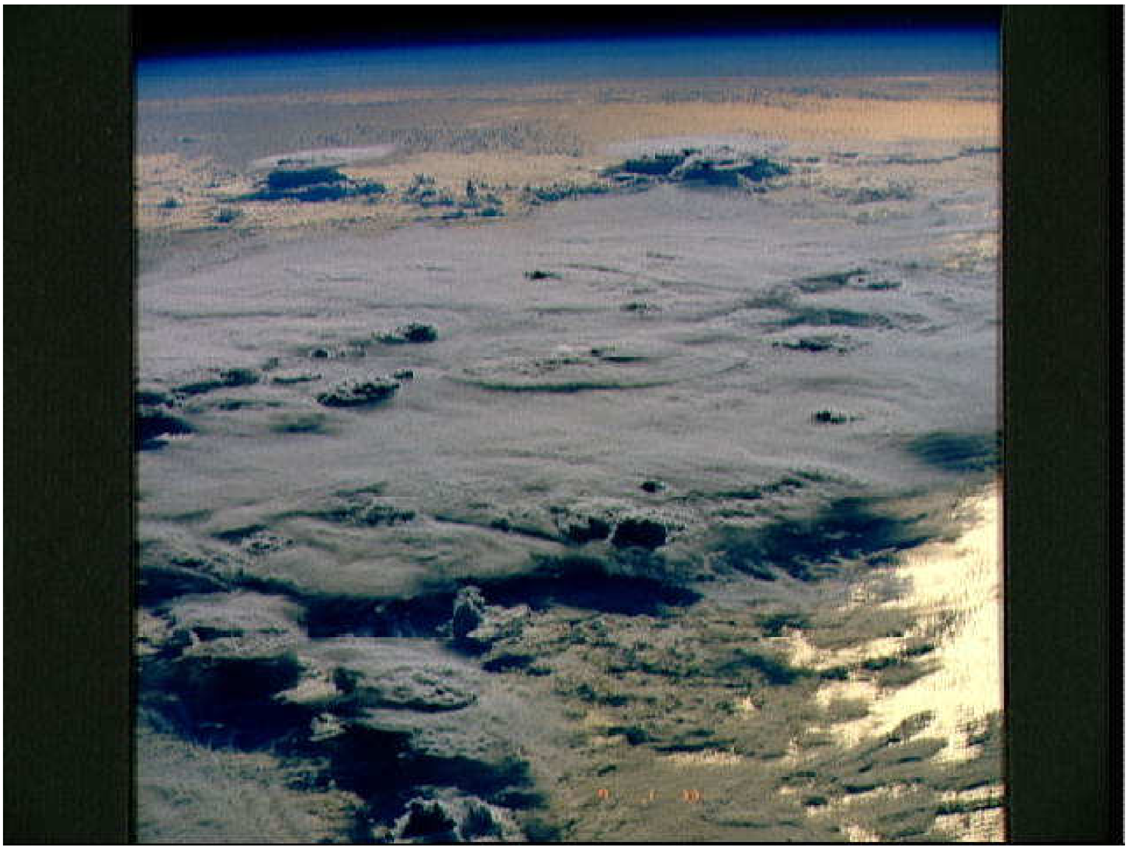
Formation of Ozone



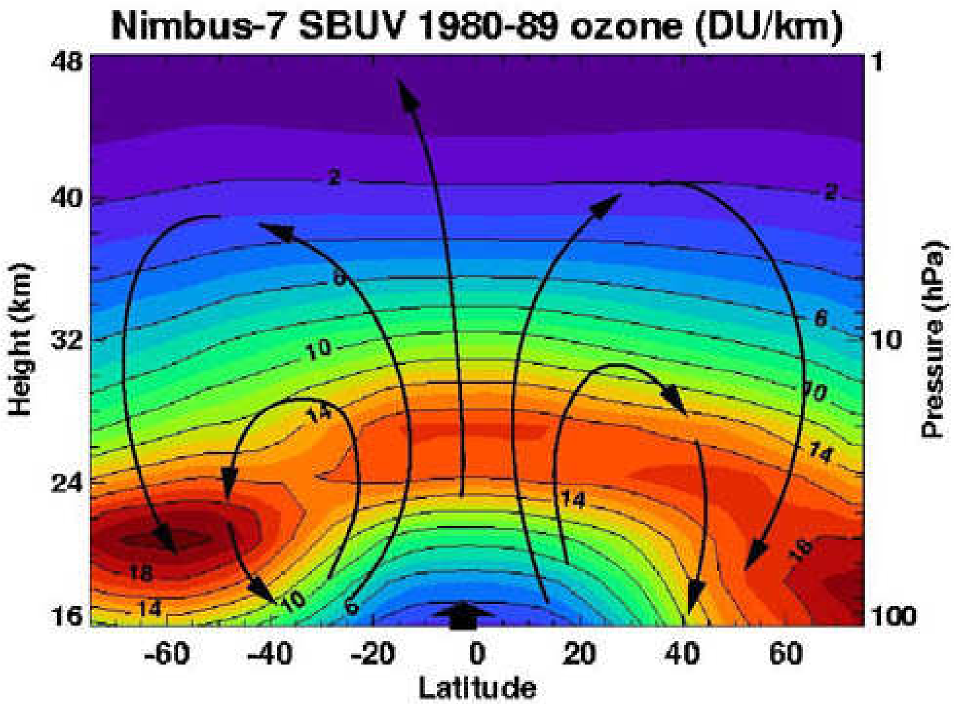
Stratospheric ozone is naturally formed in chemical reactions involving ultraviolet sunlight and oxygen molecules, which make up 21% of the atmosphere. In the first step, sunlight breaks apart one oxygen molecule (O2) to produce two oxygen atoms (2 O). In the second step, each atom combines with an oxygen molecule to produce an ozone molecule (O3). These reactions occur continually wherever solar ultraviolet radiation is present in the stratosphere. As a result, the greatest ozone production occurs in the Tropics where the Sun is overhead.
In normal circumstances, the amount of ozone produced like this is balanced by the amount of ozone being destroyed. Ozone reacts continually with a wide variety of natural and man-made chemicals in the stratosphere.

Redistribution of Ozone
Ozone producing and destroying reactions vary from time to time and place to place and ozone is transported by winds in the stratosphere. This means that the distribution of ozone is constantly changing. Ozone itself emits the energy it absorbs in the form of UV radiation, as infrared radiation. This heats the stratosphere and plays an important role in determining the structure and circulation of the atmosphere.
In general, ozone is produced in the tropics and destroyed at the poles, and transported from the tropics to the poles by large scale winds. These large scale winds are part of the Brewer-Dobson circulation.

- Air enters the stratosphere from the troposphere in the Tropics
- This relatively warm air continues to ascend through the stratosphere
- It then spreads polewards, taking with it ozone and other substances, partly because of the momentum transferred by waves propagating up from the troposphere.
- It sinks at the poles, where ozone and other substances become concentrated.
- It returns equatorward, actually taking air back into the troposphere because of the gradient in the stratosphere/ troposphere boundary in the mid-latitudes



Cumulonimbus clouds form where intense convection occurs, usually over warm land (the biggest cumulonimbus clouds are found in the tropics). The convection stops where the air hits the boundary between the troposphere and the stratosphere. At this point the air goes from becoming cooler with height to becoming warmer with height, due infrared radiation emitted by ozone. This change in profile means that the stratosphere is very stable – if air rises, it will usually end up surrounded by warmer air and therefore sink back down again. However, in big cumulonimbus clouds, the rising tropospheric air can sometimes overshoot the boundary. This overshooting very slowly moves the halogens, and other gases, from the troposphere into the stratosphere. This NASA image shows the tops of cumulonimbus clouds over the Indian Ocean.

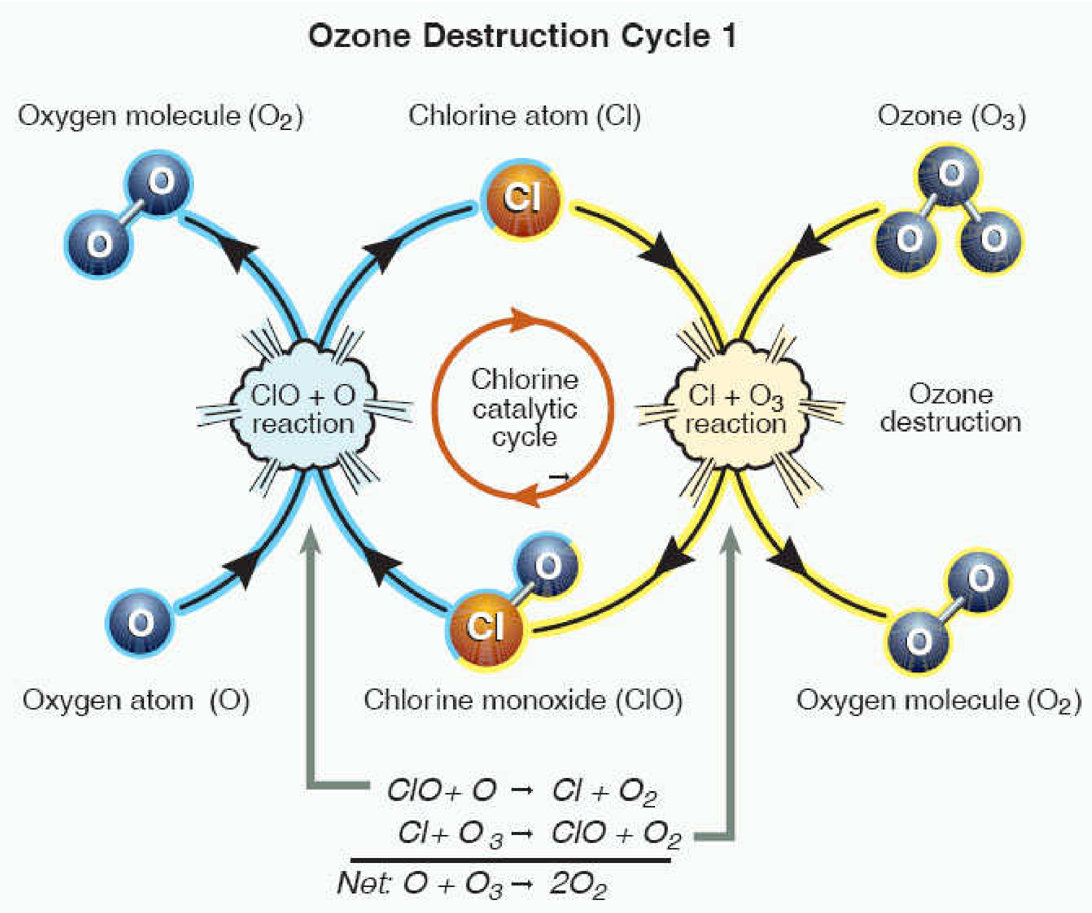


The Brewer-Dobson circulation in the stratosphere and the normal distribution of ozone in the stratosphere. Most ozone is found in the lower stratosphere, near the Poles

The destruction of ozone

The destruction of ozone depends on a many-step process:

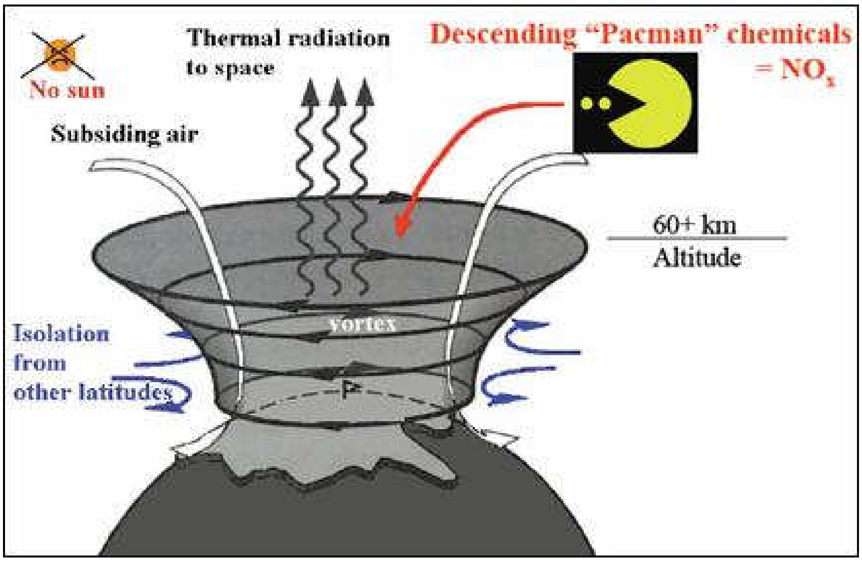
1) Halogen source gases, containing chlorine or bromine, are emitted at the Earth's surface by natural or man-made processes. Examples of these gases include chlorofluorocarbons (CFCs) which were used in fridges, aerosols and air conditioners, and halons which were used in fire extinguishers. The gases are mixed through the troposphere by turbulence and wind.
2) The most inert gases, such as CFCs, don't get incorporated into cloud droplets and rained out of the atmosphere, and so hang around in the troposphere for a long time. The time to remove or convert about 60% of a gas is often called its atmospheric "lifetime." Lifetimes can be to 100 years, allowing the gases to be slowly transported from the troposphere into the stratosphere in the tropics.
3) In the stratosphere, solar UV radiation converts the halogen gases into more reactive gases such as chlorine monoxide and bromine monoxide.
4) These act as catalysts in ozone destroying reactions in the stratosphere. In each reaction, an ozone molecule is lost but the catalyst survives.
5) Eventually, the reactive gases are transported back into the troposphere, either because they combine with polar stratospheric cloud droplets (see below) and fall under gravity, or because they follow the Brewer-Dobson circulation back into the troposphere in mid-latitudes. As the gases are now in a less inert form, they can be incorporated into cloud droplets and rained out of the system.



This cycle is most important in the stratosphere at tropical and middle latitudes, where ultraviolet sunlight is most intense.
Detail missing here of 3 types of reaction?

Polar stratospheric clouds

In the winter, the land and air inside the Antarctic circle does not receive any solar radiation at all and cools by emitting infrared radiation to space. As it does so, the air in contact with the ground is cooled by conduction and convection, as the air cools, it sinks, and the air pressure at the ground is relatively high. Conversely, the air pressure in the upper atmosphere is relatively low and it draws in more air. Because of the rotation of the Earth and the Coriolis effect (see http://metlink.org/pdf/teachers/waves.pdf), this sinking air develops a clockwise swirl. A vortex, known as the polar vortex, develops and wind speeds around the vortex may reach $100ms^{-1}$ in the middle to lower stratosphere. (in comparison, a low pressure system in the tropics is termed a hurricane when surface wind speeds reach $30ms^{-1}$). This vortex isolates the air inside it, making it very hard for it to mix with air outside the vortex.



The isolation comes about because of strong winds that encircle the poles, preventing substantial motion of air in or out of the polar stratosphere.

The very low temperatures that can be reached in the centre of the polar vortex are low enough for polar stratospheric clouds (sometimes called Nacreous clouds) to form. For these clouds to form, many of the same conditions as for the formation of 'normal' clouds need to be met (see http://www.metlink.org/pdf/teachers/physics_review_clouds.pdf): cloud condensation nuclei need to be present and the air needs to have been moved upwards. Polar stratospheric clouds are often found near mountain ranges. There are two types of polar stratospheric cloud. The first type forms when nitric acid and water vapour condense onto a pre-existing sulphur particle, at temperatures below -78ºC. When the temperature falls below -85 ºC the second type form, consisting of ice crystals coated with a liquid coating of nitric acid. In July and August, temperatures in the Antarctic lower stratosphere can reach -90 ºC. Nacreous clouds can sometimes be seen bright in the night sky, because they are high enough to be illuminated by the sun long after sunset at the ground, and diffraction or interference effects give the pastel colours in much the same way that colours appear in a film of oil on a puddle of water.

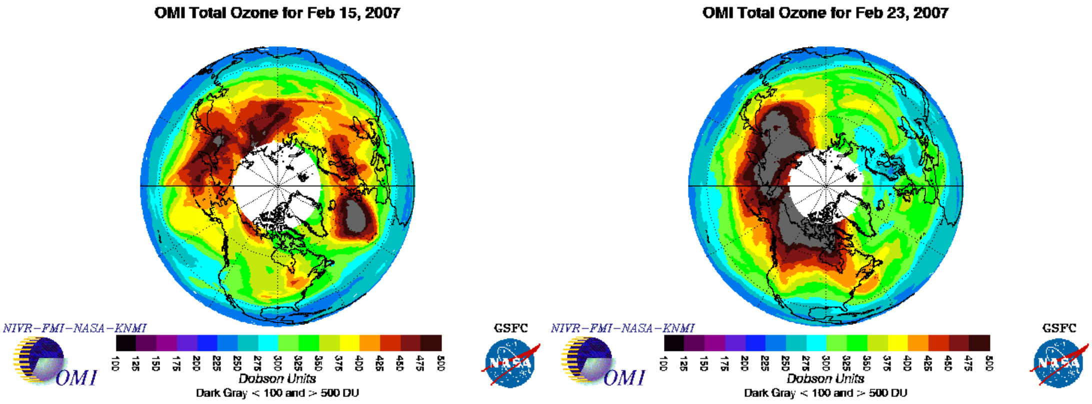

Australian Antarctica Division / Renae Baker

Polar stratospheric clouds over Antarctica. Copyright Renae Baker/ Cloud Appreciation Society

Chemical reactions on the surfaces of the cloud particles break the chlorine and bromine down to their molecular forms. In the absence of sunlight, these molecules are able to persist and accumulate because the air within the vortex is isolated from the rest of the atmosphere. As soon as sunlight returns to the stratosphere, the molecules are split into atoms, and two new ozone destroying reactions can occur using these atoms as catalysts. The rate of ozone destruction can reach 2 to 3% per day in late winter/early spring. However, when temperatures increase in the early spring, polar stratospheric clouds no longer form and the production of chlorine and bromine molecules ends. Other chemical reactions take up the chlorine and bromine into more complicated molecules, and the intense period of ozone depletion ends. As the Antarctic slowly warms, the polar vortex breaks down, and the relatively high concentrations of ozone that have accumulated at the edge of the vortex through the winter get mixed into the Antarctic air, rapidly raising the levels up again. The ozone hole disappears by December and Antarctic ozone amounts remain near normal until the next winter season.

Ozone elsewhere

The Arctic does not suffer as much ozone depletion as the Antarctic. This is mainly because of the way the land is distributed in the two hemispheres. There is much less land in the Southern Hemisphere, and the Antarctic is roughly circular with a roughly circular belt of ocean around it. This means that as air flows around the world, it doesn't get very disturbed. On the other hand, air flowing around the Northern Hemisphere gets disturbed by mountain ranges in North America, Europe and Asia – particularly the Rocky mountains and the Tibetan plateau. This results in very large waves developing in the air flow (see waves article) which in turn disturb the Arctic polar vortex, moving it around and sometimes splitting it up. The result is that air in the vortex never gets as cold as is does in the Antarctic, and sometimes gets mixed with non-polar air. In some years, PSC formation temperatures are never reached in the Arctic, and significant ozone depletion does not occur. In addition, there is more ozone in Arctic polar regions at the start of each winter because the Brewer-Dobson circulation is more active in the Northern Hemisphere. Some reduction in stratospheric ozone has also been seen over Europe. One theory suggests that this is the result of the Arctic, ozone depleted, air being mixed into European air.



This satellite image shows total ozone over the Arctic on 15th and 23rd February 2008. Although this satellite cannot 'see' into the polar night (notice how the area which the Sun is reaching increases over these 8 days) the two images show how the polar vortex, marked by the region of low ozone (grey colours mark <100 Dobson Units), has moved.

Ozone and Climate Change

The greenhouse effect and the ozone hole are frequently confused. Although some ozone destroying gases, such as CFCs, are in fact greenhouse gases, the processes that result in the destruction of stratospheric ozone are entirely separate. However, at a deeper level, the greenhouse effect and stratospheric ozone are linked in several ways.

Greenhouse gases such as water vapour, carbon dioxide and methane in the troposphere absorb outgoing infrared radiation from the Earth and reemit it in all directions, warming the troposphere. This in effect means that less infrared radiation reaches the stratosphere, which then actually cools as the troposphere warms. A cooler stratosphere would extend the time period over which polar stratospheric clouds are present in polar regions and, as a result, might increase winter ozone depletion in the lower stratosphere. Another effect of an increasing greenhouse effect is that more water vapour gets into the stratosphere, again increasing the number of polar stratospheric clouds. Conversely, higher up in the upper stratosphere where there are no polar stratospheric clouds, lower temperatures would mean that ozone destruction reactions proceed at a slower rate. In addition, warmer surface temperatures could change the emission rates of naturally occurring halogen source gases.

To complicate matters, because ozone is itself a greenhouse gas (it absorbs outgoing infrared radiation from the Earth) as the amount of ozone in the stratosphere begins to recover, it will in fact contribute to the warming of the Earth.

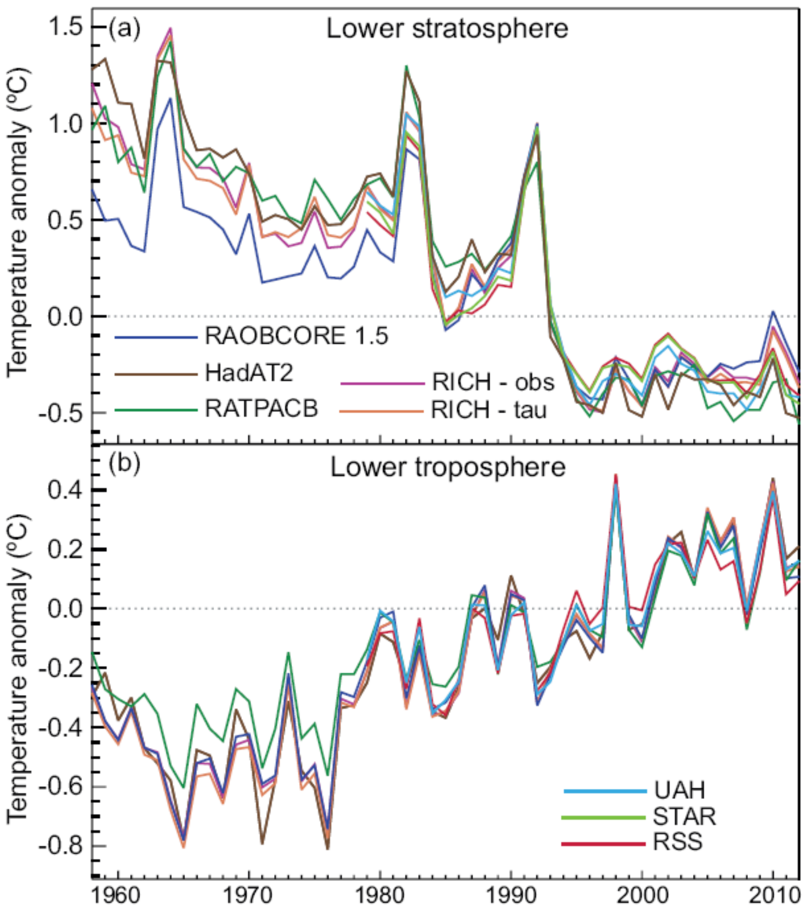


Figure 2.24 from IPCC 2013 WG1 1960-2012 global temperature trends in the stratosphere and troposphere

Projections of the Future

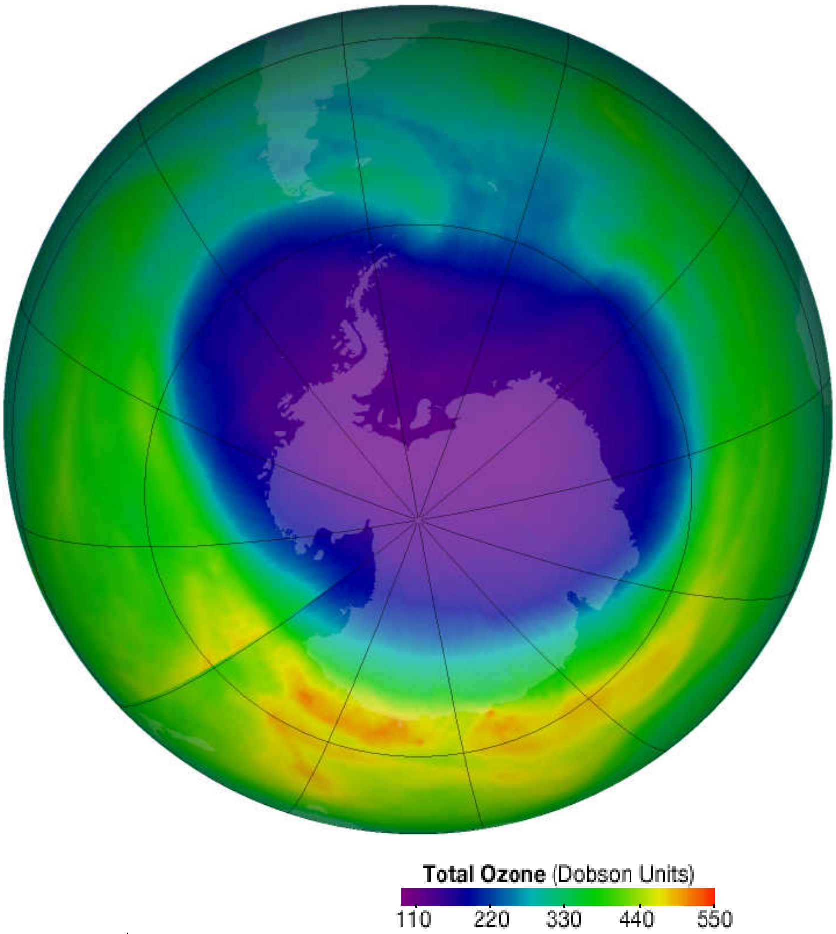
As a result of the Montreal Protocol and subsequent global agreements, the total abundance of ozone-depleting gases in the atmosphere has begun to decrease in recent years. If the nations of the world continue to follow the provisions of the Montreal Protocol, the decrease will continue throughout the 21st century. Around the middle of the 21st century, the effective abundance of ozone-depleting gases should fall to values that were present before the Antarctic “ozone hole” began to form in the early 1980s. With this, the amount of ozone in the stratosphere can return to pre-industrial levels.

This is of course complicated by the large question marks over the way greenhouse gases will continue to be emitted over the 21st century, and how the Earth’s climate system will respond. In some regions of the stratosphere, ozone may remain below pre-1980 values after chlorine levels have returned to normal.

Summary

- Ozone is predominantly formed in the tropical stratosphere.
- Chlorine and bromine enter the stratosphere from the troposphere in the tropics
- The ozone, chlorine and bromine are transported towards the poles by the large scale circulation of the atmosphere.
- The polar winter leads to the formation of the polar vortex which isolates the air within it.
- Cold temperatures form inside the vortex; cold enough for the formation of Polar Stratospheric Clouds.
- Chemical reactions take place on the cloud droplets and convert the inactive chlorine and bromine reservoirs to more active forms of chlorine and bromine.
- No ozone loss occurs until sunlight returns to the air inside the polar vortex and allows the production of active chlorine and initiates the catalytic ozone destruction cycles. Ozone loss is rapid. In October, the ozone hole currently covers a region bigger than Antarctica and extends nearly 10km in altitude in the lower stratosphere.
- However, once sunlight returns, the active chlorine and bromine combine into larger molecules stopping the reduction of ozone, and the breakdown of the polar vortex leads to an influx of ozone rich air.

Conditions in the Antarctic winter stratosphere are highly suitable for ozone depletion because of (1) the long periods of extremely low temperatures, which promote polar stratospheric cloud formation; (2) the abundance of reactive halogen gases, which chemically destroy ozone; and (3) the isolation of stratospheric air during the winter, which allows time for chemicals to accumulate.



October 1st 2007, copyright NASA. Peak depletion occurs in early October when ozone is often completely destroyed over a range of altitudes, reducing overhead total ozone by as much as two-thirds at some locations. This severe depletion creates the “ozone hole” (with less than 200 Dobson Units of ozone) in images of Antarctic total ozone made from space.

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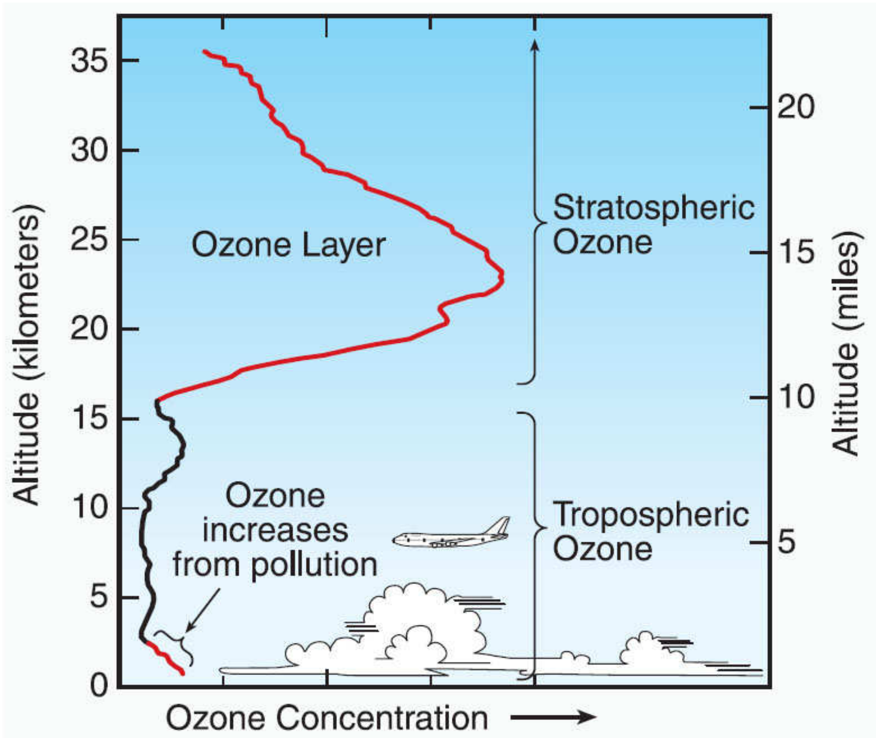

Distribution of ozone with height in the atmosphere