It is the trace composition of the atmosphere that governs the chemistry of the lower and middle atmosphere and to a large extent the climate of our planet. Accurately determining the abundance of species such as ozone (~1 ppm), nitrogen dioxide (~1 ppb), or bromine monoxide (~1 ppt) presents a large challenge. Further determining how they vary in space and time on a global scale is even more daunting. A global view of the atmospheric trace gas and aerosol composition can only be achieved from space via remote sensing. Balloons, and later rockets, were the first

Fig. 1. Illustration of the Odin satellite. The limb-scanning pattern is shown.

Into year 11 of a 2-yr mission, OSIRIS is redefining how limb-scattered sunlight can be used to probe the atmosphere, even into the upper troposphere.
platforms to provide remote sensing observations aloft. The 1960s and 1970s saw the first generation of satellite instruments measuring meteorological and composition parameters. Rapid advances in instrument technology and computing capabilities in the 1980s and 1990s led to an explosion in resolution, spectral range, and downlinking capability. For example, the advent of the array detector in the 1980s meant entire spectra could be measured simultaneously. Capitalizing on these advances, the last decade has seen an unprecedented number of missions with observation of atmospheric composition as a primary goal.

The Odin satellite represents one such example. Odin is a small satellite mission sponsored by Sweden (Swedish National Space Board), Canada (Canadian Space Agency), France (Centre National d’Etudes Spatiales), and Finland (National Technology Agency of Finland). Since May 2007, Odin has also received support as a European Space Agency Third Party Mission. The Odin concept dates back to 1990 and was the result of discussions between radio astronomers and atmospheric scientists looking for a possible synergy between their respective observing needs (Murtagh et al. 2002). An instrument sensitive to radiation in the microwave region—later to become the SMR (acronyms defined in the appendix)—was identified as a useful choice for both groups. A second instrument, OSIRIS, was added to expand the atmospheric observing capabilities of the mission. Thus Odin, formulated as a joint atmospheric and astronomy instrument, was packed inside a converted Russian ICBM and successfully launched from Svobodny in eastern Siberia on 20 February 2001 and inserted into a low-Earth, sun-synchronous orbit. From launch to mid-2007, Odin was utilized in a 50:50 astronomy–atmospheric time-sharing arrangement. After this, Odin became a purely atmospheric mission. In atmospheric mode, Odin is pointed toward the limb, or horizon, of Earth’s atmosphere. Looking at the limb increases the path of the radiation through the atmosphere, thereby increasing signal levels, and provides high vertical resolution. In this geometry, SMR measures radiation emitted by the atmosphere and OSIRIS measures sunlight scattered by the atmosphere. The entire spacecraft continuously nodds up and down through an angle of 1°–2°, and this provides information on the vertical structure of the atmospheric composition. A graphic of Odin scanning the limb is shown in Fig. 1 (see title page), and Odin specifications are provided in Table 1. Odin crosses the equator at around 1830 LST (and 0630 LST), which means observations are generally made near twilight. This choice of crossing times was made in order to maximize the power to the solar panels over an orbit.

The original science objectives of the Odin atmospheric mission focused on stratospheric and mesospheric ozone science, reactive nitrogen and halogen species that impact ozone, and coupling between the atmospheric layers (Murtagh et al. 2002). While OSIRIS has largely achieved these goals, some of its important science contributions are from applications barely envisioned at the time of launch, including its ability to measure into the upper troposphere and most recently new airglow emissions in the mesosphere.

**Table 1. Odin satellite and OSIRIS instrument properties.**

| Instrument | Launch date | Launch vehicle | Orbit | Inclination | Descending node | Platform | Size | Power | Mass | Vertical range | Imaging
|------------|-------------|----------------|-------|-------------|----------------|---------|------|-------|------|---------------|---------
| Odin       | 20 Feb 2001 | Start-1 rocket from Svobodny, Russia | Sun synchronous, circular, 610 km altitude | 97° | ~630 LST (see Fig. 4) | Three-axis stabilized | 2 m high, 1.1 m wide | 340 W | 210 kg | 2 km | 0.01–2 s |
| OSIRIS     | 2001         | N/A            | N/A   | N/A         | N/A            | N/A     | N/A  | N/A   | N/A  | N/A           | N/A     |

**THE OSIRIS INSTRUMENT.** OSIRIS measures sunlight scattered by atmospheric molecules and particles in the near-UV, visible, and near-IR regions of the electromagnetic spectrum. It is pointed toward the limb, or horizon, of the atmosphere in the forward-looking direction (in the orbit plane). The use of limb-scattered light as a source, the so-called limb-scatter technique (see sidebar on the limb-scatter remote sensing technique for a description), allows for continuous measuring on the day side of the orbit. It may be contrasted with the solar occultation technique in which the sun is below the limb and thereby limited to two profiles per orbit. A photograph and a wireframe diagram of OSIRIS are shown in Fig. 2.
OSIRIS is composed of two optically independent components, the OS and the IR imager. See Table 1 for specifications. DAS is a grating spectrometer that operates simultaneously in both first and second order using an order-sorting filter to prevent mixing.

The detector is a two-dimensional array CCD. The nominal spectral resolution is 1 nm with a sampling interval of 0.4 nm. The OSIRIS instrument is oriented in the horizontal and gives a horizontal resolution of 40 km. The effective vertical resolution is 1–2 km after accounting for integration time. A series of baffles and vanes are used to reduce stray light, and the resultant stray light levels are small. Data within the region of the order sorters (477–530 nm) are not retained, thereby resulting in a gap in the measured spectra.

The IR imager is a three-wavelength limb-viewing camera, imaging the atmospheric airglow emissions with two channels near 1.27 m and one at 1.53 m (Degenstein et al. 2003). An image of the entire atmosphere is obtained at each of these channels for microphysical properties are unknown. Perhaps the single largest obstacle encountered in limb scattering is obtaining precise knowledge of where the instrument is pointing. In low-Earth orbit, a pointing error of only 0.01° translates into a tangent height offset of 500 m, which in turn can lead to an error in ozone number density of 10% (Loughman et al. 2003). The atmosphere itself offers little help to determine tangent height since atmospheric features tend to be variable and not well defined. One feature that has been used to evaluate pointing is the peak, or knee, in limb radiances that occurs when the optical depth along the line of sight becomes large (the so-called knee method). Comparing the tangent height at which this occurs to a model-simulated value provides a measure of the pointing accuracy, but this method is ultimately limited by the accuracy of the model and model input parameters. There is no standard solution to this dilemma and so missions thus far have relied on different combinations of engineering and software approaches.

**Table SB1. Summary of past, current, and upcoming limb-scatter missions.**

<table>
<thead>
<tr>
<th>Year</th>
<th>Instrument</th>
<th>Platform</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1963–68</td>
<td>Six-channel photometer</td>
<td>Aircraft (X-1S)</td>
<td>Cunnold et al. (1973)</td>
</tr>
<tr>
<td>1981–89</td>
<td>LVS</td>
<td>Satellite</td>
<td>Barth et al. (1983)</td>
</tr>
<tr>
<td>1983</td>
<td>Five-channel spectrometer</td>
<td>Balloon</td>
<td>McElroy (1988)</td>
</tr>
<tr>
<td>2001</td>
<td>OSIRIS</td>
<td>Satellite</td>
<td>Llewellyn et al. (2002)</td>
</tr>
</tbody>
</table>

*Secondary observing mode, not optimized for limb scatter.

**Fig. SB1. Depiction of limb-scatter geometry. Here, the orbital plane coincides with the terminator (day-night boundary), which is not always the case (LOS is for OSIRIS and SCA is the angle between the incoming solar beam and the LOS).**

**Fig. SB2. (a) Illustration of multiple scattering in limb geometry and the possible scattering scenarios of sunlight before entering the OSIRIS LOS. (b) The difference between optically thin and optically thick scenarios in limb geometry. The extrema in limb-scatter geometry indicates where along the LOS the scattering signal is originating.**
Consequently, there have been several attempts to efficiently model radiative transfer for limb-viewing geometries at optical wavelengths (e.g., Griffioen and Oikarinen 2000, McLinden et al. 2002; Rozanov et al. 2005; Bourassa et al. 2007b) as well as to validate these models (Loughman et al. 2004) against benchmark codes such as the “Siro” backward Monte Carlo model (Oikarinen et al. 1999).

Accurate modeling requires both a realistic treatment of the relevant physics and accurate model input parameters, including profiles of all constituents that scatter or absorb in the spectral region of interest such as the background air number density, trace gases, aerosols, and clouds. Also required is a temperature profile and surface reflectivity. In the context of the limb-scatter retrievals, it is the role of the RT model to simulate the radiances observed by the instrument. Thus, the presence of solar and viewing conditions of the measurement must be used and instrument properties such as spectral and spatial resolutions must be taken into account. An example of a model–measurement comparison is shown in Fig. SB3, in which an OSIRIS spectrum is compared with a simulation from the SaskTRAN model (Bourassa et al. 2007b). This example illustrates how models also provide useful diagnostic information that aid in the interpretation of the observed spectra. Here the contribution to the total signal from the single-scattered, multiply-scattered, and surface-reflected components are shown.

Inversions of the primary data products are carried out for solar zenith angles less than 90°, yielding roughly 800,000 profiles of ozone, NO₂, and aerosol extinction (about 75,000 per year). As is discussed below, there are fewer profiles of BrO—about 55,000—due to a necessary averaging of spectra prior to its inversion. A brief description of selected data products and examples of their application to science are provided below.

Ozone. It is difficult to overstate the importance of ozone in Earth’s atmosphere. At the surface, ozone is a pollutant, harmful to humans and destructive to crops. In the stratosphere, ozone acts to shield the surface below from harmful ultraviolet radiation. Due to the buildup of chlorofluorocarbons and bromine in the atmosphere, a decline in global stratospheric ozone was seen through the 1980s and 1990s with an “ozone hole” forming each spring in the Antarctic. In the wake of the Montreal Protocol and its amendments that banned or phased out chlorofluorocarbons and halons, the decline in stratospheric ozone has slowed, but the ozone hole has not yet recovered (Shepherd and Jonsson 2008).

Inversion of the OSIRIS spectral data allows one to retrieve aerosol extinction, NO₂, and BrO. Each was scaled by a different factor. Ozone in the visible, shown as a dashed line, has been increased by a factor of 100 relative to the UV ozone cross sections.

SOLUTION OF THE RADIATIVE TRANSFER EQUATION IN LIMB GEOMETRY

Radiative transfer models have always been an important tool for the atmospheric science community. Such models provide the link between observation and the atmospheric state and are frequently used within data inversion processes to estimate atmospheric parameters. Thus, not surprisingly, the accuracy of retrieved parameters depends upon the accuracy of the radiative transfer model; for this reason, there has been a large research effort into radiative transfer models, particularly since satellites began observing Earth and the atmosphere.

The propagation and scattering of light within a planetary atmosphere is described by the equation of RT (e.g., Chandraresh 1969). In its most general form, the equation is five dimensional: three dimensions for positional dependence and two for the angular distribution about a point. Most solutions of the radiative transfer equation strive to reduce the number of dimensions to be solved by considering geometries with special symmetric properties. The most common approach is to use plane-parallel geometry (or a flat Earth) with the only possible dependence in the vertical, a reasonable approximation for many applications. Measurements of light scattered from the limb, however, have necessitated the development of a new class of RT models, able to accurately account for the curvature of Earth in a computational manner. Consequently, there have been several recent attempts to efficiently model radiative transfer for limb-viewing geometries at optical wavelengths (e.g., Griffioen and Oikarinen 2000, McLinden et al. 2002; Rozanov et al. 2005, Bourassa et al. 2007b) as well as to validate these models (Loughman et al. 2004) against benchmark codes such as the “Siro” backward Monte Carlo model (Oikarinen et al. 1999).

Accurate modeling requires both a realistic treatment of the relevant physics and accurate model input parameters, including profiles of all constituents that scatter or absorb in the spectral region of interest such as the background air number density, trace gases, aerosols, and clouds. Also required is a temperature profile and surface reflectivity. In the context of the limb-scatter retrievals, it is the role of the RT model to simulate the radiances observed by the instrument. Thus, the presence of solar and viewing conditions of the measurement must be used and instrument properties such as spectral and spatial resolutions must be taken into account. An example of a model–measurement comparison is shown in Fig. SB3, in which an OSIRIS spectrum is compared with a simulation from the SaskTRAN model (Bourassa et al. 2007b). This example illustrates how models also provide useful diagnostic information that aid in the interpretation of the observed spectra. Here the contribution to the total signal from the single-scattered, multiply-scattered, and surface-reflected components are shown.

Fig. SB3. Comparison of OSIRIS- and SaskTRAN-simulated limb radiance at 14 km for scan 06432012 (shown in Fig. 3), including single-scattering, multiple-scattering, and surface-reflected components. (Note that no attempt was made to include absorption by H₂O or O₃ in the model. The spectral order sorter contaminates the measurements between 475 and 530 nm.)
Huggins bands (see Fig. 3) that are much more sensitive to ozone above 30 km (Degenstein et al. 2009). The SaskMART algorithm, a multiplicative algebraic reconstruction technique, iteratively updates the ozone density profile using the ratio of measured to modeled retrieval vectors. The SaskMART ozone retrieval vectors are limb radiances pairs and triplets at wavelengths selected for their contrast in the strength of ozone absorption (see Fig. 3). The modeled vectors are calculated using the SaskTRAN radiative transfer model (Bourassa et al. 2007b). Validation studies of OSIRIS version 5 ozone indicate that the single-profile precision is 3%–6% (Bourassa et al. 2012a) and comparisons with benchmark profiling instruments, such as the SAGE II instrument, indicate agreement to within about 5% throughout the stratosphere (Degenstein et al. 2009). Comparisons in the tropical upper troposphere show significant agreement with in situ measurements and suggest a bias of approximately 5% when ozone is at 50–75 ppb (Cooper et al. 2011). This agreement suggests these data can be used to study the ozone budget of the upper troposphere (Cooper et al. 2011), a region of the atmosphere that is difficult to probe. As an example, consider OSIRIS ozone at 12 km, averaged over the entire mission into the tropics and a minimum over the equatorial Pacific. Similarly, both display a maximum over Africa; however, OSIRIS is 20 ppbv higher and covers a larger area. It is through an examination of these differences that insight into the ozone budget is obtained.

The combination of accuracy and length of the data record suggest OSIRIS ozone could be used to extend the stratospheric ozone time series measured by the SAGE instruments. SAGE I (1979–81) and SAGE II (1984–2005) together represent the standard ozone calculated using a leading-edge chemistry-transport model, GEOS-Chem (www.geos-chem.org) output for the year 2006 (Cooper et al., 2011). The overlap period, 2001–05, indicates small biases between the two instruments. Figure 6 illustrates an initial attempt to merge the two time series. Shown in Fig. 6a are the SAGE I, SAGE II, and OSIRIS zonal, monthly-mean ozone number densities at a latitude of 45°N and an altitude of 42 km. Data following the eruption of Mount Pinatubo are omitted. Figure 6b displays the ozone anomaly of the time series from an average annual cycle. Validation studies of OSIRIS version 5 ozone, in long-term stratospheric ozone time series (WMO 2010). The halogen basis function is the EESC and accounts for chlorine and bromine source gases based on their year of entry into the stratosphere. The complete multiplicative fit and the EESC + constant terms are also plotted in Fig. 6b. In this example, it was not necessary to apply a bias or offset correction to the OSIRIS data, and in general any such correction is small, less than 3%. The inferred trend in ozone through the 1980s based on the fitted EESC coefficient was ~8.3% per decade. Excluding the OSIRIS data does not change this value.

**Table 2. Summary of OSIRIS data products. OS/IRI refers to which component of OSIRIS (OS or IRI) is used. Here, P = number density profiles, (see http://odin-osiris.usask.ca/).**

<table>
<thead>
<tr>
<th>Data product (current version)</th>
<th>Retrieved quantity</th>
<th>OS/IRI</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Level 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limb radiance</td>
<td>6–110 km</td>
<td>OS + IRI</td>
<td>Llewellyn et al. (2004)</td>
</tr>
<tr>
<td><strong>Level 2 - Operational</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₃ (3.0)</td>
<td>P: 10–60 km</td>
<td>OS</td>
<td>Degenstein et al. (2009)</td>
</tr>
<tr>
<td>NO₂ (3.0)</td>
<td>P: 10–46 km</td>
<td>OS</td>
<td>Haley et al. (2004)</td>
</tr>
<tr>
<td>BrO (3.0)</td>
<td>P: 16–36 km</td>
<td>OS</td>
<td>McLinden et al. (2010)</td>
</tr>
<tr>
<td>Aerosol extinction (5.0)</td>
<td>P: 10–35 km</td>
<td>OS</td>
<td>Bourassa et al. (2012b)</td>
</tr>
<tr>
<td><strong>Level 2 - Research</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerosol effective radius</td>
<td>10–35 km</td>
<td>OS + IRI</td>
<td>Bourassa et al. (2008)</td>
</tr>
<tr>
<td>Subvisual cirrus</td>
<td>Detection, UT</td>
<td>IRI</td>
<td>Bourassa et al. (2005)</td>
</tr>
<tr>
<td>Polarization (4.0)*</td>
<td>410 nm, 6–40 km</td>
<td>OS</td>
<td>McLinden et al. (2004)</td>
</tr>
<tr>
<td>OCIO</td>
<td>P: 12–22 km</td>
<td>OS</td>
<td>Kredel et al. (2006)</td>
</tr>
<tr>
<td>NO₃</td>
<td>SCID: 15–45 km</td>
<td>OS</td>
<td>McLinden and Haley (2008)</td>
</tr>
<tr>
<td>Polar stratospheric clouds</td>
<td>Detection, 15–25 km</td>
<td>OS</td>
<td>Sorris et al. (2007)</td>
</tr>
<tr>
<td>Alternated NO₂*</td>
<td>P: 10–40 km</td>
<td>OS</td>
<td>Bourassa et al. (2011)</td>
</tr>
<tr>
<td>Alternated NO₂*</td>
<td>P: 10–41 km</td>
<td>OS</td>
<td>Sorris et al. (2007)</td>
</tr>
<tr>
<td>Alternated O₃, NO₂, aerosol</td>
<td>P: 15–50 km</td>
<td>OS</td>
<td>Takkanen et al. (2008)</td>
</tr>
<tr>
<td>O₃ emission</td>
<td>VER: 40–200 km</td>
<td>IRI</td>
<td>Degenstein et al. (2004)</td>
</tr>
<tr>
<td>O₃</td>
<td>P: 50–80 km</td>
<td>IRI</td>
<td>Degenstein et al. (2005)</td>
</tr>
<tr>
<td>OH</td>
<td>P: 55–90 km</td>
<td>OS</td>
<td>Gattigter et al. (2006)</td>
</tr>
<tr>
<td>O</td>
<td>P: 80–105 km</td>
<td>OS</td>
<td>Sheese et al. (2011)</td>
</tr>
<tr>
<td>NO</td>
<td>P: 80–105 km</td>
<td>OS</td>
<td>Gattigter et al. (2010)</td>
</tr>
<tr>
<td>Polar mesospheric clouds</td>
<td>Detection, 85 km</td>
<td>OS</td>
<td>Petela et al. (2006)</td>
</tr>
<tr>
<td>Polar mesospheric clouds</td>
<td>Size, 85 km</td>
<td>OS</td>
<td>van Savregt et al. (2005)</td>
</tr>
<tr>
<td>Sodium</td>
<td>P: 80–105 km</td>
<td>OS</td>
<td>Gunell et al. (2007)</td>
</tr>
<tr>
<td>Iron oxide</td>
<td>VER: 75–106 km</td>
<td>OS</td>
<td>Evans et al. (2010)</td>
</tr>
<tr>
<td>Temperature</td>
<td>P: 80–106 km</td>
<td>OS</td>
<td>Sheese et al. (2010)</td>
</tr>
<tr>
<td><strong>Level 3 - Derived</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO₂*</td>
<td>P: 16–44 km</td>
<td>Brueshde et al. (2008)</td>
<td></td>
</tr>
<tr>
<td>Br*</td>
<td>P: 16–36 km</td>
<td>McLinden et al. (2010)</td>
<td></td>
</tr>
<tr>
<td>Monthly and zonal means of O₃, NO₂, NO₃, BrO, aerosol extinction</td>
<td><a href="http://odin-osiris.usask.ca/">http://odin-osiris.usask.ca/</a></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Difference in linear polarization of limb radiance between two tangent heights.
* Fast retrieval based on only five wavelengths.
* Improved version.
* Derived from OSIRIS NO₂, Odin/SPA HNO₃ (Urban et al. 2005), and photochemical modeling.
* Derived from OSIRIS BrO and photochemical modeling.

![Figure 4. Characteristics of the OSIRIS dataset as a function of time: (a) SZA at location of tangent point for the descending (morning) half of the orbit (most level 2 data products (including the O₃, NO₂, BrO, and aerosol extinction) can only be retrieved for a SZA of 90° or smaller); (b) local solar time of OSIRIS as it crosses the equator on the descending (morning) half of the orbit; and (c) number of limb scans (level 1) or retrieved profiles (level 2) per day (averaged over one month).](image-url)
Nitrogen dioxide also plays an important role in both tropospheric and stratospheric photochemistry. In the middle stratosphere, nitrogen catalytically destroys ozone, while in the lower stratosphere it acts to tie up chlorine in an unreactive form and is the subject of much research. By lightning is thought to be a substantial source of reactive nitrogen (NO and NO\textsubscript{2}) created from lightning sensors (Fig. 5c), both with peaks in the same general location. This indicates that OSIRIS is detecting enhancements in upper-tropospheric NO\textsubscript{2} due to the production of reactive nitrogen from lightning events. OSIRIS is even able to resolve the vertical profile of lightning-enhanced NO\textsubscript{2} in the upper troposphere (Storri et al. 2007).

**Bromine monoxide.** Large uncertainties exist as to how much bromine resides in the troposphere and stratosphere, as well as its sources. Values of total Bry, from measurements of stratospheric BrO are roughly 20% larger than Bry inferred from a measurement of its source gases (WMO 2010). It is thought that this difference is due to a largely unmeasured class of VSLS, but it is unclear precisely what these are. In addition, there has been doubt cast on the altitude of the large enhancements in BrO seen during polar spring by nadir instruments (Salawitch et al. 2010).

The absorption signal of BrO is roughly a factor of 10 smaller than NO\textsubscript{2} and retrievals of BrO are at the limit of the OSIRIS sensitivity. Thus, these retrievals require a preprocessing of spectra. Daily, zonal-mean spectra are calculated which provide an increase in the signal-to-noise ratio by a factor of 3–5. These zonal-mean spectra are then inverted to number density profiles using the same spectral fitting (between 346 and 377 nm; see Fig. 3) and optimal estimation approach developed for OSIRIS NO\textsubscript{2} (McLinden et al. 2010).

An estimate of total Bry, derived using monthly-mean BrO profiles and a photochemical box model. In short, the box model, constrained with additional information such as OSIRIS-measured ozone and temperature from ECMWF reanalysis, is used to predict the fraction of Bry present as BrO and combined with OSIRIS Br\textsubscript{O} a value of Bry is inferred (McLinden et al. 2010).

Figure 7 shows the monthly OSIRIS Br\textsubscript{O} plotted as a function of time of day and considers all relevant chemical reactions (Brohede et al. 2008). As with ozone, a clear longitudinal variation exists with a pronounced maximum over equatorial regions and from other peaks near 30°N. These can be compared with the analogous fields from the GEOS-Chem chemical transport model (Fig. 5d) and an annual-mean climatology of lightning flash rate density from satellite lightning sensors (Fig. 5c), both with peaks in the same general location. This indicates that OSIRIS is detecting enhancements in upper-tropospheric NO\textsubscript{2} due to the production of reactive nitrogen from lightning events. OSIRIS is even able to resolve the vertical profile of lightning-enhanced NO\textsubscript{2} in the upper troposphere (Storri et al. 2007).

**Aerosols.** As with ozone, it is hard to overstate the importance of atmospheric aerosols in Earth’s chemistry-climate system. The OSIRIS components—the optical spectrometer and IR imager—provide high-quality and complementary aerosol information. By examining the departure of limb radiance images from that expected for an aerosol-free case at 1.53 μm, thin cirrus clouds can be detected between two species. An estimate of the amount of Bry from the VSLS, approximately 5 ppt, is obtained through the difference between OSIRIS Bry and the expected level of Bry considering only known bromine sources. While these data do not extend into the troposphere, they nonetheless place a constraint on the nature of the additional source of bromine coming from the troposphere. The lack of any significant vertical gradient in the lower tropical stratosphere (inferred from the lack of variation of this difference with N\textsubscript{2}O) implies the source must either be short lived with a lifetime of 6 months or less or already in an inorganic form upon entry into the stratosphere (McLinden et al. 2010).

![Fig. 5. Annual-mean ozone and NO\textsubscript{2} in the tropical upper troposphere: (a) OSIRIS ozone at 12 km averaged between 2001 and 2010, (b) ozone from the GEOS-Chem chemical transport model at 12 km for the year 2004 and averaged using the OSIRIS sampling, and (c) OSIRIS NO\textsubscript{2} at 12 km averaged between 2001 and 2010. Prior to averaging each OSIRIS NO\textsubscript{2} profile was been mapped from its original local time to 1300 LST (see text). (d) NO\textsubscript{2} from GEOS-Chem at 1300 LST and averaged using the OSIRIS sampling and (e) annual climatological-mean lightning flash rate density from combined LIS/OTD satellite data (Boccippio et al. 2002).](image)

![Fig. 6. (a) Time series of SAGE I, SAGE II, and OSIRIS monthly-mean ozone at 45°N and 42 km. (b) Time of ozone anomaly from merged individual SAGE I, SAGE II, and OSIRIS monthly-mean ozone from (a). The anomaly represents the relative departure from the monthly-mean climatological ozone. Also shown is the fit to the ozone anomalies using a trend model and the EESC component of the fit. The shading denotes the period of overlap between OSIRIS and SAGE II.](image)
true and thus the profile here is more qualitative. Many of the types of aerosols found throughout the troposphere and stratosphere, are nonspherical (Lynch 1996), which complicates the retrieval. In the stratosphere, where the assumption of sphericity is generally valid, single-profile precision is 10%-15% in the midstratosphere (Bourassa et al. 2012a) and good overall agreement is found in comparisons of aerosol extinction with the SAGE II and SAGE III instruments (Bourassa et al. 2007a). OSIRIS is also capable of deriving size information by examining the relative extinction between the optical spectrograph and that derived from the IR imager (Bourassa et al. 2008), although at present this remains a research product.

Volcanoes occasionally erupt with sufficient power to inject material directly into the stratosphere. One such example was the eruption of the Kasatochi volcano (52°N, 175°W, located in the Aleutian Islands) on 8 August 2008 that injected an estimated 2 Tg of sulphur dioxide into the lower stratosphere. On a time scale of weeks, the volcanic SO$_2$ was converted into sulphate aerosol, which OSIRIS was able to detect and track (Bourassa et al. 2010). Time series of daily, zonal-mean (10° latitude bands) OSIRIS extinction profiles were calculated and are shown in Fig. 8b. Roughly 3 weeks after the eruption, the aerosol extinction was seen to increase by an order of magnitude above the preruption background levels in the midlatitude bands and a stable layer of enhanced aerosol is seen to mix into the Arctic. OSIRIS has also detected the enhanced aerosol resulting from a series of moderate but increasingly intense eruptions primarily at tropical latitudes between 2002 and 2007. These data have helped demonstrate that the cumulative effect of these eruptions is primarily responsible for an increasing trend in stratospheric aerosol levels, disputing earlier work attributing the increase to increased pollution from Southeast Asia (Vernier et al. 2011). Similar to injection from volcanoes, the large bushfire in southeastern Australia on 7 February 2009, known as “black Saturday,” also placed a significant amount of material into the upper troposphere and lower stratosphere. OSIRIS first detected the smoke plume on 11 February and tracked its dispersion over the next several months (Siddaway and Petelina 2011). This study considered the enhancement in limb radiance over background resulting from the increased scattering caused by the smoke aerosol. The plume was observed to ascend to above 20 km and it was determined that the (1/6) lifetime of the enhancement was roughly 4 weeks.

**Other data products.** Beyond the operational data products, there are many research data products in various stages of development, which are also listed in Table 2. Of particular note is a measure of the linear polarization of the limb radiance that is very sensitive to aerosols. By exploiting the polarization-sensitive nature of the OSIRIS diffraction grating (McLinden et al. 2002), the change in the linear polarization can be derived as a function of tangent height (McLinden et al. 2004). In an aerosol-free atmosphere, there would be little change with tangent height. Scattering from aerosol, however, leads to a pronounced departure in the limb polarization and so this data product represents a complementary source of aerosol information to that in the operational product, derived from radiances.

A suite of mesospheric constituents are also measured, including the OH and NO chemical radicals (Gattinger et al. 2006, 2010). Recently, the OSIRIS team has discovered new airglow emission features, attributed to metal oxides, after careful analysis and removal of known features. This includes chemiluminescent features of FeO measured in the orange region (Evans et al. 2010) and NO in the blue region (Evans et al. 2011) of the night airglow. The meteoritic origin of these metals means the airglow spectrum can vary monthly given the strong temporal variations in meteors. Future space travel by civilian traffic will alter the night airglow spectrum as more sources of iron are added to the 90-km region. Another discovery involves atomic oxygen, also in the upper mesosphere, retrieved from OSIRIS observations of airglow emission features, such as iron oxides and various other species in the upper stratosphere and mesosphere.
The authors acknowledge...

...a snapshot of selected OSIRIS data products is shown in Fig. 10 (along with the average temperature from ECMWF reanalysis). Shown are zonal means averaged over three days (1–3 October 2007). This period was selected as it coincides with the Antarctic ozone hole. There is a clear depletion in ozone between 15 and 22 km poleward of 70°S that coincides with temperatures of about 190 K in the Antarctic polar vortex. Likewise, the aerosol extinction (expressed here as the ratio of aerosol extinction to Rayleigh scattering extinction and so is dimensionless) and the linear polarization aerosol proxy show enhancements indicating the presence of polar stratospheric clouds necessary for catalyzing the chemical reactions responsible for ozone destruction. Also note the corresponding decrease in the NO2 and NOy plots indicate that reactive nitrogen has been removed from the gas phase via an uptake into aerosol particles.

**SUMMARY AND CONCLUSIONS.** After more than a decade in orbit and 1.8 million limb scans, OSIRIS continues to make high-quality measurements of atmospheric composition. Scientists throughout the world continue to discover new applications for these data and with them new insights into our atmosphere. The OSIRIS data record is now approaching a complete solar cycle and so can be used to assess trends in important chemical and climate parameters. Thanks to its sensitivity and the fidelity of its retrieval algorithms, OSIRIS is able to look into the upper troposphere and provide a unique picture of trace gases, aerosol, and clouds in this difficult-to-measure region. As part of the greater Odin mission, OSIRIS is an example of how international and interdisciplinary partnerships can be used to great advantage.

**ACKNOWLEDGMENTS.** The authors acknowledge the contribution made by the many engineers and scientists who contributed to OSIRIS through the design, fabrication, testing, launch, validation, and science phases. Odin is a Swedish-led satellite project funded jointly by Sweden (SNSB), Canada (CSA), France (CNES), and Finland (Tehes). Odin is also partially funded as a European Space Agency Third Party Mission.

**REFERENCES**


—, —, —, A. L. Broadfoot, and E. J. Llewellyn, 2011: The observation of chemiluminescent NO\textsuperscript{+} emissions in the laboratory and in the night airglow. Atmos. Chem. Phys. Discuss., 11, 9595–9603, doi:10.5194/acp-11-9595-2011.


APPENDIX: GLOSSARY OF TERMS.

ACE Atmospheric Chemistry Experiment
BrO Bromine monoxide
Bry Total inorganic bromine
CCD Charge-coupled device
ClO Chlorine monoxide
ClONO2 Chlorine nitrate
CPFM Composition and photodissociative flux measurement
DOAS Differential optical absorption spectroscopy
ECMWF European Centre for Medium-Range Weather Forecasts
EESC Effective-equivalent stratospheric chlorine
ER-2 Earth Resources–2
FeO Iron oxide
GEOS-Chem A global, three-dimension computer model that simulates atmospheric composition
GOMOS Global Ozone Monitoring by Occultation of Stars
HNO3 Nitric acid
ICBM Intercontinental ballistic missile
IRI Infrared imager
LIS Lightning Imaging Sensor
LORRE Limb Ozone Retrieval Experiment
LOS Line of sight
MSIS Mass Spectrometer Incoherent Scatter
N2O Nitrous oxide
N2O5 Dinitrogen pentoxide
NiO Nickel oxide
NO Nitric oxide
NO2 Nitrogen dioxide
NO3 Nitrate radical
NOy Total reactive nitrogen
NPOESS National Polar-orbiting Environmental Satellite System
NPP NPOESS Preparatory Project
O Atomic oxygen
O3 Ozone
OCIO Chlorine dioxide
OH Hydroxyl radical
OMPS Ozone Mapping and Profiling Suite
OS Optical spectrophotograph
OSIRIS Optical Spectrograph and Infrared Imager System
OTD Optical Transient Detector
pp(m/b/t) Parts per (million/billion/trillion)
RT Radiative transfer
SAGE Stratospheric Aerosol and Gas Experiment
SaskMART A Multiplicative Algebraic Reconstruction Technique inversion algorithm developed at the University of Saskatchewan
SaskTRAN A spherical-geometry radiative transfer computer model developed at the University of Saskatchewan
SCD Slant column density
SCIAMACHY Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
SME Solar Mesosphere Explorer
SMR Submillimetre Radiometer
SO2 Sulfur dioxide
SOLSE Shuttle Ozone Limb Scanning Experiment
SSA Single-scattering angle
START Strategic Arms Reduction Treaty
STP Subtangent point
SZA Solar zenith angle
Tg Teragram (10^12 g)
TP Tropopause
UT Upper troposphere
UVS Ultraviolet Spectrometer (on SME)
VER Volume emission rate
VSLS Very-short-lived bromine substance


ABSTRACT

On 20 February 2001, a converted Russian intercontinental ballistic missile (ICBM) delivered Odin, a small Swedish satellite, into low-Earth orbit. One of the sensors on board is a small Canadian spectrometer called Optical Spectrograph and Infrared Imager System (OSIRIS). By measuring scattered sunlight from Earth’s horizon, or limb, OSIRIS is able to deduce the abundance of trace gases and particles from the upper troposphere into the lower thermosphere. Designed and built on a modest budget, OSIRIS has exceeded not only its 2-yr lifetime but also all expectations. With more than a decade of continuous data, OSIRIS has recorded over 1.8 million limb scans. The complexities associated with unraveling scattered light in order to convert OSIRIS spectra into high-quality geophysical profiles have forced the OSIRIS team to develop leading-edge algorithms and computer models. These profiles are being used to help address many science questions, including the coupling of atmospheric regions (e.g., stratosphere–troposphere exchange) and the budgets and trends in ozone, nitrogen, bromine, and other species. One specific example is the distribution and abundance of upper-tropospheric, lightning-produced reactive nitrogen and ozone. Arguably OSIRIS’s most important contributions come from its aerosol measurements, including detection and characterization of subvisual cirrus and polar stratospheric and mesospheric clouds. OSIRIS also provides a unique view of the stratospheric aerosol layer, and it is able to identify and track perturbations from volcanic activity and biomass burning.