

Monitoring Stratospheric Ozone with Lidars and other Instruments

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Abstract: Lidars measure stratospheric ozone and temperature and are an important component of the Network for the Detection of Atmospheric Composition Change (NDACC). They complement other ground-based instruments like ozone sondes, microwave radiometers, or Fourier Transform Infrared Radiometers (FTIRs). Lidars provide some of the longest stratospheric ozone records from single instruments, dating back to the late 1980s. Major advantages of the lidars are good accuracy, inherent self-calibration, and long-term stability. Here we compare lidar ozone measurements with those from other instruments. We show example profiles, as well as the long-term evolution of ozone observed by ground- and satellite-based instruments. The expected end of the microwave limb sounder satellite instrument in 2025 will leave an important gap. It makes continuation of the ground-based measurements by lidars and other NDACC instruments even more important, providing a reference for future satellite observations, but also to observe and verify the expected recovery of the ozone layer.

1. Lidars for Ozone Profiling

In the late 1980s and early 1990s, lidars at a few stations of the Network for the Detection of Stratospheric Change (NDSC, now NDACC) started regular measurements of ozone and temperature in the stratosphere [1,2]. Main goals were to monitor the depletion and future recovery of the ozone layer expected under the international Montreal Protocol [3], and to document temperature changes in a changing climate (Kyoto Protocol). In addition, the lidars should serve as ground-based references for satellites, which provide much better spatial coverage, but often have shorter lifetimes and sometimes issues with instrumental drift.

A major advantage of the lidars is that their measurement is essentially self-calibrating and long-term stable [1,4]: in the case of ozone, due to using the ratio of return signals from two ranges and at two fixed wavelengths; in the case

of temperature by Rayleigh scattering, due to the only marginal influence of the chosen far end initial value.

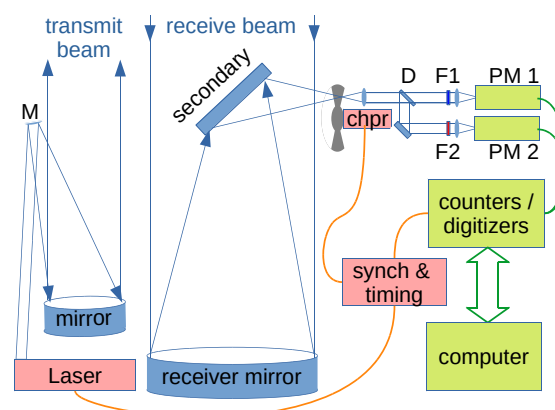


Figure 1. Typical setup of a differential absorption lidar for stratospheric ozone and temperature. A key component is the high-speed chopper (chpr), which is used to block the intense return signals from lower altitudes

In addition, the lidars are fixed and easily accessible instruments on the ground, which can be repaired and upgraded as necessary.

Typically, the lidars are differential absorption lidars, with powerful Excimer lasers generating pulses at 308 nm for the absorbed “on” wavelength, and H₂ Raman shifters or tripled NdYAG lasers generating pulses at 353 or 355 nm for the non-absorbed “off” wavelength. The receivers use large collecting mirrors, typically 60 to 100 cm in diameter, and photomultipliers in photon counting mode [5,6]. Mechanical choppers are necessary to block the intense near-field returns and avoid signal induced noise. In addition, the remaining large dynamic range of the return signals needs to be handled, e.g. with grey-filters, attenuated channels, or additional small telescopes.

2. Other Instruments

Other methods used for monitoring ozone profiles in NDACC [2], are balloon-borne ozone sondes [7], (based on the electrochemical reaction of ozone in an aqueous potassium-iodide solution), microwave radiometers [8], (based on measuring pressure broadened thermal microwave emission lines of atmospheric ozone at 110.8 or 142.2 GHz), and Fourier Transform Infrared Radiometers (FTIRs) [9], which retrieve ozone profiles (and many other trace gases) from absorption lines measured in the infrared region of sunlight, or from thermal emission lines measured in the atmosphere.

All these ground-based measurements have accuracies around 5% or better, but differ substantially in their vertical resolution. The ozone sondes provide a vertical resolution of about 150 meters, the lidars’ vertical resolutions range from a few 100 meters near 20 km altitude to a few kilometers near 50 km. The vertical resolution of ozone profiles from μ Wave radiometers and FTIRs is much coarser, only of the order of 10 to 20 km. Both techniques use optimal estimation (OEM) [10], which provides ozone profiles consistent with the measured spectra and with expectations from climatology. Typically, the retrieved profiles have wide averaging kernels and provide only 3 to 4 independent ozone values for broad atmospheric layers.

The space-based Microwave Limb Sounder (MLS) [11], also uses microwave emissions

from ozone in limb geometry and provides an altitude resolution of 1 to 2 km. The Ozone Mapping and Profiler Suite (OMPS) Limb Profiler [12], uses scattered sunlight in the ultra-violet part of the spectrum, resulting in similar altitude resolution.

3. Typical Ozone Profiles

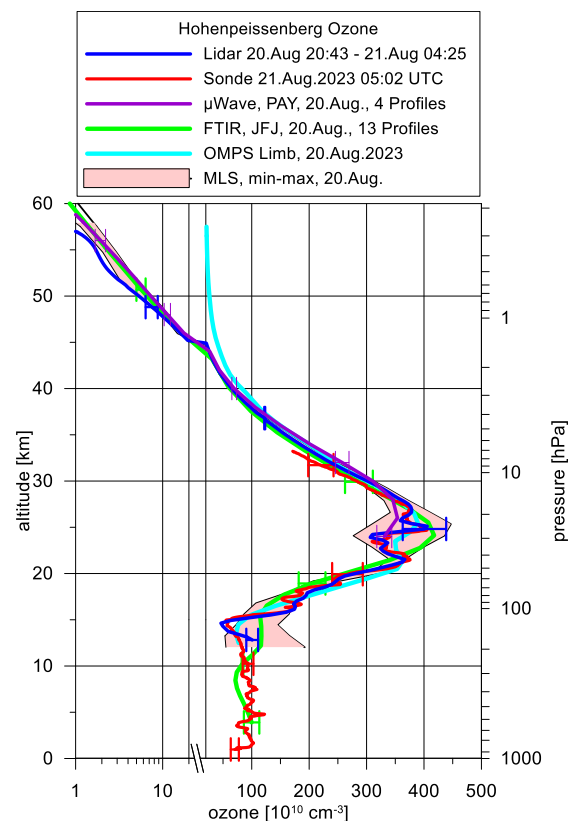


Figure 2. Ozone profiles from lidar and ozone sonde at Hohenpeissenberg, μ Wave at Payerne, FTIR at Jungfraujoch, and the satellite Microwave Limb Sounder (MLS) and OMPS Limb Profiler near Hohenpeissenberg. For MLS the envelope of 9 profiles within $\pm 5^\circ$ latitude and $\pm 8^\circ$ longitude is plotted, for OMPS the closest profile (603 km south-west).

Fig. 2 shows typical examples for ozone profiles measured near Hohenpeissenberg. Overall, all instruments provide quite similar ozone profiles, with the best agreement from 30 to 45 km. Ozone from the sondes tends to become too low above 30 km. Above 45 km, retrieved ozone from OMPS-Limb is unrealistically high, whereas agreement of lidar, FTIR, μ Wave and MLS is good up to 55 km.

The different altitude resolutions are most notable near 23 km. There, lidar, ozone sondes, and the satellite limb instruments see a clear dip

in the ozone profile, which is not recorded by the coarse resolution μ Wave and FTIR profiles.

4. Long-Term Records

The long-term evolution of ozone since the late 1970s is shown for two levels (upper and lower stratosphere) in Figs. 3 to 5. The satellite records in Fig. 3 are zonal means around 45°N and are merged from multiple instruments. The GOZCARDS record is based largely on SAGE I, HALOE and SAGE II up until 2004. From 2004 on GOZCARDS is largely based on MLS. The SAGE-OSIRIS-OMPS record is based on SAGE II (before 2005), OSIRIS (since 2002) and the OMPS Limb Profiler (since 2012). Agreement between the different stations and instruments is usually better than 5% in the lower stratosphere (50 hPa / 22 km). In the upper stratosphere (2 hPa / 42 km) larger differences are seen. For the lidars this is in part due to increasing noise resulting from the few photons received at these higher altitudes.

Averaging over the different NDACC instruments and stations (magenta line) gives a better and less noisy picture of the ozone evolu-

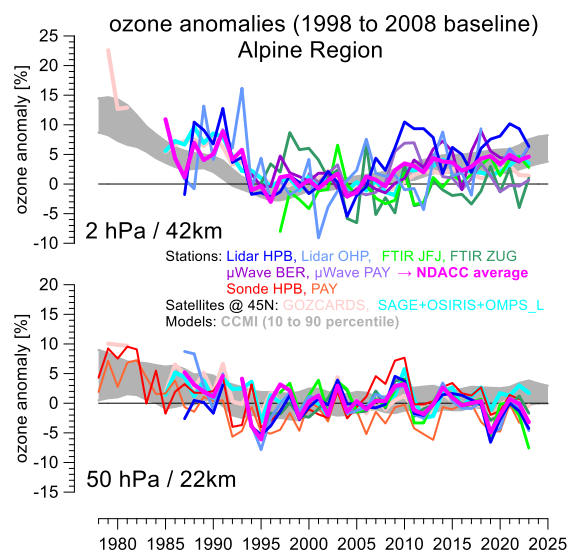


Figure 3. Annual mean ozone anomalies at two levels in the stratosphere from lidar measurements at Hohenpeissenberg (HPB) and Observatoire Haute Provence (OHP), from FTIRs at Jungfrauoch (JFJ) and Zugspitze (ZUG), from microwave radiometers at Bern (BER) and Payerne (PAY), and at 50 hPa / 22km also from ozone sondes at Hohenpeissenberg (HPB) and Payerne (PAY). In addition, zonal mean anomalies at 45°N are shown from two merged satellite data sets and from model simulations.

tion. Consistent with the satellite zonal means and the model simulations it shows decreasing ozone until the mid-1990s, more or less constant ozone since 2000 in the lower stratosphere, and slightly increasing ozone in the upper stratosphere (see also [13]).

The subtropical station at Hawaii (Fig. 4), as well as Lauder in the Southern Hemisphere (Fig. 5) show similar long-term behavior of ozone: A tendency for increasing ozone since about 2000 in the upper stratosphere, more or less constant, or even slightly decreasing ozone in the lower stratosphere. In some years, certain

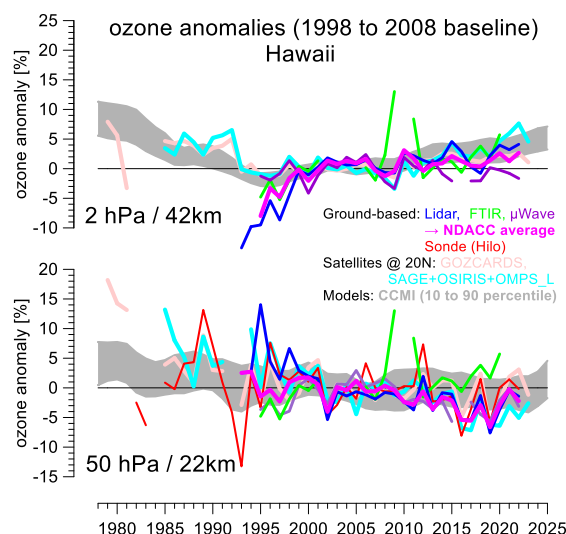


Figure 4. Same as previous figure, but for the Mauna Loa station on Hawaii. Note that measurements at Mauna Loa have been suspended since November 2022, when lava flows destroyed electrical power and road access to the station.

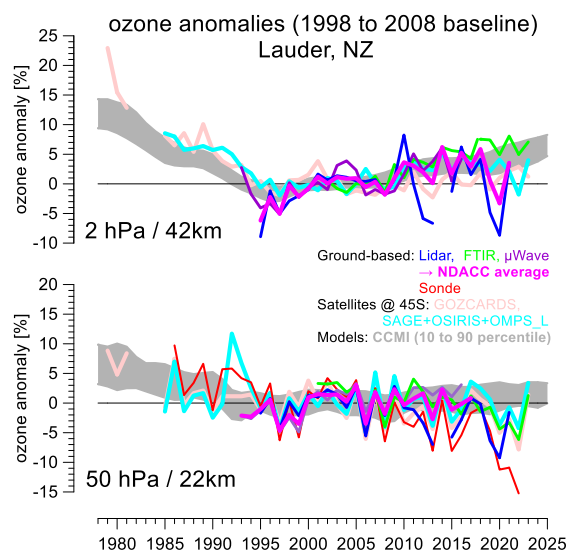


Figure 5. Same as previous figures, but for Lauder, New Zealand.

instruments provide values quite different from the others. Having multiple independent data sets is, therefore, very important to discover such outliers, and to obtain a representative average value.

Table 1. Stations used in this study

Station	Latitude	Longitude	Altitude
Hohenpeisenberg	47.8° N	11.0° E	975 m
Zugspitze	47.4° N	11.0° E	2964 m
Jungfraujoch	46.6° N	8.0° E	3580 m
Bern	47.0° N	7.5° E	550 m
Payerne	46.8° N	7.0° E	491 m
Observatoire Haute Provence	43.9° N	5.7° E	650 m
Table Mountain	34.4° N	117.7° W	2300 m
MaunaLoa, Hawaii	19.5° N	155.6° W	3397 m
Lauder, NZ	45.0° S	169.7° E	370 m

Table 2. Data sets used in this study

Data set	URL
NDACC ground-based data	https://www-air.larc.nasa.gov/pub/NDACC/PUBLIC/stations/
MLS station overpass data	https://avdc.gsfc.nasa.gov/pub/data/satellite/Aura/MLS/V05/L2GPOVP/
OMPS-LP station overpass data	https://avdc.gsfc.nasa.gov/pub/data/satellite/Suomi_NPP/L2OVP/LP-L2-O3-DAILY_v2.6/
GOZCARDS zonal means (and MLS after 2013)	https://search.earthdata.nasa.gov/search for MLS, Atmospheric Chemistry, Ozone,
SAGE-Osiris OMPS LP zonal means	https://research-groups.usask.ca/osiris/data-products.php go to OSIRIS level 3 and Merged Data Products

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