

1. Motivation

- Validation of two decades of ACE-FTS ozone measurements in the stratosphere and mesosphere against ground-based observations from lidar, microwave radiometer (MWR) and Fourier Transform Infrared Spectrometer (FTIR) instruments within the NDACC network.
- Validation of ACE-FTS temperature measurements against ground-based lidar observations and examination of the relationship between ozone recovery in the upper stratosphere and stratospheric cooling.
- Examination of data consistency between ACE-FTS and ground-based instruments with the consideration of ozone diurnal variations in the upper stratosphere and mesosphere and averaging kernel smoothing for the MWR and FTIR instruments.

2. Introduction

ACE-FTS (Atmospheric Chemistry Experiment – Fourier Transform Spectrometer) is a Canadian instrument aboard the SCISAT satellite that has routinely measured vertical profiles of more than 70 atmospheric molecules and isotopologues using the solar occultation technique since February 2004.

The ACE-FTS ozone record averaged over 60°S–60°N, 25.5–40.5 km shows a small, statistically non-significant recovery of stratospheric ozone (Bernath et al., 2020). The recovery is primarily attributed to the successful implementation of the Montreal Protocol and the resulting decline in ozone-depleting substances (ODSs). Increasing greenhouse gas concentrations cause tropospheric warming and stratospheric cooling with the latter promoting upper-stratospheric ozone recovery by slowing temperature-dependent ozone-destroying reactions (Steinbrecht et al., 2025; Stolarski et al., 2012).

This study focuses on validating ACE-FTS ozone measurements from the stratosphere to the mesosphere using regional observations within the framework of NDACC (Network for the Detection of Atmospheric Composition Change). NDACC includes a suite of instruments deployed worldwide. To maximize spatial and temporal coverage, multiple instrument types are considered, including lidar, MWR, and FTIR instruments. ACE-FTS temperature profiles are also compared with NDACC lidar measurements. Global ozone data have previously been used to validate ACE-FTS ozone measurements from the upper troposphere to the mid-stratosphere (Zou et al., 2024).

3. Datasets

3.1 ACE-FTS v5.3 data

ACE-FTS v5.3 ozone volume mixing ratio (VMR) data together with the temperature and pressure data (Boone et al., 2023) were downloaded from <https://data.bas.csiat.ca/level2/in dex.php>. The ACE-FTS profiles are provided on a regular vertical grid with 1-km spacing. Data screening was performed based on the quality flags assigned to individual data points (Sheese et al., 2015). The quality flags were obtained from Sheese and Walker (2025).

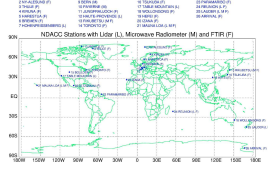


Figure 1. NDACC stations equipped with Lidar (L), Microwave Radiometer (M) and FTIR (F) instruments.

3.2 NDACC data

NDACC data are available at <https://www-air.larc.nasa.gov/pub/NDACC/PUBLIC/stations>. The NDACC stations equipped with lidar, MWR, and FTIR instruments included in this study are shown in Fig. 1, and the corresponding data periods are listed in Table 1.

4. Methods

4.1 Coincident data pairs for bias determination

The primary method for determining biases between ACE-FTS and NDACC instruments is to use coincident data pairs. The coincidence criteria vary among the different station instruments, with the measurement sampling frequency being a major factor (e.g., Sects. 5.1 and 5.2).

4.2 Monthly averaged regional data for long-term trending

ACE-FTS observations were selected within a predefined geographic region surrounding each NDACC station (e.g., $\pm 5^\circ$ in latitude and $\pm 20^\circ$ in longitude). Monthly mean time series were then generated for both the ACE-FTS and corresponding ground-based observations. De-seasonalized time series were subsequently constructed to determine long-term linear trends.

Monthly mean data records from both ACE-FTS and ground-based instruments were also used to determine the biases.

4.3 Diurnal variability in the upper stratosphere and mesosphere

Ozone in the upper stratosphere and mesosphere exhibits prominent diurnal variations, which can be captured by some high-frequency MWR measurements (Savaguet et al., 2023). These stations are therefore given particular consideration when comparing ACE-FTS and ground-based ozone measurements in these altitude regions.

4.4 Smoothing with averaging kernel

For the ground-based MWR and FTIR instruments, the measured ozone profiles are retrieved profiles that represent weighted combinations of the a priori and true ozone profiles through the application of the averaging kernel. The ACE-FTS profiles were smoothed using the averaging kernels of the corresponding ground-based measurements. This approach was applied particularly to the coincident data pairs.

5. Results

5.1 Lidar

Lidar data from the Hohenpeißenberg, Haute-Provence, Mauna Loa, and Lauder stations were compared with the ACE-FTS ozone and temperature profiles. The lidar profiles were first interpolated onto the ACE-FTS vertical grid.

(a) Time series comparisons

To explore the dynamical and photochemical processes, the time series derived from the ACE-FTS and lidar measurements at Hohenpeißenberg are shown in Fig. 2a for ozone VMR at different altitudes and in Fig. 2b for temperature. Both ACE-FTS and lidar show very good agreement in ozone and temperature. At 45.5 km, both ACE-FTS and lidar show stable, slightly increasing ozone trends from 2004 to 2025. A noise level change around 2018 is due to the changed of the lidar instrument. At 35.5 km, ozone peaks in summer driven by photochemical activities, while 25.5 km is a transitional altitude and shows weaker variability. At 22.5 km, ozone peaks in late winter and early spring, likely reflecting enhanced Brewer–Dobson circulation transporting ozone-rich air masses from lower latitudes and higher altitudes.

(b) Bias estimates

Figures 3a and 3b show the ozone and temperature profile comparisons between ACE-FTS and lidar at Hohenpeißenberg, based on coincident data pairs using criterion of ± 6 hours, $\pm 5^\circ$ latitude, and $\pm 10^\circ$ longitude. Narrower temporal criteria yield substantially fewer coincident pairs. Ozone differences exceed 10% above 45 km, likely due to strong diurnal variability, while differences remain around 3% between the tropopause and 45 km. The correlation profile shows a minimum near 25 km, consistent with the reduced variability seen in Fig. 2a. Monthly mean results show similar behavior (not shown).

(c) Long-term ozone and temperature trends

Figure 4 shows the linear trends in ozone and temperature profiles derived from ACE-FTS and lidar measurements at Hohenpeißenberg, Haute-Provence, and Mauna Loa over two decades. In the upper stratosphere, both ACE-FTS and lidar measurements, except for the lidar measurements at Haute-Provence, show non-significant positive ozone trends. In the lower stratosphere, ozone trends are predominantly negative, albeit statistically non-significant. Stratospheric temperature trends are non-significant negative, suggesting a tendency toward stratospheric cooling. This cooling is consistent with the expected response to increasing greenhouse gas concentrations. The observed positive ozone trends in the upper stratosphere are broadly consistent with ozone recovery following the implementation of the Montreal Protocol, with stratospheric cooling also contributing to the observed ozone changes.

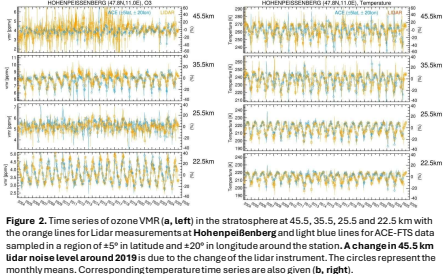


Figure 2. Time series of ozone VMR (a, left) in the stratosphere at 45.5, 35.5, 25.5 and 22.5 km with the orange lines for ACE-FTS and light blue lines for ACE-FTS data sampled in a region of $\pm 5^\circ$ in latitude and $\pm 20^\circ$ in longitude around a change in 45.5 km lidar noise level around 2018 is due to the change of the lidar instrument. The circles represent the monthly means. Corresponding temperature time series are also given (b, right).

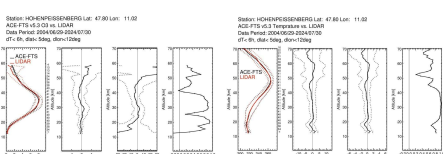


Figure 3. Comparison of ozone profiles (a, left) from coincident ACE-FTS and lidar measurements at Hohenpeißenberg, with panels from left to right showing (1) mean vertical profiles, (2) absolute differences, (3) relative differences, and (4) correlation coefficients. Comparison of temperature profiles are also given (b, right).

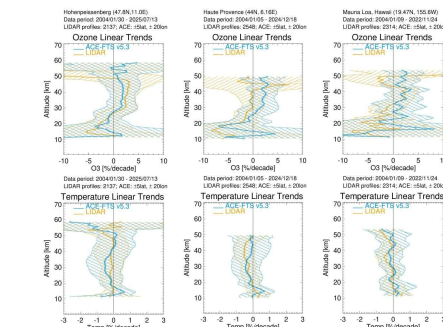


Figure 4. Linear trends in ozone (top panels) and temperature (bottom panels) profiles derived from ACE-FTS (light blue) and lidar (orange) measurements at Hohenpeißenberg (left panels), Haute-Provence (middle panels), and Mauna Loa (right panels; 2004–2023). The hatched areas indicate twice the standard errors of the estimated trends.

5.2 Microwave Radiometer

The MWR measurements at Bern, Payenne, Mauna Loa, and Lauder were compared with ACE-FTS ozone measurements. The Bern and Payenne instruments have high temporal sampling frequencies, with approximately one measurement per hour, and can operate under nearly all-weather conditions, providing ozone measurements from the stratosphere to the mesosphere. Their high temporal resolution also allows diurnal ozone variations in the upper stratosphere and mesosphere to be characterized (Savaguet et al., 2023). To facilitate comparisons ACE-FTS profile data were interpolated on the MWR profile grid, approximately 2 km even vertical spacings throughout the altitude.

a) Bias determination

ACE-FTS measurements are obtained during sunrise and sunset occultations, corresponding to morning and evening local times. Coincident data pairs at Bern and Payenne were selected within a short temporal window of ± 1 hour and a spatial window of $\pm 5^\circ$ latitude and $\pm 10^\circ$ longitude. The ACE-FTS ozone profiles were smoothed using the averaging kernels provided with the coincident MWR retrievals. To ensure that the MWR retrievals were primarily constrained by the measurements rather than the a priori profiles, a sensitivity threshold of 0.5 was applied (e.g., Griffin et al., 2025). The comparison results for Bern are shown in Fig. 5. Over the altitude range of approximately 16–80 km, the ozone VMR differences are within 10% in the stratosphere and 20% in the mesosphere.

At Mauna Loa and Lauder, a wider temporal window of ± 3 hours was used to obtain a sufficient number of coincident pairs. At Mauna Loa, the ozone VMR differences in the mesosphere remain within approximately 20% (not shown), whereas at Lauder, the mesospheric differences are substantially larger (Fig. 6).

Monthly mean time series from the MWR measurements were also compared with the corresponding unsmoothed ACE-FTS monthly mean time series. Only MWR measurements within ± 1.5 hours of the mean local measurement times of ACE-FTS were included. The comparisons (not shown) show reasonable agreement in the stratosphere but substantial discrepancies in the mesosphere.

(b) Changes in decade-long MWR measurements?

For reliable estimation of long-term trends, it is essential that the measurement record remains consistent over time. Figure 7 shows the seasonal mean differences between ACE-FTS and MWR measurements at Bern over the 20-year record. An apparent change is observed around mid-2010 in the lower stratosphere and mesosphere. This can substantially affect the estimation of long-term trends, particularly in these altitude regions. This will be further discussed with the MWR team.

(c) Long-term ozone linear trends

Figure 8 shows the linear trends in ozone profiles derived from ACE-FTS and MWR measurements at Bern, Payenne, and Mauna Loa over two decades. The out-of-range trends in the MWR data observed in the mesosphere are likely related to the changes shown in Fig. 7. In addition, ozone concentrations are very low in these altitude regions, making the trend estimates less reliable. The trends in the middle part of the stratospheric profiles are more reliable.

In the upper stratosphere, both ACE-FTS and MWR measurements, except for the MWR measurements at Mauna Loa, show positive ozone trends, although these trends are not statistically significant. In the lower stratosphere, ozone trends are predominantly negative but are also not statistically significant.

(d) Lauder

Lauder is one of the few stations located at mid-latitudes in the Southern Hemisphere. The MWR instrument at Lauder provided measurements from 1992 to 2016 (Table 1; Fig. 9a), followed by lidar measurements beginning in 2017 (Table 1; Fig. 9b). At 35–36 km, ACE-FTS measurements show a steady increase in ozone over the study period, with both the MWR and lidar measurements showing consistent positive trends during their respective measurement periods. Combining the MWR and lidar records extends the ground-based measurement record and provides a longer observational basis for assessing the ozone trend.

5.3 FTIR

More than 20 FTIR stations are distributed across a wide range of latitudes, providing near-global coverage. The initial assessment focuses on evaluating the consistency of vertical ozone profiles measured by ACE-FTS and ground-based FTIR instruments. Figure 10 presents comparisons between ACE-FTS and FTIR ozone profiles using coincident data pairs. Applying the averaging kernels from the coincident FTIR measurements to smooth the ACE-FTS profiles generally improves the agreement between the two datasets (Fig. 10a). However, in some cases, averaging kernel smoothing introduces artifacts at lower altitudes (Fig. 10b). Applying a sensitivity threshold to exclude unreliable data points does not eliminate these artifacts. Instead, it reduces the vertical range over which the data are considered valid (Fig. 10c).

6. Conclusions

- Two decades of ACE-FTS v5.3 ozone and temperature profile data were compared with measurements from a suite of ground-based instruments in the NDACC network, with particular emphasis on long-term trends. At mid-latitudes in the Northern Hemisphere, where most of the stations are located, ACE-FTS consistently shows non-significant positive ozone trends. Similar features are observed at some lidar stations (Hohenpeißenberg and Mauna Loa) and MWR stations (Bern and Payenne), but are less pronounced or absent at other stations, including lidar at Haute-Provence and MWR at Mauna Loa.
- Stratospheric cooling was observed in both the ACE-FTS and lidar measurements at Hohenpeißenberg, Haute-Provence, and Mauna Loa.
- As an example, an apparent change in the MWR measurement record at Bern around 2010 may introduce an out-of-range long-term ozone trends, particularly in the mesosphere. This highlights the importance of assessing the consistency of ground-based measurements when deriving long-term trends. Given the longevity and consistency of ACE-FTS observations, ACE-FTS data can provide an independent reference for identifying such changes.
- To validate ACE-FTS ozone measurements against MWR observations in the mesosphere, a narrow temporal coincidence criterion of ± 1 hour is required to achieve biases within approximately 20%. Only a few stations, such as Bern and Payenne, can meet this criterion because of their high daily measurement frequencies.
- The validation against FTIR data is still in its preliminary stage. The objective is to compare partial column ozone trends derived from FTIR and ACE-FTS data with and without averaging kernel smoothing.

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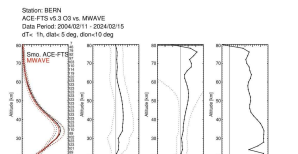


Figure 5. Comparison of ozone profiles from coincident ACE-FTS and MWR measurements at Bern with a criterion of ± 1 hour, $\pm 5^\circ$ latitude and $\pm 10^\circ$ longitude, with panels from left to right showing (1) mean vertical profiles, (2) absolute differences, (3) relative differences, and (4) correlation coefficients.

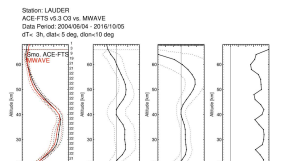


Figure 6. Similar as Fig. 5, but for Lauder with a coincidence criterion of ± 3 hour, $\pm 5^\circ$ latitude and $\pm 10^\circ$ longitude.

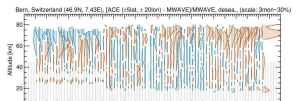


Figure 7. Seasonally averaged differences between ACE-FTS and MWR ozone profiles at Bern, derived from the corresponding de-seasonalized time series.

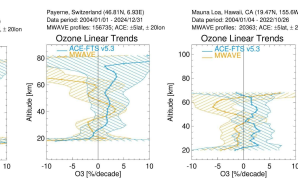


Figure 8. Linear trends in ozone profiles derived from ACE-FTS (light blue) and MWR (orange) measurements at Bern (left panel; 2004–2024), Payenne (middle panel; 2004–2024), and Mauna Loa (right panel; 2004–2023). The hatched areas indicate twice the standard errors of the estimated trends.

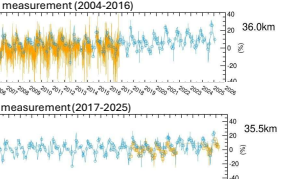


Figure 9. Ozone volume mixing ratio (VMR) time series at Lauder: (a, top) at 36 km, measured by ACE-FTS (blue) and MWR (orange); (b, bottom) at 35.5 km, measured by ACE-FTS (blue) and lidar (orange).

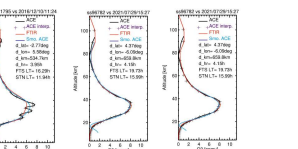


Figure 10. Comparisons of ozone profile between ACE-FTS (black), FTIR (red) and smoothed ACE-FTS profile (blue) without applying sensitivity values check for s71795 (a, left), for s97672 (b, middle) and with applying sensitivity check for s97672 (c, right). Symbols '+' denote ACE-FTS interpolation points on the FTIR grid.

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