



**Characterization of
Odin-OSIRIS ozone
profiles with the
SAGE II dataset**

C. Adams et al.

**Characterization of Odin-OSIRIS ozone
profiles with the SAGE II dataset**

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| | |
|--------------------------|--------------|
| Title Page | |
| Abstract | Introduction |
| Conclusions | References |
| Tables | Figures |
| ⏪ | ⏩ |
| ◀ | ▶ |
| Back | Close |
| Full Screen / Esc | |
| Printer-friendly Version | |
| Interactive Discussion | |



Abstract

The Optical Spectrograph and InfraRed Imaging System (OSIRIS) on board the Odin spacecraft has been taking limb-scattered measurements of ozone number density profiles from 2001–present. The Stratospheric Aerosol and Gas Experiment II (SAGE II) took solar occultation measurements of ozone number densities from 1984–2005 and has been used in many studies of long-term ozone trends. We present the characterization of OSIRIS SaskMART v5.0x against the new SAGE II v7.00 ozone profiles for 2001–2005, the period over which these two missions had overlap. This information can be used to merge OSIRIS and other satellite ozone measurements with SAGE II into a single ozone record from 1984 to the present. Coincident measurement pairs were selected for ± 1 h, $\pm 1^\circ$ latitude, and ± 500 km. The absolute value of the resulting mean relative difference profile was $< 5\%$ for 13.5–54.5 km and $< 3\%$ for 24.5–53.5 km. Correlation coefficients $R > 0.9$ were calculated for 13.5–49.5 km, demonstrating excellent overall agreement between the two datasets. Coincidence criteria were relaxed to maximize the number of measurement pairs and the conditions under which measurements were taken. With the broad coincidence criteria, good agreement ($< 5\%$) was observed under most conditions for 20.5–40.5 km. However, mean relative differences do exceed 5% under several cases. Above 50 km, differences between OSIRIS and SAGE II are partly attributed to the diurnal variation of ozone. OSIRIS data are biased high compared with SAGE II at 22.5 km, particularly at high latitudes. The OSIRIS optics temperature is low ($< 16^\circ\text{C}$) during May–July, when the satellite enters the Earth’s shadow for part of its orbit. During this period, OSIRIS measurements are biased low by 5–12% for 27.5–38.5 km. Biases between OSIRIS ascending node (northward equatorial crossing time $\sim 18:00$ LT) and descending node (southward equatorial crossing time $\sim 06:00$ LT) measurements are also noted under some conditions. This work demonstrates that OSIRIS and SAGE II have excellent overall agreement and characterizes the biases between these datasets.

Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



1 Introduction

Continuous and consistent long-term atmospheric datasets are essential for the assessment of ozone recovery. The Optical Spectrograph and InfraRed Imaging System (OSIRIS) satellite instrument has been measuring ozone profiles from 2001 to the present, yielding a consistent dataset that spans 11 yr, a full solar cycle. These limb-scattered measurements have a vertical resolution that is comparable to solar occultation measurements, but with far better global coverage. While good agreement between OSIRIS ozone profiles and some of those other datasets has been demonstrated (e.g. Degenstein et al., 2009; Dupuy et al., 2009), they have not yet been fully characterized through intercomparisons.

Owing to its precision, stability, and data-record length, the Stratospheric Aerosol and Gas Experiment II (SAGE II) ozone dataset has formed a benchmark for World Meteorological Organization (WMO) Ozone Assessments (e.g. WMO, 2006, 2010). The SAGE II dataset spans 21 yr, has been compared extensively against other instruments (e.g. McPeters et al., 1994; Morris et al., 2002; Wang et al., 2002; Liu et al., 2005; Nazaryan and McCormick, 2005; Brinksma et al., 2006; Froidevaux et al., 2008; Dupuy et al., 2009; Kroon et al., 2011), and has been used to determine stratospheric ozone trends (e.g. Stolarski et al., 1992; Cunnold et al., 2000; Newchurch et al., 2000, 2003; Randel and Thompson, 2011). Therefore the SAGE II dataset is an excellent baseline for satellite ozone measurements.

OSIRIS and SAGE II ozone datasets are both included in the SI²N (SPARC – Stratospheric Processes and their Role in Climate, IO₃C – International Ozone Commission, IGACO-O3 – Integrated Global Atmospheric Chemistry Observations, NDACC – Network for the Detection of Atmospheric Composition Change) initiative, which aims to compile short-term satellite, long-term satellite, and ground-based ozone measurements in a consistent manner (SI²N, 2012). Short-term efforts include the European Space Agency’s (ESA) Climate Change Initiative (CCI), which aims to compile the comprehensive observations that are necessary to characterize the global climate system

Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



and its variability. These datasets must be validated, have well-characterized errors, and be distributed in data formats that are useable for a wide range of users (Bennett, 2012). In order to produce a multi-decadal ozone record, SI²N plans to merge modern ozone measurements with the 1979–2005 SAGE I and SAGE II datasets. In order to merge datasets spatially and temporally, they must be very well-characterized, and biases must be well-documented.

We present the characterization of OSIRIS ozone profiles against SAGE II measurements from 2001–2005 and demonstrate that OSIRIS ozone data are suitable for analysis of ozone trends and have the potential to be combined with the SAGE II dataset. Section 2 gives an overview of the OSIRIS and SAGE II satellite instruments and ozone datasets. In Sect. 3, the intercomparison methodology is presented. The results of the satellite intercomparisons are discussed in Sect. 4 and conclusions are given in Sect. 5.

2 OSIRIS and SAGE II ozone profiles

The Canadian-made OSIRIS instrument, aboard the Swedish satellite Odin, was launched into a sun-synchronous orbit on 20 February 2001 (Murtagh et al., 2002; Llewellyn et al., 2004). The optical spectrograph measures limb scattered sunlight at 280–810 nm with a spectral resolution of approximately 1 nm. Odin has a polar orbit with a 96 min period that stays very near local dusk on the ascending track (northward equatorial crossing at ~ 18:00 LT) and near local dawn on the descending track (southward equatorial crossing at ~ 06:00 LT), going through local midnight near the south pole and local noon near the north pole. This process repeats itself every orbit, with a slow precession in the local time of the ascending node throughout the lifetime of the mission. The orbit provides measurement coverage from ~ 82.2° S to ~ 82.2° N latitude. Note that due to the precession in the local time of the ascending node, OSIRIS coverage is improving in time. Due to Odin’s orbit, measurements are only taken in the summer hemisphere, with coverage in both hemispheres in the spring and fall. A review of the first decade of OSIRIS measurements is given by McLinden et al. (2012).

Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The OSIRIS SaskMART v5.0x ozone data were used in this study. The Multiplicative Algebraic Reconstruction Technique (MART) retrieval algorithm (Roth et al., 2007; Degenstein et al., 2009) combines ozone absorption information in both the UV and visible parts of the spectrum to retrieve number density profiles from the cloud tops to 60 km (down to a minimum of 10 km in the absence of clouds). Radiative transfer is calculated using the SASKTRAN model (Bourassa et al., 2008b). Aerosol and NO₂ are retrieved at the same time as ozone to reduce biases (Bourassa et al., 2007, 2008a, 2011). The SaskMART v5.0x ozone dataset has a vertical resolution of ~ 2 km and an estimated precision of 3–4 % in the middle stratosphere (Bourassa et al., 2012). Prior to data distribution, OSIRIS data are screened using the methods described in Appendix A. Furthermore, data were screened for polar stratospheric clouds at Southern Hemisphere high latitudes. For 60–90° S, if the aerosol extinction exceeded 0.0005 km⁻¹ at a given altitude, ozone data were removed from 2 km above the given altitude down to the bottom of the profile. This screening technique was selected based on comparisons between OSIRIS ascending and descending node measurements and against ozonesonde measurements. Note that similar screening was attempted at other latitudes, but removed many profiles and did not significantly improve comparison results.

SAGE II was launched in October 1984 aboard the Earth Radiation Budget Satellite (McCormick, 1987) and was in operation until late 2005. From 1984–2000, SAGE II took about 15 sunrise and 15 sunset solar occultation measurements per day, covering 80° S to 80° N in latitude. Due the degradation of the charging system, in 2000 the SAGE II sampling was reduced to ~ 15 measurements per day, with the observation cycle focused on either sunrise or sunset measurements. At reduced sampling, quasi-global coverage was achieved on a monthly basis. Successive measurements were separated by approximately 24° in longitude and a fraction of a degree in latitude (McCormick et al., 1989). SAGE II had measurement channels centred at 385, 453, 448, 525, 600, 940, and 1020 nm.

SAGE II v7.00 ozone data, which were released in November 2012, were used in this study. Ozone slant columns are inverted to a 1-km vertical resolution and placed onto

Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



found that the smoothing width had minor effects on the comparison results, unless it was set to values that were much larger than the OSIRIS vertical resolution. The two datasets were then compared on the OSIRIS altitude grid. The mean relative difference, Δ_{rel} , at a given altitude, z , between sets of coincident OSIRIS (M_1) and SAGE II (M_2) measurements was calculated as

$$\Delta_{\text{rel}}(z) = 100\% \times \frac{1}{N} \sum_{i=1}^N \frac{(M_{1i}(z) - M_{2i}(z))}{(M_{1i}(z) + M_{2i}(z))/2}. \quad (1)$$

The standard deviation of Δ_{rel} was also calculated.

4 Results

Figure 2 shows a time series of OSIRIS and SAGE II ozone data for 40–45° N at 35.5 km and 25.5 km. This time series is included for qualitative purposes only and demonstrates that good agreement is observed between the two datasets. The time dependent variability of each dataset is similar and there are no obvious biases, illustrating the potential for using OSIRIS ozone profiles to continue the long-term SAGE II record. Furthermore, the SAGE II and OSIRIS datasets complement one another during their period of overlap, with excellent summertime coverage from OSIRIS and winter coverage from SAGE II. OSIRIS does not measure ozone in the winter hemisphere and, therefore, to produce a merged long-term time series with global coverage, other current satellite datasets would be required to complement the OSIRIS measurements. There are periods during which some disagreement is visually evident. However, some differences are expected as the instruments do not uniformly sample the latitude band: more OSIRIS measurements are skewed toward 40° N, while SAGE II measurements are skewed toward 45° N. Care has been taken to minimize the impact of sampling biases for coincident measurement pairs, as discussed in Sect. 3. The results shown in Fig. 2 are typical and consistent with time series comparisons at other altitudes and latitudes covered by both SAGE II and OSIRIS.

Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

given in Fig. 4. For the broad coincidence criteria, 5174 coincidences were found. The standard deviations in OSIRIS and SAGE II ozone number density profiles are similar indicating that they sample similar large-scale seasonal variability in air masses.

The mean relative difference for OSIRIS minus SAGE II is very similar to the results for the narrow coincidence criteria (Fig. 3c) for 15.5–40.5 km. Below 13.5 km, agreement improves due to the inclusion of more high-latitude measurements, and therefore a smaller contribution from tropospheric measurements. Above 50 km, OSIRIS is biased low compared with SAGE II. This is primarily due to the diurnal variation of ozone, as discussed in Sect. 4.2. The standard deviation in the relative differences in the middle stratosphere ($\sim 8\%$) is larger for the broad than for the narrow coincidence criteria, and is no longer within the combined precision of the OSIRIS (3–4%) and SAGE II (4%) measurements at these altitudes. Furthermore, the R correlation coefficients are smaller for the broad than for the narrow coincidence criteria. The addition of dynamical coincidence criteria to match similar air masses did not significantly improve correlation coefficients or standard deviations. This suggests that for the broader coincidence criteria, the reduced correlation is not caused by mismatches between the air masses sampled by the coincident measurements, due to the relaxed time and distance criteria. Instead, this is probably the result of measurements being compared under a larger variety in conditions (e.g. latitude, OSIRIS measurement SZA).

4.1 Latitude

Figure 5 is a contour plot of mean relative differences and R correlation coefficients, calculated for coincidences within 10° latitude bins. Mean relative differences with absolute values $< 5\%$ and correlation coefficients $R > 0.5$ are observed at most altitudes and latitudes. Below the tropopause, both positive and negative biases are observed, reaching magnitudes of up to 30% for some altitude-latitude bins. Furthermore, $R < 0.5$ was calculated for much of troposphere, indicating that these measurements are not well correlated. For 60°S – 40°N , between the tropopause and 21.5 km, OSIRIS is biased low by up to 23% compared with SAGE II. The high bias in OSIRIS data at

22.5 km is strongest at high latitudes, reaching 6% in the Southern Hemisphere. For 23.5–38.5 km, mean relative differences are < 5% at all latitudes. Small R correlation coefficients are observed at 80° S. Most coincidences within this latitude bin do not meet the dynamical coincidence criteria, suggesting mismatched air masses arising from the structure of the polar vortex are causing these discrepancies. Above 40 km, latitudinal biases are observed and can partly be attributed to the diurnal variation of ozone, as discussed in Sect. 4.2.

4.2 The diurnal variation of ozone at high altitudes

In the upper stratosphere and mesosphere, ozone has a diurnal variation, with larger number densities at night than during the day. Therefore, if two instruments sample ozone at different SZAs, biases can be introduced to the comparisons. Figure 6 shows the correlation between OSIRIS and SAGE II coincidences at 54.5 km, with various measurement SZAs highlighted. Agreement between OSIRIS and SAGE II coincidences has a strong SZA-dependence, with better agreement for OSIRIS SZAs near twilight. The measurement SZA at the OSIRIS 25-km tangent height ranges from 59–91°, with lower SZAs sampled at high latitudes during the hemisphere’s summer. SAGE-II occultations are always at twilight SZAs of 89–90° at the 30-km tangent height. Therefore, mismatches in measurement SZA are expected to cause discrepancies between the SAGE II and OSIRIS datasets at high altitudes.

Furthermore, errors can be introduced to satellite measurements through the “diurnal effect”, which is also known as “chemical enhancement” (e.g. Fish et al., 1995; Newchurch et al., 1996; Natarajan et al., 2005; Hendrick et al., 2006; McLinden et al., 2006). Sunlight can pass through a range of SZAs before reaching the instrument. Therefore, ozone is sampled at various points in its diurnal cycle, not just the reported SZA at the tangent point. At twilight, when ozone varies rapidly with SZA, this effect is the largest. Natarajan et al. (2005) calculated the impact of the diurnal effect on Halogen Occultation Experiment (HALOE) solar occultation ozone measurements. They found that the diurnal effect leads to an overestimation of ozone at 55 km of ~ 10%

Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



($\sim 3\%$) for measurements taken at local sunrise (sunset). They reported that below 50 km, the diurnal effect was zero. Since HALOE has viewing similar to SAGE II, these values should be similar for SAGE II. For OSIRIS measurements, the magnitude of the diurnal effect depends on the azimuthal angle between incoming sunlight and the instrument as well as the SZA (McLinden et al., 2006), and therefore varies on a scan-by-scan basis.

In order to assess the impact of the diurnal variation of ozone on the OSIRIS versus SAGE II comparisons, a photochemical model (McLinden et al., 2000) was used to calculate the diurnal variation of ozone in 10° latitude bands from 80° S to 80° N for 21 March, 21 June, 21 September, and 21 December, using climatological ozone profiles (McPeters et al., 2007). Relative differences were calculated between profiles at typical OSIRIS measurement SZAs and a typical SAGE II measurement SZA (89.5°). For OSIRIS measurement SZAs $< 80^\circ$, a negative bias appears in the modeled relative difference profiles at 40–45 km, reaching -5% by 47–50 km. At 54.5 km, the relative differences calculated with the photochemical model range from -15 to -23% , depending on the measurement latitude and season. This is consistent with the average relative difference for OSIRIS measurements taken at SZA $< 80^\circ$ minus coincident SAGE II measurements of $17.2 \pm 0.3\%$ (where error is the standard error, σ/\sqrt{N}). Note that the diurnal effect should not have a large impact on the OSIRIS measurements for SZAs $< 80^\circ$ because ozone is not varying as rapidly as at twilight. Furthermore, when the solar scattering angle, the azimuthal angle between the sun and OSIRIS, is $\sim 90^\circ$, the diurnal effect does not impact OSIRIS measurements. In order to assess this fully, OSIRIS and SAGE II measurements would have to be corrected for the diurnal effect and then scaled to a common SZA prior to comparison.

4.3 OSIRIS optics temperatures

Around June each year, the earth is between OSIRIS and the sun as Odin passes over the Southern Hemisphere. During this period of eclipse, OSIRIS cools due to lack of sunlight, as is apparent in the OSIRIS optics temperatures (Fig. 1). A contour plot of

Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

mean relative differences, calculated in 1° temperature intervals, is shown in Fig. 7a. For 28.5–47.5 km, the OSIRIS data are biased low by 5–12 % for optics temperatures < 16 °C. Above 47.5 km, a larger low bias is observed, but this may be due in part to the diurnal variation of ozone. The positive bias in measurements for altitudes above 40 km and optics temperatures > 25 °C is due to the inclusion of more measurements at southern high latitudes, for which OSIRIS is biased high compared with SAGE II. Below 20 km, mean relative differences vary with temperature, likely due to differences in sampled latitudes. The number of OSIRIS measurement for all processed ozone data (2001–2012) within each temperature bin is also shown. Most measurements are taken at optics temperatures of 18–22 °C, for which the bias between datasets is very small. 20 % of all OSIRIS measurements were taken for optics temperatures < 16 °C. Note that the OSIRIS optics temperature distributions for coincidences with SAGE II is qualitatively similar to the 2001–2012 distribution, but only 11 % of the OSIRIS scans were taken at optics temperatures below 16 °C.

The low bias in OSIRIS ozone for low optics temperatures is likely due to errors in pointing and/or spectral wavelength calibration. Low temperatures may cause misalignment between OSIRIS and the star tracker due to thermal bending, flexing, or deformation torque, leading to an estimated 200–400 m error in the measurement altitude (McLinden et al., 2007). Altitude corrections as a function of OSIRIS optics temperature were estimated, but did not significantly improve the comparisons results. Defocusing, reduced spectral resolution, and wavelength shifts of the instrument at low temperatures (Llewellyn et al., 2004) may also contribute to this bias. Systematic errors can be introduced if the ozone cross-section is not convolved to the resolution of the spectra. These errors are expected to be largest in spectral regions for which the ozone cross-section varies rapidly with wavelength, e.g. errors will be larger at UV wavelengths than at visible wavelengths. For the OSIRIS SaskMART profile retrievals, the visible spectrum is used below ~ 25 km and UV data are used above this (Degenstein et al., 2009). Since the low bias in OSIRIS measurements at low optics temperatures occurs above 25 km, defocussing of the instrument is likely contributing to the bias.

throughout much of the stratosphere. Some of these discrepancies may be due to the diurnal variation of ozone or the diurnal effect (see Sect. 4.2), however the magnitudes of these biases are larger than photochemical model predictions at lower altitudes (40–50 km), suggesting that there may be contributions from other effects.

5 Mean relative differences for OSIRIS descending and ascending node measurements minus coincident SAGE II occultations are also shown in Fig. 8. The positive bias in the OSIRIS measurements at 22.5 km occurs primarily at 50–80° S in ascending node measurements and at 40–70° N in descending node measurements. The low bias in OSIRIS data above 27.5 km at 50–80° N is evident only in the descending node
10 measurements. This corresponds to the period of measurements with low optics temperatures (see Sect. 4.3).

5 Conclusions

OSIRIS has been taking limb-scattered measurements of ozone number density profiles from 2001 to the present. OSIRIS measurements cover the summer hemisphere
15 daily, with a ~ 2 -km vertical resolution. The 1984–2005 SAGE II ozone dataset has been used in many studies to establish ozone trends. In the present study, OSIRIS SaskMART v5.0x ozone data were characterized with SAGE II v7.00 measurements for 2001–2005. Excellent overall agreement was observed between the OSIRIS and SAGE II datasets, with magnitudes of mean relative differences $< 5\%$ for 13.5–54.5 km and $< 3\%$ for 24.5–53.5 km and correlation coefficients $R > 0.9$ for 13.5–49.5 km, for a narrow set of coincidence criteria.
20

The OSIRIS data were characterized against the SAGE II data for various latitudes and observation conditions, using a broad set of coincidence criteria. Mean relative differences between OSIRIS and SAGE II were $< 5\%$ under many conditions, again
25 showing excellent consistency between these two datasets. Several biases were identified and are summarized in Table 2. These biases should be considered if the OSIRIS

Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



and SAGE II datasets are combined into a single time series. Efforts are also underway to improve OSIRIS SaskMART retrievals, which should lead to the reduction in some of these biases in future versions of the dataset.

Overall, excellent agreement between OSIRIS and SAGE II satellite ozone records demonstrates the potential for merging the OSIRIS and SAGE II datasets. Prior to merging, the long-term stability of OSIRIS measurements should be assessed through comparisons other datasets. Furthermore, at least one additional ozone dataset will be required in order to cover the winter hemispheres. Biases between OSIRIS and additional datasets should must be identified and quantified. Following this process, an ozone record including OSIRIS and SAGE II measurements spanning from 1984 to the present could be created.

Appendix A

Routine screening of OSIRIS ozone data

This document describes the screening procedure that is applied to the retrieved OSIRIS ozone profiles prior to distribution. This involves a three-step process: (1) radiances are screened for evidence of clouds and cosmic rays; (2) retrieved ozone profiles are screened using statistical techniques; and (3) retrieved ozone profiles are assessed visually. These screening procedures are described in detail in the paragraphs below.

The altitudes at which OSIRIS ozone profiles are contaminated with clouds are calculated in the SaskMART retrievals and excluded from the final product. However, in some cases, cloud altitudes are not correctly characterized. To determine if a scan is likely contaminated with a cloud, a detection ratio, v_z , is calculated at each altitude

$$v_z = \log(\bar{I}_z / \bar{I}_{40\text{km}}) / (\rho_z / \rho_{40\text{km}}), \quad (\text{A1})$$

Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

where $\bar{I}_z/\bar{I}_{40\text{km}}$ is the mean radiance of the spectrum at 743 nm and 745.5 nm normalized to 40 km, and $\rho_z/\rho_{40\text{km}}$ is the neutral density normalized to 40 km. The radiance of the spectrum is considered at 743 nm and 745.5 nm because clouds have a larger impact toward the red part of the spectrum and at these wavelengths emission lines from other atmospheric constituents are avoided. If $v_z > 0.6$ anywhere for 15–40 km, then the scan is likely contaminated by clouds and is removed. This cloud criterion leads to the rejection of $< 2\%$ of scans. In future versions, the retrieval software will detect these issues prior to retrieval so that the altitude range of the retrieval is appropriate.

Spectra are also scanned for radiation hits due to cosmic rays in the detector, which typically cause a large, isolated spike in the spectrum. In order to identify spectra contaminated by cosmic rays, spectra at a given altitude level, I_z , are normalized relative to the spectra at altitude layers above and below

$$I_{\text{normalized}} = \log(I_z) / \{[\log(I_{z+1}) + \log(I_{z-1})]/2\}. \quad (\text{A2})$$

Then, around each pixel that is used for aerosol and ozone retrievals, the mean and standard deviation of normalized intensities of the ten surrounding pixels are calculated. If there is a spike in the mean and standard deviation around a given pixel, the scan is rejected. Less than 5% of scans were rejected due to radiation hits for 2001–2011. In future versions of the retrieval algorithm, cosmic ray hits will be identified and handled prior to retrieval.

Infrequently, unstable retrievals may result in extremely large, unphysical ozone values that are not apparent in the radiance data. Therefore, for each week, ozone and aerosol data are grouped in 10° latitude bins at each altitude. For each bin the standard deviation and the median absolute deviation of ozone and aerosol are calculated. Scans with ozone or aerosol values that deviate from the ozone or aerosol values well beyond the variance are rejected. Additionally, scans are removed if at any altitude the ozone volume mixing ratio or aerosol exceeds 1, as these values are non-physical. This filtering scheme led to the removal of $< 8\%$ scans for 2001–2011.

Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Very infrequently, some outlier profiles pass the radiance and statistical profile criteria described above. Therefore, the profiles are inspected visually prior to approval, comparing them collectively in bins of latitude and month. This technique has led to the identification and removal of 0.1 % of retrieved profiles for 2001–2011, the vast majority of which are attributed to periods of incorrect altitude registration.

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Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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**Characterization of
Odin-OSIRIS ozone
profiles with the
SAGE II dataset**

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


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Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 1. Coincidence criteria for SAGE II and OSIRIS comparisons.

| | Time | Distance | Latitude |
|-----------------------------|------------|---------------|---------------|
| Narrow coincidence criteria | ± 1 h | ± 500 km | $\pm 1^\circ$ |
| Broad coincidence criteria | ± 24 h | ± 1000 km | $\pm 1^\circ$ |

Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

Table 2. Summary of biases between OSIRIS and SAGE II ozone profiles.

| Altitude | Latitude | Season | Description |
|--------------|-------------------|----------|--|
| ≤ 21.5 km | 60° S–40° N | All | From the tropopause to 21.5 km OSIRIS is biased low compared with SAGE II by up to 23 %. |
| 21.5–23.5 km | 60–80° S 50–70° N | All | OSIRIS biased high (2–6 %) compared with SAGE II. Strongest for 60–80° S in descending node measurements. |
| ≥ 27.5 km | 0°–80° N | May–July | OSIRIS ozone is biased low by 5–12 % when OSIRIS optics temperatures < 16 °C during the eclipse period of the orbit. Strongest for descending node measurements. |
| ≥ 40.5 km | All | All | Latitudinal dependent biases between OSIRIS and SAGE II, due partly to the diurnal variation of ozone. |

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Characterization of
Odin-OSIRIS ozone
profiles with the
SAGE II dataset**

C. Adams et al.

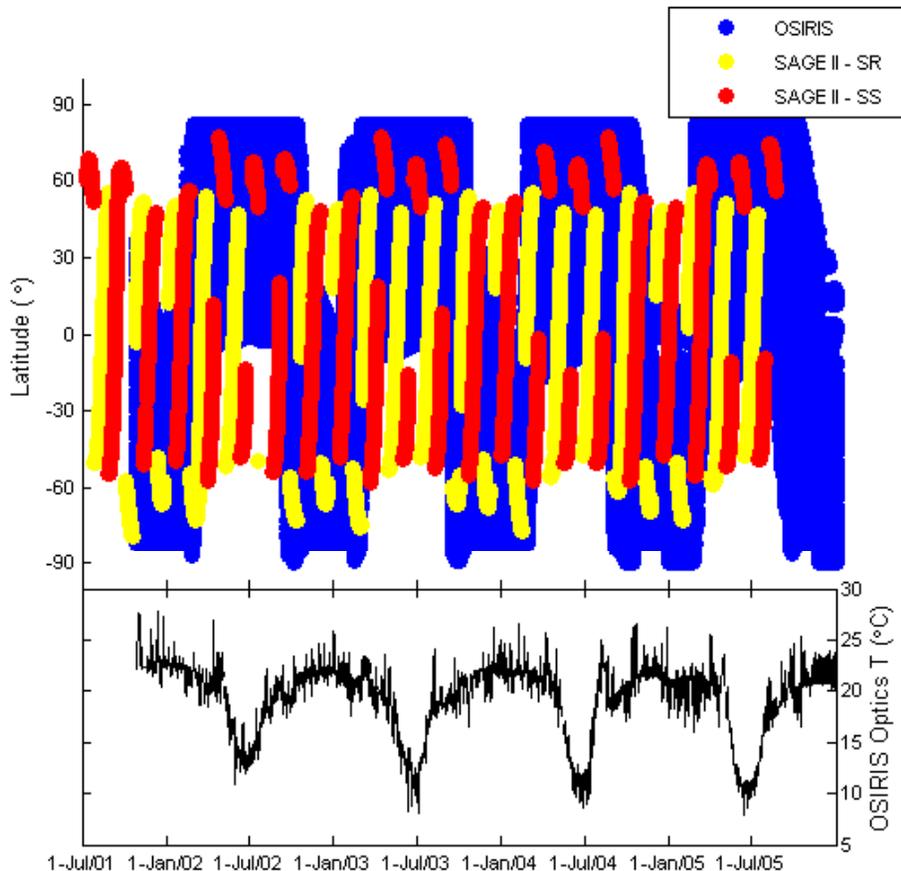


Fig. 1. Sampling of SAGE II and OSIRIS during the comparison period. (Top) Latitude of OSIRIS 25-km tangent height (blue) and SAGE II 30-km tangent height for satellite sunrise (yellow) and sunset (red) occultations versus measurement date. (Bottom) OSIRIS optics temperature versus measurement date.

Characterization of
Odin-OSIRIS ozone
profiles with the
SAGE II dataset

C. Adams et al.

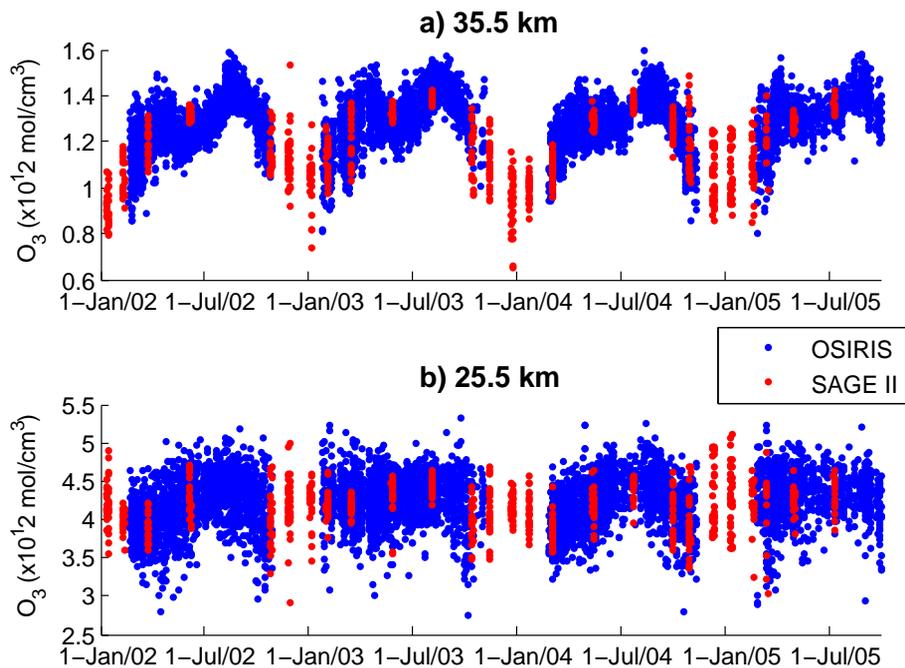


Fig. 2. Time series of OSIRIS (blue) and SAGE II (red) ozone measurements for 40–45° N at **(a)** 35.5 km and **(b)** 25.5 km.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

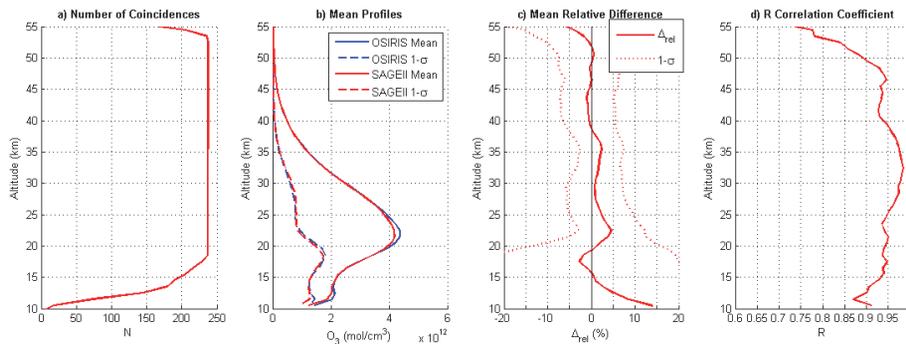


Fig. 3. Comparison results for narrow coincidence criteria (see Table 1). **(a)** Number of coincidences. **(b)** Mean number density profiles (solid lines) and standard deviation (dashed lines) for OSIRIS (blue) and SAGE II (red). **(c)** Mean relative difference for OSIRIS minus SAGE II (red solid line) with standard deviation (red dashed lines). **(d)** R correlation coefficient for OSIRIS vs. SAGE profiles.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

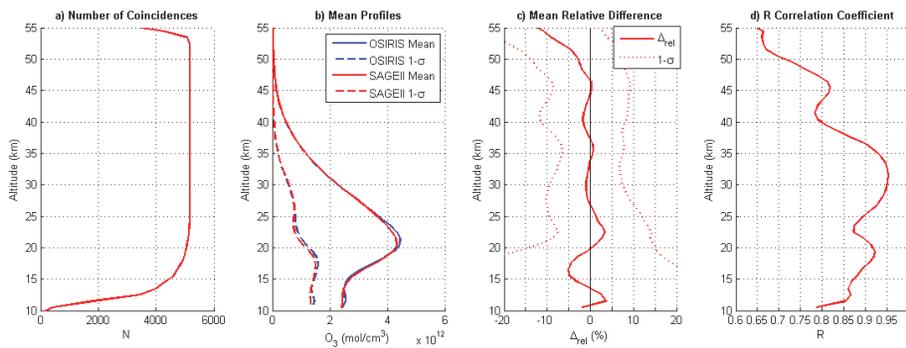


Fig. 4. As for Fig. 3 for broad coincidence criteria (see Table 1).

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

Characterization of
Odin-OSIRIS ozone
profiles with the
SAGE II dataset

C. Adams et al.

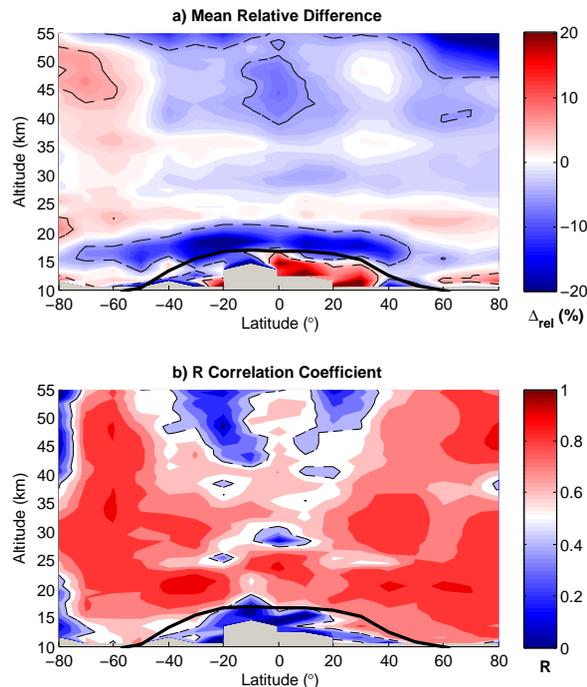


Fig. 5. Latitudinal variation for comparisons between OSIRIS and SAGE II measurements, calculated for 10° latitude bins (x-axis) at various altitudes (y-axis). **(a)** Contours of mean relative differences (color-scale), with the black dashed lines indicating $\pm 5\%$ mean relative difference. **(b)** Contours of the correlation coefficient, R , with the black dashed lines indicating $R = 0.5$. The thick black lines indicate the average World Meteorological Organization thermal tropopause height of the coincident measurements, calculated from European Center for Medium-Range Weather Forecast analysis data. The grey shading indicates regions for which there are fewer than 10 coincidences. Measurement pairs were selected with broad coincidence criteria (see Table 1).

Characterization of
Odin-OSIRIS ozone
profiles with the
SAGE II dataset

C. Adams et al.

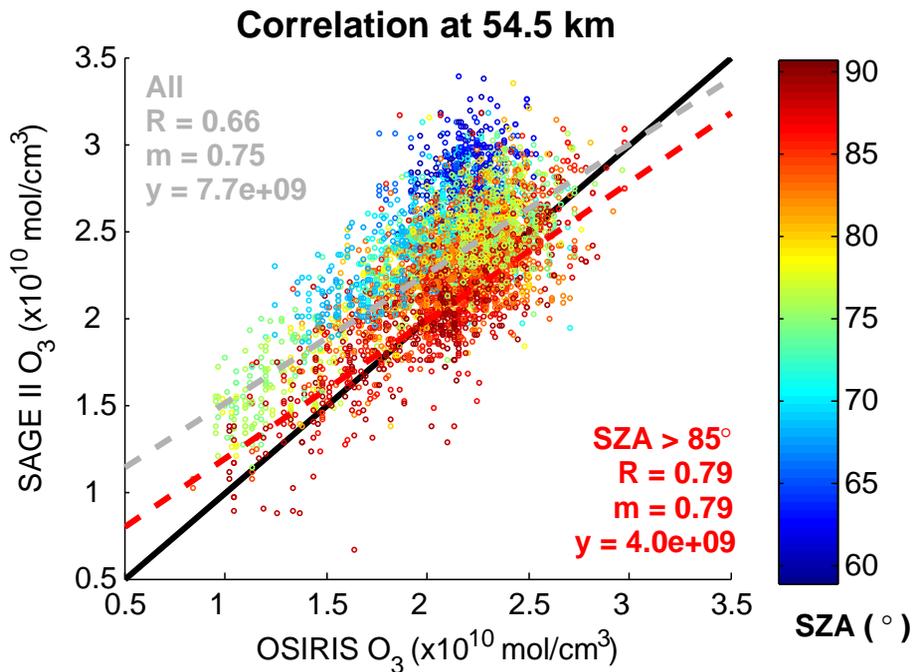


Fig. 6. Correlation plot of OSIRIS versus SAGE II ozone number densities at 54.5 km altitude. The color scale indicates the SZA of the OSIRIS measurements. Linear fits (dashed lines) and fitting statistics (text) are indicated for all coincidences (grey) and for coincidences with OSIRIS measurement SZA > 85° only (red). The black line indicates 1-1. Measurement pairs were selected for broad coincidence criteria (see Table 1).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Characterization of Odin-OSIRIS ozone profiles with the SAGE II dataset

C. Adams et al.

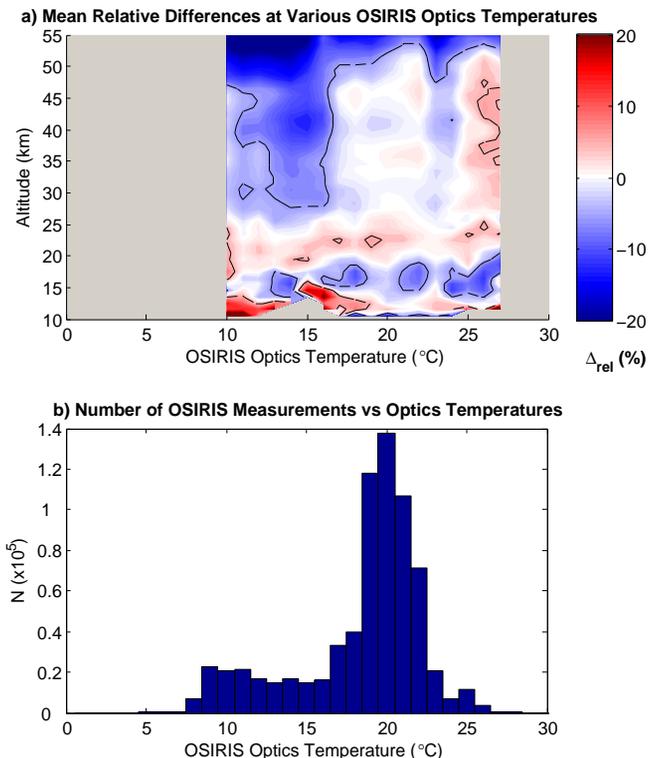


Fig. 7. Variation in relative differences for OSIRIS minus SAGE II at various OSIRIS optics temperatures. **(a)** Contours of mean relative differences (color-scale) calculated for 1°C OSIRIS optics temperature bins (x-axis) at various altitudes (y-axis). The black dashed lines indicate $\pm 5\%$ mean relative difference. The grey shading indicates regions for which there are fewer than 5 coincidences. Measurement pairs were selected with broad coincidence criteria (see Table 1). **(b)** Number of OSIRIS measurements (y-axis) at various optics temperatures (x-axis) for the entire processed dataset (2001–2012).

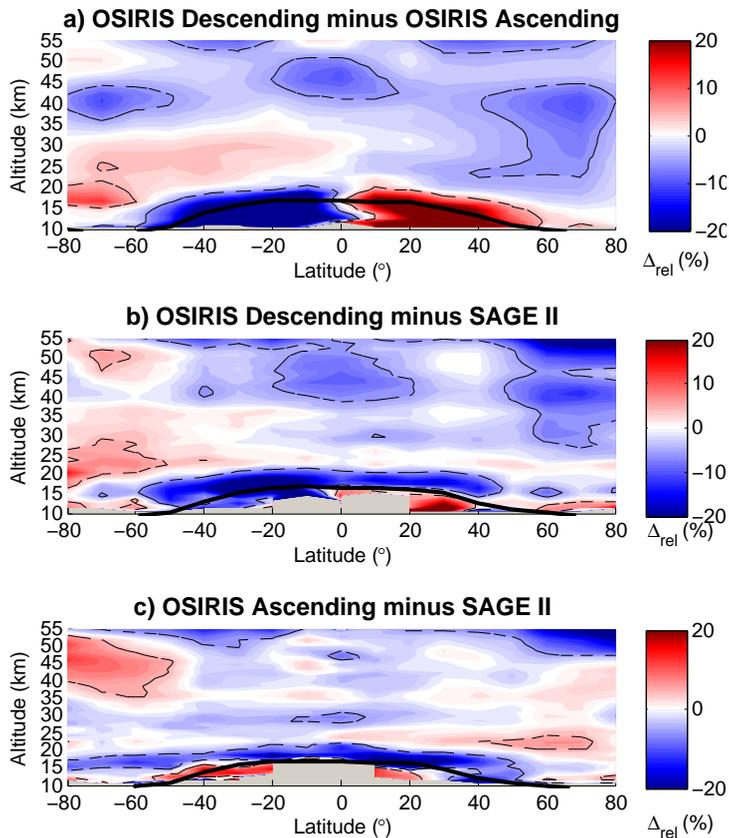


Fig. 8. As for Fig. 5a for **(a)** OSIRIS descending node minus OSIRIS ascending node measurement pairs for 2001–2005, **(b)** OSIRIS descending node minus SAGE II measurement pairs, and **(c)** OSIRIS ascending node minus SAGE II measurement pairs. OSIRIS ascending and descending node measurement pairs and OSIRIS and SAGE II measurement pairs were all selected with broad coincidence criteria (see Table 1).

**Characterization of
Odin-OSIRIS ozone
profiles with the
SAGE II dataset**

C. Adams et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

