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# SATELLITES AND SATELLITE REMOTE SENSING | Measuring Ozone from Space – TOMS and SBUV

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## Measuring Ozone from Space - TOMS and SBUV

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### Introduction and History

The Total Ozone Mapping Spectrometer (TOMS) is a satellite-borne instrument that measures the total column amount of ozone in the atmosphere by measuring the ultraviolet sunlight scattered from the atmosphere. The Solar Backscatter Ultraviolet spectrometer (SBUV) is a companion instrument that measures how that ozone is distributed with altitude. The idea that ozone could be measured quantitatively from a satellite was first put forward in 1957 by Singer and Wentworth. In 1967, Dave and Mateer published a theory for the derivation of the total column amount of ozone from a satellite backscatter instrument. This theory was used for the interpretation of the data from the first instrument to measure the total column amount of ozone from space, the backscatter ultraviolet (BUV) instrument, launched on the Nimbus 4 satellite in 1970. It made nearly-global measurements for two years and then operated more sporadically for an additional five years.

In the beginning only a few scientists were interested in ozone. Popular interest came later, in the late 1970's, when the possible destruction of the ozone layer by CFCs was realized The TOMS measurements are best known for images of the ozone hole. When Farman's paper on low ozone in the Antarctic was published in 1985, TOMS images revealed that this was a continent-wide phenomenon and not local. TOMS (and now OMI and NPP) maps the development of the ozone hole each Antarctic spring.

The modern data record of global ozone measured from space starts with the launch of the Nimbus 7 satellite in 1978. The satellite carried two ozone-measuring instruments, the Solar Backscatter Ultraviolet (SBUV), and the Total Ozone Mapping Spectrometer (TOMS). The TOMS instrument measured the backscattered radiation at six wavelengths from 312 to 380 nm so that the total column amount of ozone could be deduced. TOMS was a single monochromator with a scanning mirror that allowed the instrument to make measurements at 35 scan angles from left to right across the ground track of the satellite. TOMS was thus able to measure over the entire sunlit portion of the globe each day. The SBUV instrument was a double monochromator designed to measure backscattered radiation at 12 wavelengths from 255 nm to 340 nm. Because the shorter wavelengths penetrate only to the upper stratosphere, these wavelengths can be used to deduce both the upper-stratospheric concentration profile of ozone and the total column amount of ozone, but only along the nadir track of the satellite.

The TOMS instrument on Nimbus 7 made measurements for more than 14 years. The instrument finally failed in May 1993. A second TOMS instrument was launched on the Russian Meteor 3 satellite in 1991. This cooperative project was the first time an American instrument was flown on a Soviet spacecraft. This instrument made total ozone measurements until the end of 1994. A third TOMS instrument was launched on the Japanese ADEOS satellite in 1996 but the satellite power array failed after only seven months of operation. A fourth TOMS instrument was launched on the Earth Probe satellite, also in 1996. Designated EP-TOMS, it operated through December 2005. A final TOMS instrument, QuikTOMS, was lost in 2001 when it failed to achieve orbit.

The successor instrument to the TOMS series of instruments is OMI, the Ozone Monitoring Instrument launched on the Aura spacecraft in July 2005. OMI, which was built by the Dutch for flight on Aura, is an imaging spectrometer that measures over the range 270 - 500 nm. OMPS, the Ozone Mapping Profiler Suite, is also an imaging spectrometer, designed to continue the US program of ozone monitoring begun by TOMS and SBUV. OMPS was launched on the Suomi NPP satellite in 2011.

A series of SBUV/2 instruments have been flown by NOAA to monitor long term changes in ozone. Instruments were flown on NOAA 9 (1985-1998), NOAA 11 (1989-2000), NOAA 14 (1995-2006), NOAA 16 (2001-present), NOAA 17 (2002-present), NOAA 18 (2005-present), and NOAA 19 (2009-present).

## The Theory of Ozone Measurement

TOMS and SBUV can measure ozone from space because ozone absorbs very strongly in the ultraviolet. By comparing a measurement at a wavelength strongly absorbed by ozone to one weakly absorbed by ozone, an accurate estimate of the amount of ozone in the atmosphere can be made from space. The instruments measure sunlight scattered by the atmosphere and reflected from clouds and the ground.

### *Rayleigh Scattering*

Light from the Sun penetrates into the atmosphere, with most of the visible light reaching the ground. Light is scattered by the molecules that make up the atmosphere in a process called Rayleigh scattering, named after Lord Rayleigh who first described it in the late nineteenth century. The probability of Rayleigh scattering depends inversely on to the fourth power of the wavelength ($\lambda^{-4}$). Thus, an ultraviolet photon of 300 nm wavelength is 16 times more likely to be scattered than a visible photon of wavelength 600 nm. This is why the sky is blue. When we look at the sky away from the Sun, blue light is much more likely to be scattered towards us than is red light.

*Surface Reflection and Clouds*

Radiation that does reach the ground can be absorbed or reflected by the surface. The probability of reflection depends on the nature of the surface. In the ultraviolet, the Earth is a very poor reflector. The UV reflectivity of the ocean in the 300-350 nm region of the spectrum is only about 4%. Most land surfaces have similarly low reflectivities, no more than 5% except in desert areas. Only areas covered by ice and snow have very high reflectivities, reaching 90% in the Antarctic.

When clouds are present, radiation reaching them is reflected back to space with high efficiency. Cloud reflectivities can reach 80-90% for thick clouds. Solar radiation that is reflected by clouds does not pass through the part of the atmosphere below the cloud and has no opportunity to be absorbed by the ozone below the clouds. The TOMS measurement is thus a measurement of the ozone above the cloud layer. Fortunately, this is a small effect since 90% of the ozone in the atmosphere is in the stratosphere. Only part of the 10% of the ozone column in the troposphere will be masked by clouds. This amount can be estimated from climatology, so that the measurement can be transformed into a fairly accurate estimate of the total column of ozone in the atmosphere.

*Aerosols*

Aerosols (dust particles in the atmosphere) also scatter radiation, further adding to the atmosphere's overall reflectivity. Their scattering does not follow the $\lambda^{-4}$ dependence of Rayleigh scattering but is close to a $\lambda^{-1}$ dependence. This means that when dust is in the atmosphere, the sky appears more nearly white. Aerosols do not affect our ability to measure ozone. However, the multiple reflectivity wavelengths can be used to deduce some information about the properties of aerosols. Measurement of the deviations from the expected result for a Rayleigh scattering atmosphere can be used to determine an aerosol index and used to track dust and smoke plumes (see results section below).

*Ozone Absorption*

Sunlight can be absorbed in the atmosphere by a variety of molecules. The principal absorber of ultraviolet light in the Earth's atmosphere is ozone. Absorption in the ultraviolet (UV) by ozone is so strong that a few parts per million of ozone remove all of the sunlight at wavelengths shorter than about 300 nm before they can reach the ground. We are thus provided with a shield from the high-energy radiation that could break important DNA bonds in living cells. The absorption of UV by ozone is the property that we generally use to measure the amount of ozone in the atmosphere. From the ground, we can look upward and measure how much radiation reaches us at a wavelength that is absorbed by ozone. We can compare this to the radiation received at a nearby wavelength that is not absorbed by ozone to determine the amount of ozone that must be between us and the Sun. Such measurements have been used to measure ozone since the 1920's. From satellites, we can look down and measure the radiation that is scattered back out of the atmosphere through Rayleigh scattering and again compare the amount at an absorbed wavelength with an unabsorbed (or less absorbed) wavelength.

**Description of the TOMS Retrieval Algorithm**

TOMS measures ultraviolet light scattered from the atmosphere and the Earth and clouds. An algorithm is needed to infer ozone from these measurements. The instrument looks downward at the Earth but also uses a diffuser plate to look at direct sunlight before it enters the atmosphere. The basic measured quantity is the ratio of the backscattered radiance to the direct solar irradiance. This is usually expressed as the N-value, or logarithm of the ratio:

$$N = -100 \log(I_0/F) \qquad (1)$$

where F is the solar irradiance at the particular wavelength and $I_0$ is the backscattered radiance. TOMS measures the light scattered from the Earth/atmosphere system ($I_0$) at a range of wavelengths, and measures F, the direct sunlight, by periodically deploying a reflective diffuser plate in front of the instrument.

Using the ratio of backscattered radiation to direct solar flux cancels some of the main instrumental errors; that is, the instrument throughput is the same for each measurement and cancels when the ratio is taken. The reflectivity of the diffuser plate affects the solar irradiance measurement, but not the backscattered radiance measurement. If a pair of wavelengths is used in the analysis, then the diffuser reflectivity can be canceled out in the ratio if that reflectivity is the same for both wavelengths. Thus we form the pair N-value as in eqn [2].

$$\begin{aligned} N_P &= N(\lambda_1) - N(\lambda_2) \qquad (2) \\ &= \log(I_{01}/F_1) - \log(I_{02}/F_2) \end{aligned}$$

These N-values reflect the effects of scattering, reflection, and absorption. Figure 1 illustrates the dependence of N-value on wavelength, clearly showing that an ozone signal can be derived from the data. The actual algorithm used for the TOMS retrieval uses a radiative transfer code based on the early work of Dave. Forward calculations are carried out for a matrix of parameters including total ozone. These then form a lookup table that is interpolated to derive total ozone.

**Description of the SBUV Retrieval Algorithm**

SBUV is similar to TOMS but is used to measure the altitude distribution of ozone. Like TOMS, its measurements are used as N values, but covering wavelengths further into the ultraviolet - 12 wavelengths from 250 nm to 400 nm. The key is that the very short wavelengths do not penetrate to the ground. At 255 nm light only penetrates to about 50 km altitude, at 290 nm light penetrates to 40 km, and 302 nm penetrates to 30 km. Thus the SBUV wavelength scan is equivalent to an altitude scan of ozone. In the actual profile retrieval the Rodgers optimal estimation technique varies a first guess ozone profile until the set of measured N values is matched.

## TOMS and SBUV

*Instruments*

The TOMS instruments are single, fixed monochromators with exit slits at six near-UV wavelengths. The slit functions are triangular with a nominal 1 nm bandwidth. The order of individual measurements is determined by a chopper wheel. As it rotates, openings at different distances from the center of the wheel pass over the exit slits, allowing measurements at the different wavelengths. The order was not one of monotonically increasing or decreasing wavelength; instead, the wavelengths were interleaved to minimize the effect of spacecraft movement on the ozone retrieval. The advantage of the more modern OMI and OMPS instruments is that they measure the complete spectrum at one time rather than sequentially measuring 6 wavelengths.

A ground aluminum diffuser plate is deployed to reflect sunlight into the instrument for measurement of the solar irradiance. This diffuser plate was shared by TOMS and SBUV experiment on the Nimbus 7 satellite. It was normally deployed once a week for TOMS solar irradiance measurements, in addition to the SBUV deployments. On the Earth Probe TOMS a triple diffuser was used to eliminate the problem of the diffuser darkening as it was exposed to ultraviolet light in space. One diffuser was used daily, another was used weekly, and the third was used only a couple of times a year to serve as the clean reference.

SBUV is a double monochromator. Because light at the longer wavelengths is so much stronger than light at short wavelengths, scattered light within the instrument itself is a problem. By dispersing the light twice this scattered light can be reduced. Over 32 seconds SBUV scans from 250 nm to 400 nm in 12 steps. Because more light is needed to measure the weak signal at short wavelengths, SBUV only measures along the orbit track, rather than scanning from side to side as TOMS does to cover the entire Earth.

*Orbit*

The Nimbus 7, ADEOS, Earth-Probe, Aura, and NPP satellites were all in sun-synchronous polar orbits. The nearly circular orbit is oriented perpendicular to the plane of the Earth's orbit around the Sun such that the satellite comes over the south pole of the Earth toward the equator; crosses the equator near local noon; and then passes over the north pole onto the nightside of the Earth. The satellite crosses the equator again on the nightside at near midnight local time. By the time the satellite comes back onto the dayside, the Earth has rotated for approximately 90 minutes and the satellite passes over a point at the equator that is 27 degrees of latitude to the west of the previous orbit, but again at local noon. In this way, the satellite orbits l5 times per day, fixed relative to the Sun, and the Earth rotates underneath so that the satellite sees the whole of the surface of the Earth within a 24-hour period.

This is a qualitative description of the orbits. Actually, for the purpose of orbit stability, the satellite does not pass exactly over the pole. A sun synchronous orbit requires an orbital inclination of approximately 98 degrees, which gives a maximum orbit latitude of about 80 degrees. A slightly inclined orbit precesses just enough to stay exactly in the noon plane over the course of the year. From this orbit TOMS can see the pole itself by scanning to the far right or left. The Meteor 3 spacecraft was in a polar orbit but was not Sun synchronous. Its Equator-crossing time drifted from near noon to near sunset and back to near noon in a 220-day cycle. The NOAA series of satellites carrying SBUV/2 instruments were also in sun synchronous orbits, but ones that drifted slowly away from noon over a few years.

*Geometry and Timing*

The instrument field of view for TOMS is 3 x 3 degrees. At an altitude of 950 km for Nimbus 7, this projects to a nadir spot size on the surface of 50 km by 50 km. Earth-Probe was launched initially into a 500 km orbit. This resulted in a nadir spot size of 26 km. In December of 1997, it was boosted to an altitude of 740 km, increasing the nadir spot size to 40 km.

For each of the TOMS instruments, a mirror scans perpendicular to the orbital plane in 35 steps of 3 degrees. The scan angles range from 51 degrees on the right side of spacecraft nadir to 51 degrees on the left (relative to the direction of flight). At the end of the scan, the mirror returns to the first position and begins another scan. For Nimbus 7, the cross-track scans from consecutive orbits overlapped, creating a completely filled global map of the sunlit part of the Earth each day. The lower altitude of the Earth-Probe TOMS results in small areas between orbits near the Equator where no measurements are made. The location of these gaps shifts from day to day so that no place fails to be measured over the span of a few days.

During the cross-track scan, each of the 35 measurement locations is observed for 200 milli-seconds. The total duration time for a single scan is 7.8 s, during which time the satellite travels approximately 40 km. One orbit consists of nearly 400 cross-track scans or 13,000 measurements. Fifteen orbits result in about 190,000 measurements of total ozone every day. SBUV is similar to TOMS but does not scan. SBUV looks only at a 200 km square field of view directly beneath the spacecraft.

The imaging instruments, OMI and OMPS, project an entire strip of the Earth onto a CCD detector. As the satellite moves this strip maps out the Earth. This is known as a push-broom system. The images strip (x direction on the CCD) is also dispersed in wavelength (in the y direction on the CCD).

## Some Results from TOMS Measurements

*Ozone Maps*

The original purpose for building TOMS was its capability to map global ozone on a daily basis to help understand its relationship to changes in the meteorology of the atmosphere. The problem of the relationship of total ozone to meteorology goes back to Dobson in the 1920s. Dobson had six of his spectrophotometers built and distributed throughout Europe to examine this problem. He found that when a high-pressure system was present, ozone was low; and when a low-pressure system was present, ozone was high. TOMS was designed to map the entire sunlit portion of the globe in a single day (see Figure 2).

When the discovery of the ozone hole was announced in 1985, TOMS was immediately used to map the extent of the ozone-depleted region (Figure 3). Using TOMS, the daily progress of the hole could be followed. These maps demonstrated how the depleted region rotated around the pole, was distorted by the meteorology, and was finally broken up by a series of wave events that eroded the polar vortex. TOMS can produce similar maps of ozone over the Arctic polar region (not shown). The maps clearly demonstrate the day-to-day and year-to-year variability of ozone over the Arctic. As global warming changes the dynamics of the atmosphere, such maps will show the effect on the global ozone distribution.

*Ozone Trends*

While the Nimbus 7 TOMS instrument was originally designed to map ozone on a daily basis to study day-to-day variability in total ozone, by the 1990's TOMS data were also being used as part of a satellite-based measurement system for detecting long-term trends in stratospheric ozone. A number of features in the TOMS measurements made it possible to detect calibration drifts of the instrument well enough that small changes in ozone could be detected - trends as small as 1% per decade (2 sigma).

More recently a unified long term time series of global ozone, a Merged Ozone Data Set, has been created using data from multiple SBUV instruments. Data from the series of 9 NASA and NOAA SBUV(/2) instruments were re-processed with a coherent calibration covering the period 1970-1972 and 1979-2012. The advantage of concentrating on SBUV instruments is the long time span covered by instruments of similar design and their high accuracy. Because the profile retrieval uses wavelengths that have high sensitivity to ozone, the total column ozone derived by integrating the retrieved profile is estimated to have accuracy better than 1%.

Figure 4 compares ozone measured by satellite instruments since 1979 with that measured by ground-based instruments in Arosa, Switzerland since 1926. This puts the current ozone decrease in the context of the historical record and emphasizes that both satellites and ground based instruments are seeing the same ozone changes. Satellite instruments are necessary to measure global ozone change and show that such ozone decreases are not a local phenomenon.

*Dust and Smoke*

TOMS measures the reflectivity of the Earth-atmosphere system at several wavelengths not absorbed by ozone. If the atmosphere were perfectly clean, the backscattered radiation received by the satellite could be determined from a Rayleigh scattering calculation that would predict a specific ratio of radiation between two wavelengths. Aerosols disturb this ratio in a predictable manner; one direction for absorbing aerosols, the opposite for non-absorbing aerosols. Using these facts, the TOMS data has been used to determine an 'aerosol index'. Reasonable assumptions about the nature of the aerosols lead to global maps of the spread of dust from deserts and smoke from biomass burning in Africa and South America. There are now 40 years' worth of such data from the TOMS instruments and now OMI and OMPS.

Figure 5 is a map of the aerosol index for March 10, 2006, showing dust from deserts in China being carried across the Pacific. Similar maps are used to track dust from the Sahara crossing the Atlantic, smoke from forest fires, and ash from volcanoes.

*Reflectivity*

The basic TOMS measurement is of reflected radiation at six wavelengths. The longer of these wavelengths are not affected by ozone absorption and are thus a measure of the reflectivity of the atmosphere in the ultraviolet. The algorithm calculates the expected backscattered radiation from a pure Rayleigh-scattering atmosphere. Deviations from this expectation are driven primarily by clouds and secondarily by aerosols. The deviation caused by clouds, which are different spectrally than the deviation caused by aerosols, can be represented as a percentage reflectivity.

The scene reflectivities of the Earth at blue and ultraviolet (UV) wavelengths are low over most surfaces (except ice and snow), and are almost independent of the seasonal changes in vegetation on land and in the oceans. This makes it ideal for examining changes in radiation reflected back to space from changes in cloud and aerosol amounts, especially as affected by the start of climate change. The aerosol index shown in Figure 5 is overlaid onto a map of cloud reflectivity.

*Volcanoes*

When a volcano erupts it releases large quantities of ash and sulfur dioxide, both of which can be mapped by TOMS, OMI, and the OMPS total column mapper. Sulfur dioxide (SO2) is an even stronger absorber of ultraviolet light than ozone, but with a very different spectral signature. When El Chichon erupted in 1982, SO2 absorption produced a false apparent enhancement of TOMS ozone. When this was realized, the TOMS algorithm was modified to distinguish ozone from SO2. Figure 6 shows a plume of SO2 from the eruption of the Grimsvotn volcano in Iceland on May 21, 2011. TOMS (and OMI and OMPS) can easily track plumes of SO2 from volcanic eruptions. The effect of SO2 from a volcano is usually short lived because SO2 is converted rapidly to sulfuric acid aerosols. Because they have full spectral data, OMI and OMPS can even detect SO2 from power plants and other pollution sources in the lower troposphere.

*UV at Surface*

Many of the concerns about ozone depletion are related to the increase in ultraviolet radiation received at the surface of the Earth. Increases in UV would lead to increased incidence in skin cancer (among humans) and possible damage to the biosphere. TOMS measures the outgoing, absorbed UV radiation and the reflectivity due to clouds and aerosols. These data can be combined with a radiative transfer model to estimate the UV flux at the surface daily over the globe. TOMS and OMI data have been used to generate detailed maps of average UV flux over the Earth.

*Tropospheric Ozone*

TOMS measures the total column amount of ozone with some adjustments for the inefficiency of the penetration of UV sunlight into the boundary layer. In the tropics, most of the variability of total ozone around a circle of constant latitude is in the troposphere rather than the stratosphere. Several schemes have been developed for taking advantage of this property of the total ozone measurements to derive tropical tropospheric ozone column amounts. The first of these combined the TOMS measurements with concurrent measurements from the SAGE (Stratospheric Aerosol and Gas Experiment) occultation measurements of the stratospheric amount. The difference between TOMS total column ozone and SAGE stratospheric ozone will be the amount of ozone in the troposphere. Similarly, OMI measurements of ozone have been combined with ozone profile measurements by MLS (the microwave limb sounder), also on the Aura spacecraft, to give very accurate measurements of tropospheric ozone. Alternatively, the stratospheric ozone amount can be estimated directly from TOMS measurements above the location of the highest clouds. That amount can be subtracted from the total ozone, yielding a tropical map of column tropospheric ozone.

Application of these techniques for deriving tropical tropospheric ozone gives maps showing the ozone generated by the products of biomass burning. The ozone development and transport can be seen far downwind from the burning source.

**Summary and Future of TOMS and SBUV Measurements**

We now have more than 40 years' worth of global total ozone data from TOMS instruments, and ozone profile measurements from SBUV. The Earth Probe TOMS was the last of the series, but OMI on Aura and the OMPS total column mapper have continued the measurement series. The SBUV/2 instrument on NOAA 19 is the last of the SBUV series, but the OMPS nadir profiler continues the ozone profile measurements. OMI and the OMPS instruments represent a new generation of ozone-mapping instruments, instruments that use charge-coupled-device arrays to image the Earth at a large number of wavelengths. These instruments allow us to continue the long time series of ozone measurements to document the expected recovery of the Earth's ozone layer.

**Further Reading**

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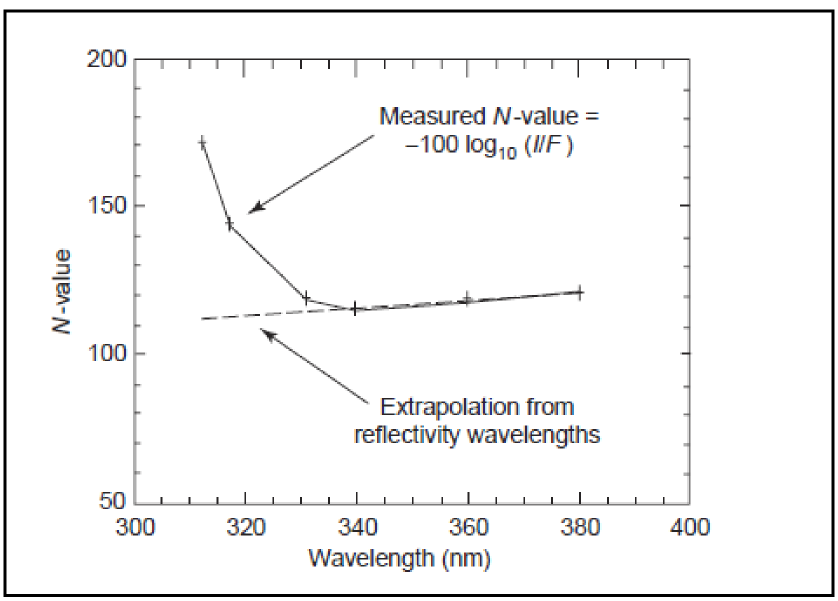

Figure 1. Illustration of the dependence of N-value on wavelength. The N-values for all of the TOMS measurements for one day (1 January 1985) within one degree of latitude of 351N were averaged to make the plot. The linear straight line is fitted to the three longest wavelengths to illustrate an extrapolation to shorter wavelengths. The actual TOMS algorithm uses a full radiative transfer code to determine this extrapolation. The difference between the short-wavelength N-values and the extrapolation represents the absorption by ozone.

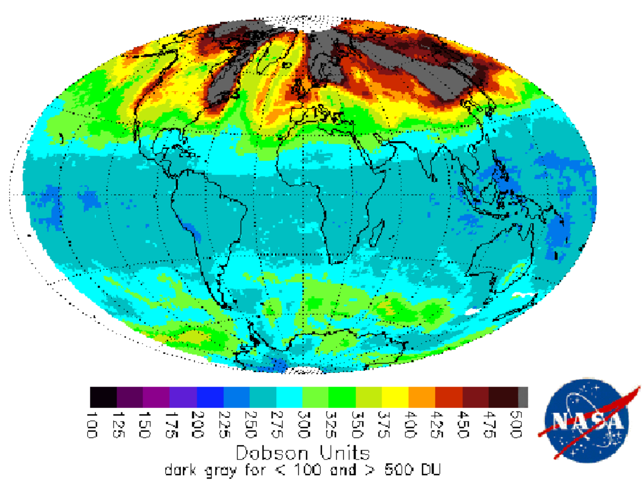

Figure 2. Global ozone mapped by TOMS on March 16, 1979, soon after launch. Note regions of very high ozone in the arctic and low ozone near the equator.

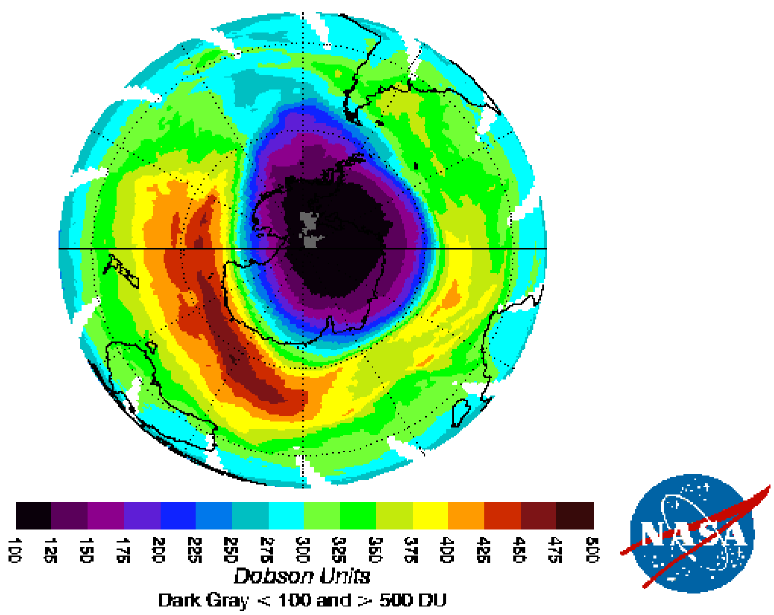


Figure 3. Single-day (5 October 2000) ozone map over the Antarctic. Dark blue to purple shades near pole indicate where total ozone amount is less than 220 DU, a common definition for the region of the Antarctic ozone hole. The map is a polar orthographic projection with the south pole at the center and the equator at the outer boundary.

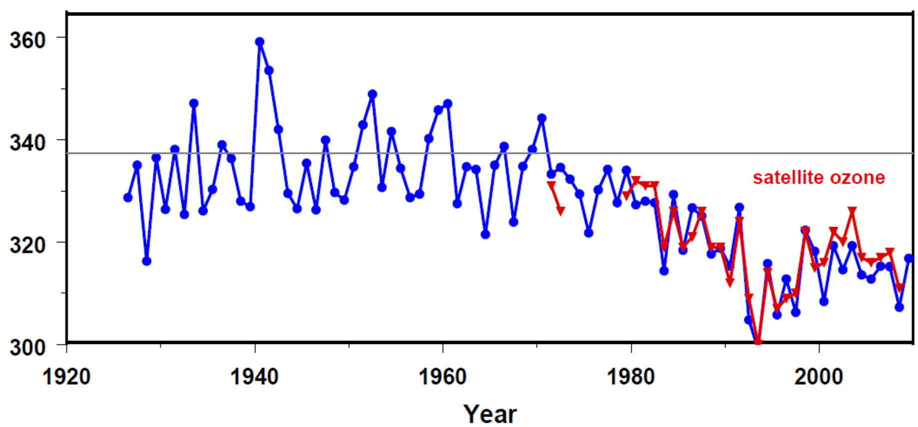


Figure 4. The long term change in ozone as measured by a series of satellite instruments (in red) compared with ozone measured by ground based instruments in Switzerland (in blue) since 1926.

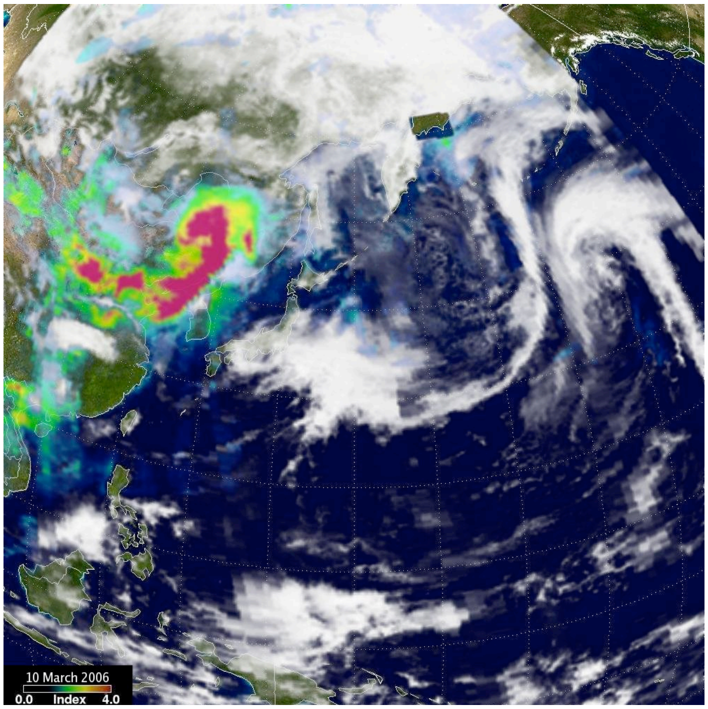


Figure 5. Aerosol index measured by OMI on March 10, 2006 showing dust blowing out of deserts in China. Here aerosol index is mapped with reflectivity over a world map.

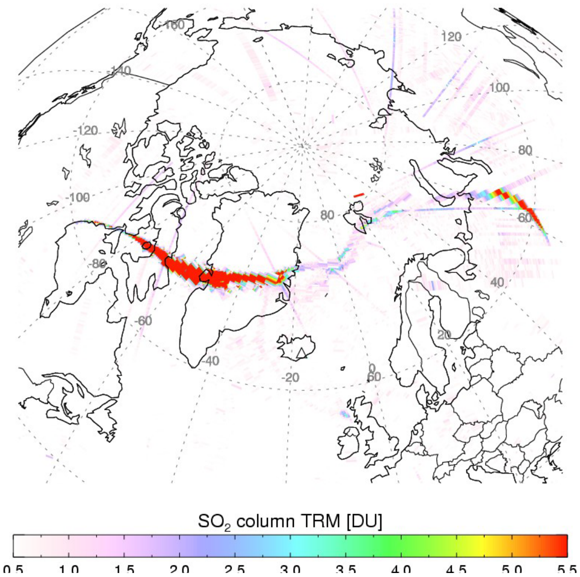


Figure 6. An OMI map of sulfur dioxide shows that SO2 from the May 21, 2011 eruption of the Grimsvotn volcano in Iceland has been transported over Greenland two days later.