Stratospheric ozone, tropospheric ozone, and the case for continuing ozone research

NASA's Earth Science Research and Analysis program (R&A) collects and analyzes ozone data from Earth-observing satellites, airborne campaigns and surface-based instruments to advance our understanding of stratospheric and tropospheric ozone. These data allow scientists to determine the distribution, physical and chemical properties of ozone throughout the atmosphere and how it affects Earth's climate and human health.

Ozone, climate and health

Whether it's in the stratosphere or the troposphere, ozone impacts our environment, health and safety. Depending on its elevation in the atmosphere, however, it can have a positive or negative effect on radiative forcing and health. For example, stratospheric ozone (~10-50km) is typically seen as "good" ozone, whereas tropospheric ozone (~7-20km), or ozone near the boundary layer where humans live and breathe, is typically seen as "bad" ozone.

- <u>Stratospheric ozone, climate and health:</u> Naturally occurring stratospheric ozone acts as a protective layer, absorbing harmful solar radiation that damages our skin and eyes and the cell structure of plants. Human-made chemical compounds that contain chlorine and other halons react with the sun to destroy stratospheric ozone, limiting its ability to absorb harmful UV rays. This, in turn, increases our chances of being exposed to dangerous levels of solar radiation and also causes the stratosphere to cool, since fewer ozone molecules exist to absorb the sun's radiation.
- <u>Tropospheric ozone, climate and health:</u> Although ozone occurs naturally in small quantities in the lower troposphere, unhealthy levels of tropospheric ozone are created when high levels of human-made pollutants, such nitrogen oxides (NO_x), and volatile organic compounds (VOCs) react with solar radiation. These excess ozone molecules act as pollutants and greenhouse gases, creating harmful smog that damages our lungs and contributes to higher temperatures near Earth's surface. High levels of ozone in the lower troposphere cause a variety of respiratory health problems, including chest pain, coughing and difficulty breathing. It also damages plants and agriculture, reducing crop yields in some areas by as much as 50%. However, in the upper troposphere, ozone can have a positive effect on pollution: it reacts to form the hydroxyl radical (OH), which scrubs the atmosphere of pollutants like methane.

Integrated ozone measurements

Because stratospheric and tropospheric ozone are transported worldwide, we need a way to monitor them globally. Earth-observing satellites from NASA, our domestic and international partners provide space-based regional and global observations on the distribution and transportation of ozone at all altitudes. Complementary air- and surface-based measurements taken around the world help validate these datasets, ensuring a complete and accurate picture of global ozone.

- <u>Surface-based measurements</u>: Surface-based measurements provide the most accurate picture of ozone and its precursors near the surface of the Earth. They use in situ chemical observations, ground-based lidar and ozonesondes (meteorological balloons that carry ozone sensors) to provide data and critical on-the-ground validation measurements for airborne campaigns and satellites. These data, however, offer only a limited view of ozone as the instruments are sparsely distributed, constrained to measurements primarily in the troposphere and provide limited information on the vertical distribution of ozone.
- <u>Airborne measurements</u>: Airborne measurements provide the best information on the vertical distribution of ozone and its precursors in the atmosphere. Airborne campaigns use in situ chemical observations, radar, limb-scanning instruments and dropsondes to collect information that provide critical validation measurements for satellites. Although these campaigns are incredibly data-rich, they offer only a limited view of ozone, as the one-off campaigns are constrained in their regional coverage and confined mostly to upper tropospheric and lower stratospheric measurements. They are also relatively expensive.
- <u>Satellite measurements</u>: Satellite observations provide the broad spatial and temporal coverage necessary for consistent, long-term datasets. Scientists use these datasets to identify trends and draw conclusions about the seasonal and inter-annual variations of ozone and its precursors in the atmosphere. Space-

based instruments use reflected and transmitted light across the electromagnetic spectrum to measure ozone and its precursors. These data, however, are at a much coarser resolution than airborne or surface-based measurements and are limited primarily to the stratosphere. Therefore, they require the additional data from surface- and air-based measurements to provide a complete picture of global ozone.

Advancing ozone science

Since the 1970s, NASA's Earth Science Research and Analysis Program has been funding research across different continents, countries and science centers to advance our understanding of ozone in the atmosphere. Since that time, NASA and its partners have discovered important physical and chemical properties of stratospheric and tropospheric ozone, as well as areas for future research.

Ozone up high: Stratospheric ozone

Current NASA assets that measure ozone in the stratosphere include**: Aura satellite - Ozone Monitoring Instrument (OMI)**, UV/vis; **Aura satellite - Microwave Limb Sounder (MLS)**, microwave; **Suomi-NPP satellite - Ozone Mapping Profiler Suite (OMPS)** UV/vis; **Aqua satellite - Atmospheric Infrared Sounder (AIRS)**, IR; **International Space Station - Stratospheric Aerosol and Gas Experiment III (SAGE III)**, UV/vis

- What we knew: Researchers with the British Antarctic Survey first discovered the thinning of the stratospheric ozone layer using a ground-based Dobson Spectrophotometer at the Halley Bay Observatory in the 1950s (figure 1). After this initial discovery, scientists at NASA and other international space agencies launched satellites to directly measure the thinning stratospheric ozone layer and what later came to be known as the Antarctic Ozone Hole. These early ozone monitoring instruments were limited to nadir-scanning views, which provided total ozone measurements, but gave little insight into the vertical distribution of ozone in the atmosphere—especially the lower troposphere. NASA's Total Ozone Mapping Spectrometer (TOMS) on the Nimbus-7 and later the Meteor-3 satellite further confirmed the thinning stratospheric ozone layer, as well as the presence of human-made chemical precursors that led to it (figures 2 and 3). Scientists then began devising ways to halt the troubling trend, resulting in the establishment of the Montreal Protocol in 1987.

- What we know: Today, NASA's Aura satellite has greatly enhanced our modern understanding of global stratospheric ozone. Launched in 2004, Aura's series of ozone monitoring instruments have refined the ways in which we are able to detect total ozone concentrations (OMI), as well as the vertical distribution of ozone (MLS). These tools, along with complementary airborne campaigns and ground-based measurements, have now begun to show the Ozone Hole's recovery (figure 4), which is largely attributed to the successful Montreal Protocol and the limiting of CFCs and other ozone-destroying halons. Today, we have a much better grasp of which chemical compounds will react to destroy stratospheric ozone, as well as its seasonal trends, thanks to the long-term datasets afforded by NASA's ozone monitoring satellites.

- What we still need to figure out: To ensure the stratospheric ozone layer's continued recovery, it is necessary to maintain NASA's stratospheric ozone measurements. NASA's OMPS instrument on the US/Finnish Suomi-NPP satellite is designed to track the Hole's progress, offering daily total atmospheric ozone column measurements and 15km to 60km vertical ozone measurements. It is still too early to tell whether our efforts to curb the thinning of the stratospheric ozone layer are as effective or as long-lasting as we hope and whether its recovery is due to human-made or natural changes. For example, recent shifts in the Quasi-Biennial Oscillation (QBO) have led some researchers to believe that natural causes may be helping to further expedite the healing of the Ozone Hole (figure 5). Furthermore, new chemicals, such as dichloromethane, continue to be invented and introduced that could potentially reverse the small amount of progress made in recent decades.

Ozone down low: Tropospheric ozone

Current NASA assets that measure ozone in the troposphere include: **Aura satellite - Tropospheric Emissions Spectrometer (TES)**, **Aura satellite - Microwave Limb Sounder (MLS)**, IR; **Ozonesondes**, which can take vertical profiles and measure ozone chemically; and **ground-based systems**, which measure ozone chemically and with lidar technology.

- What we knew: Despite the smog-inducing ozone that used to blanket Los Angeles, incomplete measurements of tropospheric ozone before the 1970s led scientists to believe that the lower troposphere was relatively ozone free. Without space-based measurements, scientists relied on sparsely distributed ground-based systems that only provided snapshots of tropospheric ozone and were further complicated by its relatively short lifespan lower in the atmosphere. These measurements led scientists to believe that tropospheric ozone was relatively isolated. However, with the launch of NASA's TOMS instrument in 1978, scientists were able to indirectly measure the amount of ozone in the troposphere by subtracting stratospheric ozone from total ozone measurements (figure 6). In addition, the introduction of advanced computer modeling further revealed that ozone was collecting in the troposphere in larger quantities than previously believed.
- What we know: We now have a much clearer picture of the distribution of tropospheric ozone thanks to the TES instrument aboard NASA's Aura satellite. TES employs nadir- and limb-scanning views to directly measure ozone and its precursors using infrared radiation. Today, scientists understand that tropospheric ozone, like stratospheric ozone, can travel thousands of miles and is not isolated to an emission source. In fact, some of the most hazardous levels of tropospheric ozone can be found miles from the source of pollution downwind from more industrial emission centers. For example, despite the western United States' efforts to decrease its tropospheric ozone levels through reductions in NO_x emissions, tropospheric ozone levels there remained high due to transported pollution from Asia (figure 7). In addition, we now also understand that some tropospheric ozone can be good when it's located in the upper troposphere. Up there, it helps to form OH, a "detergent molecule" that scrubs the atmosphere of other pollutants.
- What we still need to figure out: We are just beginning to scratch the surface of the complex chemical and dynamic properties of tropospheric ozone. Because unhealthy levels can form from human-induced and natural causes, scientists need a way to identify chemical signatures so that they can determine how best to mitigate hazardous levels when they arise. Also, because the distribution of tropospheric ozone is so dependent on atmospheric circulation and weather patterns, scientists need a better way to measure how much tropospheric ozone was produced *in situ* and how much was transported from (or into) the stratosphere through injection. The Tropospheric Emissions: Monitoring of Pollution (TEMPO) satellite, a geostationary satellite set to launch in 2018 that will hover over the United States, will provide more detailed information on the dynamics and distribution of tropospheric ozone in the future.

The future of ozone research at NASA

In the future, NASA will continue its efforts to research stratospheric and tropospheric ozone in a holistic manner, integrating datasets from across NASA facilities, domestic and international partners, and across instrument platforms. Similar to how water is now viewed as an integrated system, no longer separated into surface- and groundwater, ozone too will be researched as a whole system. With the onset of geostationary satellites over the United States and around the world, we will begin to discover with more precision how ozone is transported from the stratosphere into the troposphere, and vice versa. However, as satellites progress, it is critical that we maintain our air- and surface-based measurements to ensure these global measurements remain accurate.

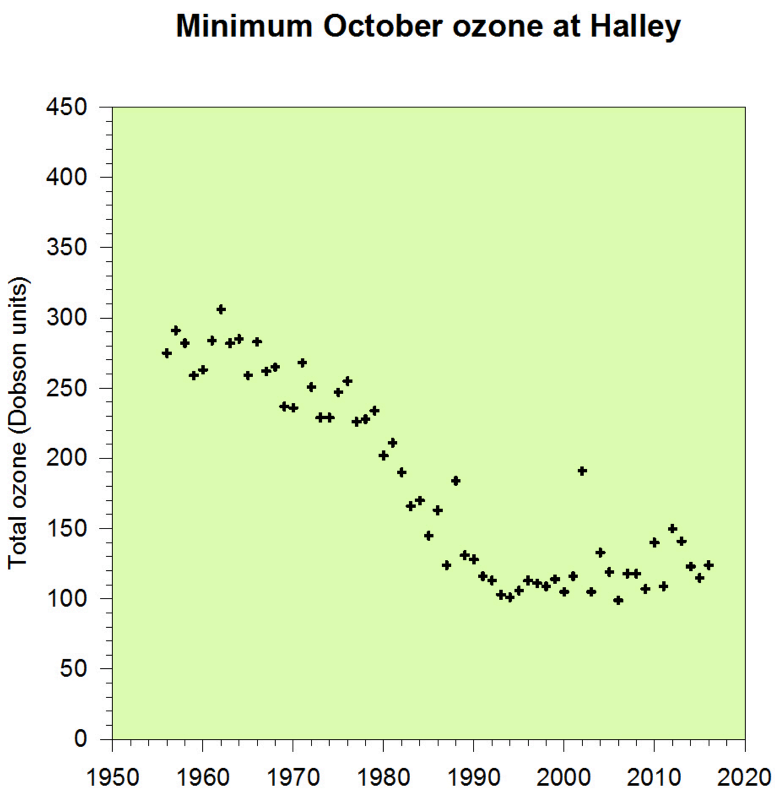
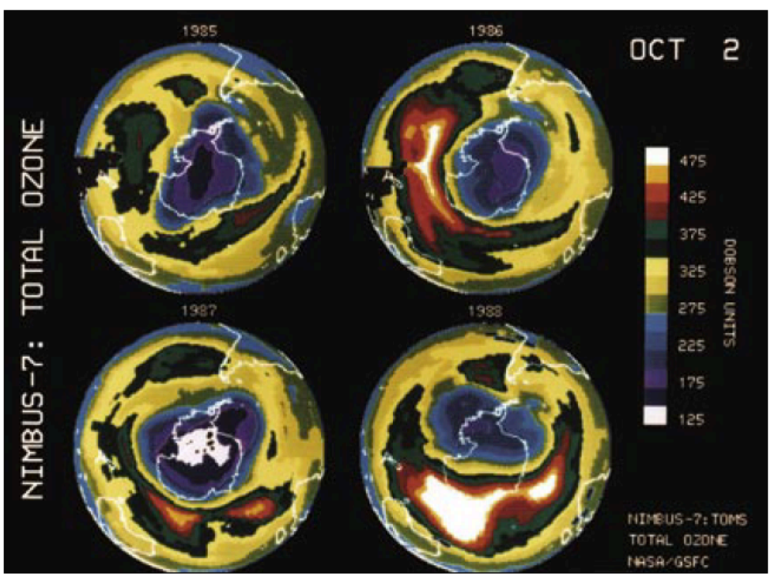


Figure 1. *Minimum October ozone measurements (Dobson Units) from 1956 to 2017. Image credit: https://legacy.bas.ac.uk/met/jds/ozone/*



Southern Hemisphere ozone cover 1985–88, as mapped by Nimbus 7: TOMS. (NASA Image No. 89-HC-10)

Figure 2. *Total ozone measurements from NASA's Nimbus 7/TOMS instrument from 1985-1988. Image credit: The Case of Ozone Depletion, NASA and the Environment*

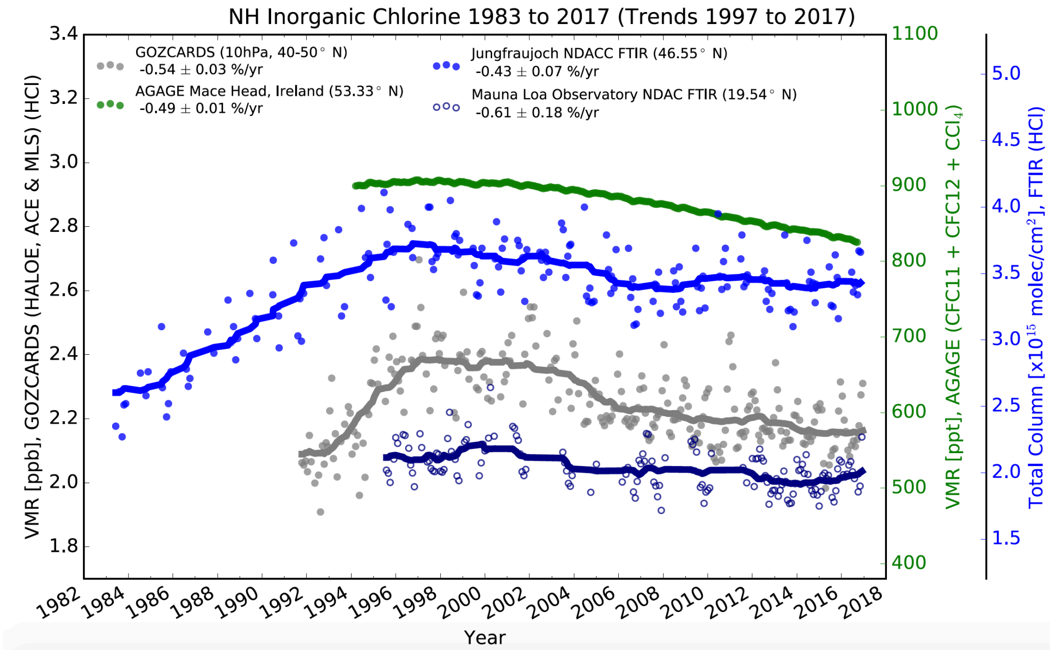


Figure 3*. NH inorganic chlorine levels from 1983-2017. Image credit: Ken Jucks et al.*

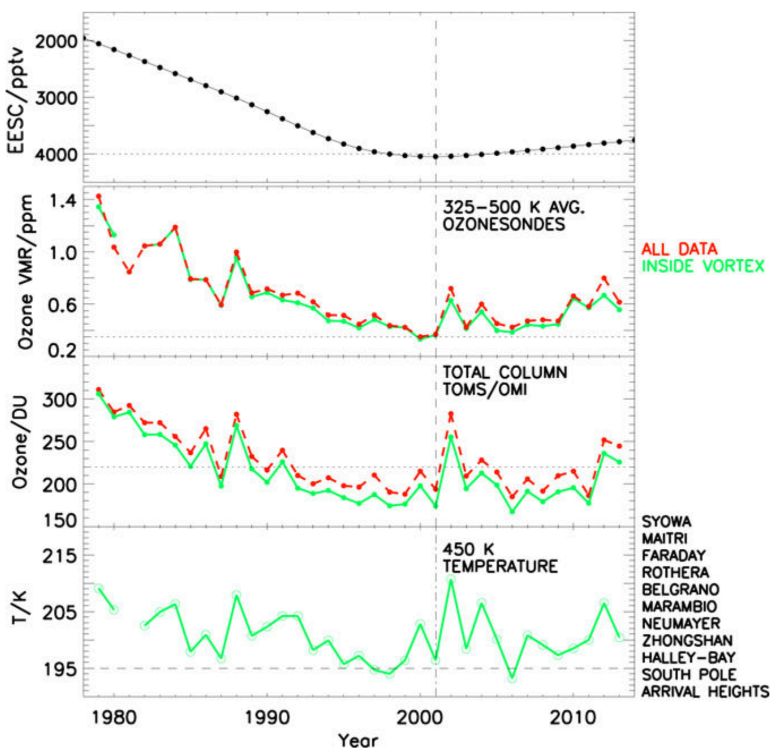


Figure 4. *Total ozone column measurements from the TOMS/OMI instruments showing the tentative recovery of the Ozone Hole. Image credit:* *https://www.nature.com/articles/s41598-017-00722-7*

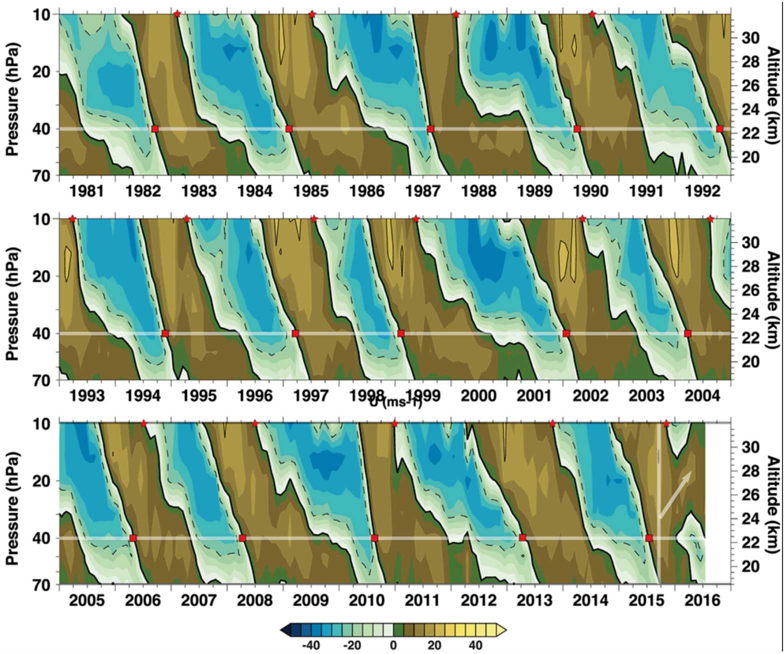


Figure 5. Chang in the quasi biennial oscillation in 2015-2016. Image credit: http://onlinelibrary.wiley.com/doi/10.1002/2016GL070373/full

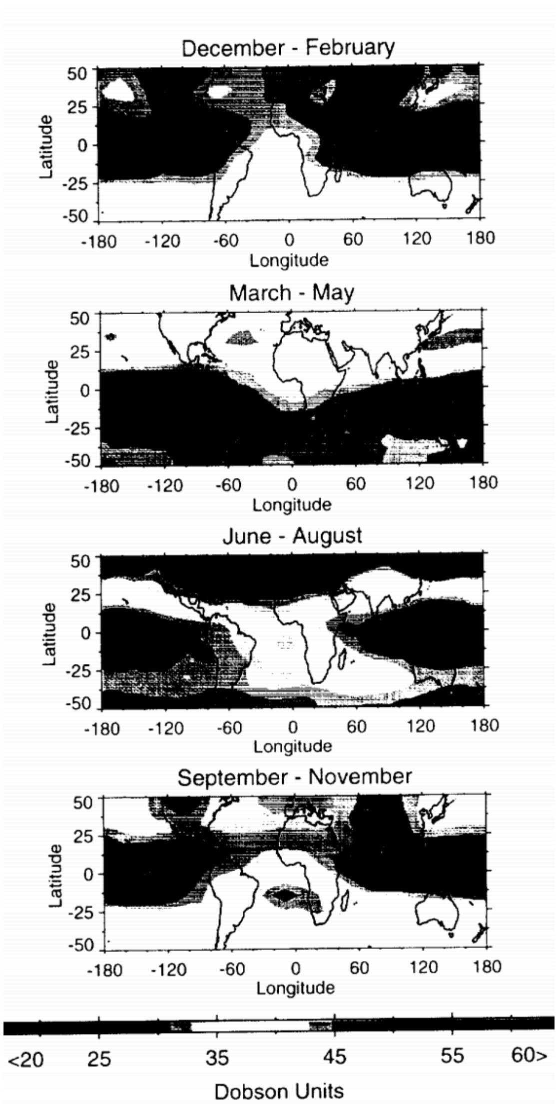


Figure 6. Seasonal climatology of tropospheric ozone derived from the TOMS and SAGE datasets using the tropospheric ozone residual method. Image credit: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20010021137.pdf

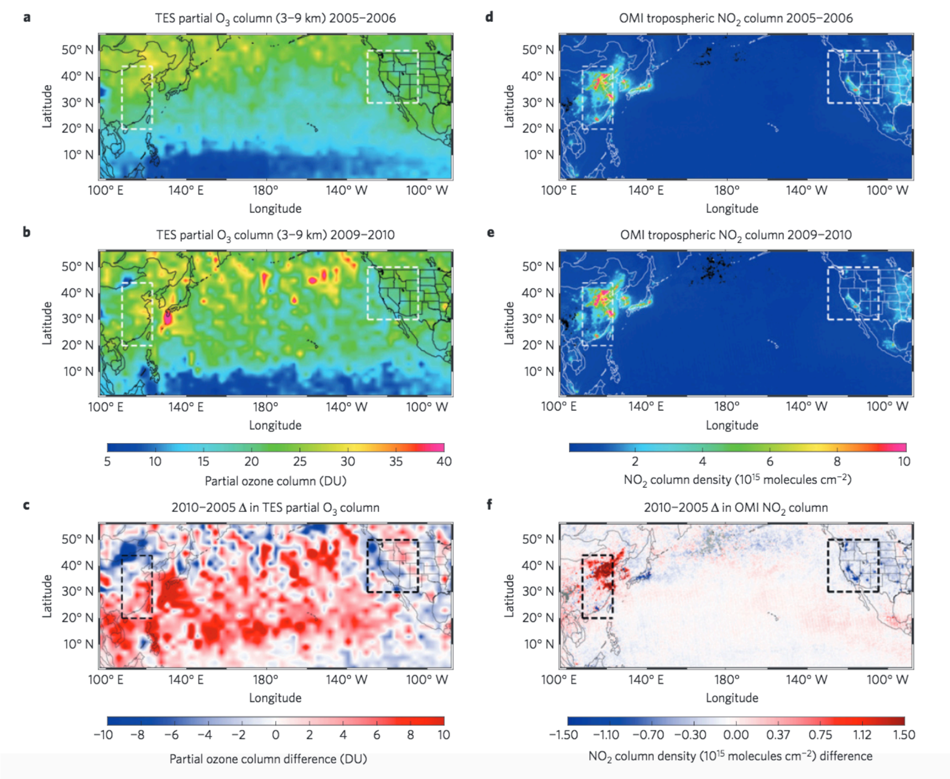


Figure 7. *Summertime tropospheric O3 and NO2 distributions for 2005-2006 and 2009-2010 from TES/Aura and OMI/Aura. Image credit: http://www.readcube.com/articles/10.1038/ngeo2493*