# Twenty-two years observations of stratospheric ozone concentration, temperature and aerosol over Tsukuba, Japan

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**ABSTRACT:** Differential absorption lidar (DIAL) at the National Institute for Environmental Studies (NIES) in Tsukuba (36°N, 140°E), Japan has been making routine observation for almost 22 years. Since 1988, more than 650 vertical profiles of stratospheric ozone and temperature have been obtained. We compared the lidar data with satellite data from the Stratospheric Aerosol and Gas Experiment (SAGE II) and assimilation data from the National Center for Environmental Prediction (NCEP). The lidar and SAGE II ozone profiles agreed within 5% in altitude range from 18 km to 40 km and within 10% up to 45 km. The lidar and NCEP temperatures agreed within 7 K in the 35- to 50-km range. Ozone levels were highest in spring at altitudes below 20 km. Above 30 km, the ozone maximum occurred during summer. The annual cycle of temperature is observed with a spring maximum for all altitudes in the 35- to 50-km range. Ozone variations caused by the Quasi-Biennial Oscillation (QBO) and the 11-year solar cycle are discussed, along with ozone trends observed after subtraction of the natural variations.

## INTRODUCTION

Over the last several decades, increasing attention has been paid to stratospheric species and parameters related to ozone depletion and climate change. To understand the characteristics and their changes in the stratosphere, long-term measurements of ozone concentrations, aerosols and temperature have been conducted by means of ground-based sensors. In this paper, we present an overview of ozone and temperature data obtained with the lidar system at the National Institute for Environmental Studies (NIES) in Tsukuba, Japan, in the context of long-term observation of ozone concentration and temperature for period from 1988 to 2010. The lidar data are compared with data obtained from the Stratospheric Aerosol and Gas Experiment (SAGE II) and the National Center for Environmental Prediction (NCEP).

## METHODS AND APPARATUS

The NIES ozone lidar system (located at 36°N, 140°E) is a typical UV differential absorption lidar (DIAL) system for low stratospheric ozone measurements. The lidar system has been in operation since 1988, and several replacements and improvements have been made since it was first installed (Nakane *et al*. 1992a; Nakane *et al*. 1992b). The system parameters and improvements were presented in detail by Park *et al.* 2006. Currently, the NIES ozone lidar system uses wavelength channels of 308/355-nm (for the Mie/Rayleigh scattering DIAL mode) and 332/386-nm (for the Raman scattering DIAL mode). The 355-nm signal is used for aerosol and temperature measurements. The SAGE II is a satellite instrument (McCormick *et al.* 1989), that measured ozone absorption at various altitudes by comparing the visible part of solar spectra obtained with different absorption cross-sections through the atmosphere. The SAGE II data were obtained from ftp://ftp-rab.larc.nasa.gov/pub/sage2/v6.20 using retrieval algorithm version 6.20. The vertical profiles were restricted to data obtained within ±3° latitude and ±20° longitude from the NIES lidar location. In this study, we used only values of ozone concentration with statistical errors smaller than 20% for both instruments. The NCEP vertical profiles of temperature were obtained from ftp://ftp.cpc.ncep.noaa.gov/wd53rl/ndscdata/ncep/temp. The NIES lidar vertical profiles of temperature were restricted to data obtained with statistical errors smaller than 15%.

# RESULTS AND DISCUSSIONS

Figure 1 plots point-to-point long-term temporal variations of ozone concentration measured at altitudes of 15, 20, 25, 30, 35, and 40 km. The solid circles present results of measurements by NIES ozone DIAL during period from 1988 to 2007. The open squares show results from SAGE II up to July 2005. The time series plotted on the Fig.1 are based on 549 vertical profiles of the NIES ozone DIAL and 374 profiles of SAGE II.

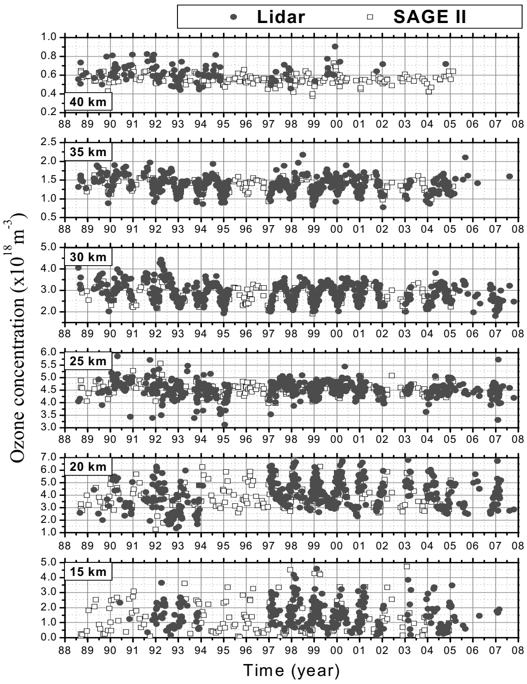


Figure 1. Time series of ozone concentrations obtained with the NIES ozone lidar (solid circles) and by the SAGE II (open squares)

In general, the variations in ozone observed with the NIES ozone lidar agree well with those measured with the SAGE II, at all altitudes and over the entire period. The two instruments did not obtain measurements at exactly the same place and or time, and therefore there were small differences between individual data points for the two instruments. Systematic differences due to diurnal variations of ozone concentration have to be considered because the SAGE II measurements were taken at sunrise and sunset, whereas the lidar measurements were taken only at night. The fact that most of the profiles were not obtained during the same day, might result in overestimation of the disagreement between the DIAL and SAGE II data. To minimize these effects, we used monthly mean values of ozone concentration for the following analysis.

The time series of ozone exhibited not only long-term trends but also shorter time scale variations, in which annual cycle, Quasi-Biennial Oscillation (QBO) and the 11-year solar cycle are significant. Among these, only annual variations of ozone can be clearly distinguished for all the altitude in Fig. 1. Therefore, to accurately analyze other variations and the long-term trends, subtraction of annual cycle is required.

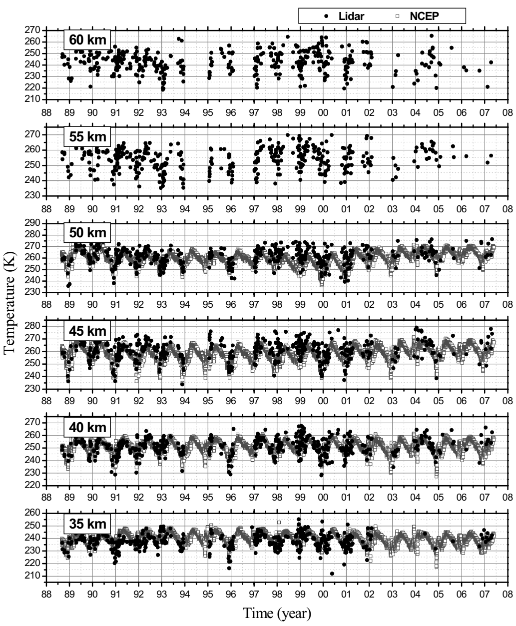


Figure 2. Time series of temperature at 35, 40, 45, 50, 55, and 60 km obtained with NIES lidar (solid circles) and temperatures at 35, 40, 45, and 50 km obtained from the NCEP (open squares).

Figure 2 plots point-to-point long-term temporal variations in temperature measured at altitudes of 35, 40, 45, 50, 55, and 60 km. The solid circles present results of measurements by NIES DIAL during period from 1988 to 2007. On the same figure by open red squares are also shown the temperature time series obtained by interpolation from the three-dimensional grid data (NCEP upper atmosphere data) on the same day and at the same time. The figure plots 574 temperature profiles retrieved from lidar signals and 6791 NCEP temperature profiles. In general, seasonal variations and year-to-year variations in temperature exhibit good agreement between two data sets. The variations in temperatures measured with the NIES lidar and the NCEP temperatures agreed within 7 K in the 35- to 50-km altitude range, which corresponding to relative difference smaller than 2%

The climatological mean vertical profiles obtained by lidar and SAGE II, and the relative differences between them, are shown in Figure 3. These profiles were obtained by averaging of all available monthly mean profiles from 1988 to 2005, separately for the two instruments. The climatology mean ozone profiles measured by lidar and SAGE II agreed within ±5% in the altitude range from 16 to 37 km and within 20% up to 44 km. At 15 km, the climatological mean obtained by lidar was markedly smaller then the SAGE II mean (relative difference 23%; Figure 3). This large difference might have been caused by the presence of small-scale structures in the lower stratosphere and by meteorological inhomogeneties. In the altitude range from 37 to 45 km, the lidar climatological means were larger than the means obtained from the satellite data.

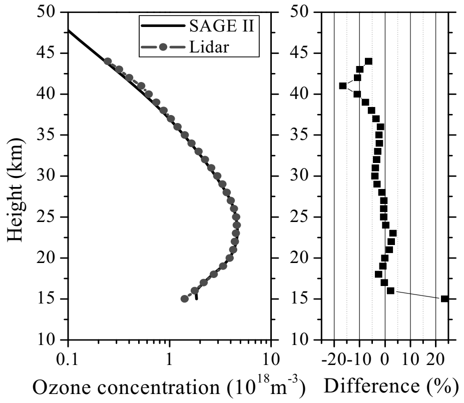


Figure 3. Climatological mean vertical ozone concentration profiles obtained with the NIES ozone lidar and the SAGE II, along with relative difference between them.

On the basis of the vertical profiles of the climatological means, we limited the experimental data to the altitude range where the difference between the lidar and SAGE II profiles was smaller than 5%, namely from 16 to 35 km.

The average annual cycles of ozone concentration recorded by the two instruments are shown in Figure 4 for altitudes of 20, 25, 30, and 35 km. We obtained these average annual cycles by averaging all the monthly mean profiles separately for each month of the year. The annual cycles for the lidar data agreed well with the SAGE II data for the presented altitudes, as relative difference was less than 4%. All the features of annual cycles are typical for the Northern Hemisphere [8].

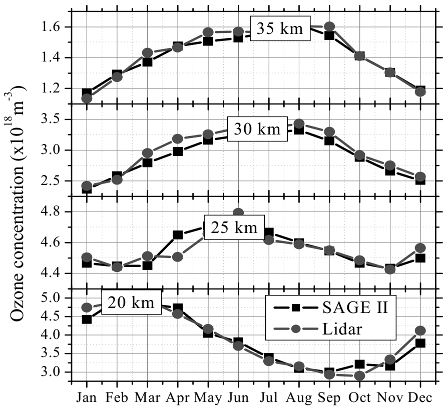


Figure 4. Annual cycles of ozone concentrations reported with the NIES ozone lidar and by SAGE II over the 1988 to 2005.

In the lower stratosphere (20 km), the annual cycle of the ozone shows the highest ozone levels occurred in late winter and early spring – February to March. At 25 km the maximum of the ozone concentration is found to be in late spring – May to June. It is caused by the global Brewer-Dobson circulation that transports ozone to low altitudes in late winter in high altitude. In the middle stratosphere (30 km and 35 km heights), a maximum of the ozone concentration was observed in summer. The general form of the annual cycle in the middle stratosphere mainly reflects the photochemical production of ozone by solar radiation, which is low in winter and high in summer.

The vertical profiles of the climatological mean of temperature obtained from the lidar data, the NCEP data, and CIRA'86 atmospheric model are shown in Figure 5, along with the relative differences between the three sets of data. These profiles were obtained by averaging all the available monthly mean profiles from 1988 to 2008, separately for three instruments.

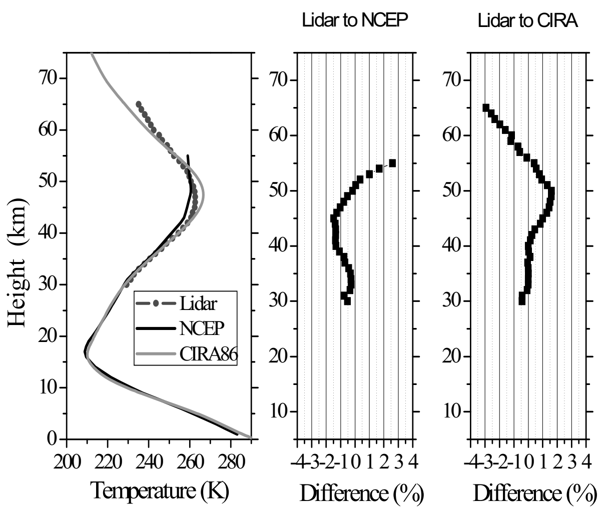


Figure 5. Climatological mean vertical temperatures profiles (left panel) based on monthly means obtained with NIES lidar, from the NCEP and with CIRA86 model, along with relative differences (center and right

The climatological mean temperature profiles measured by lidar and by NCEP agreed within ±1.5% in altitude range from 30 km to 53 km and within 3% up to 55 km. Temperature profiles measured by lidar and profiles obtained with the CIRA86 model agreed ±2% in altitude range from 30 km to 60 km and within ±3% up to 65 km.

The average annual cycles of temperature recorded by the lidar and NCEP are shown in Figure 6 for altitudes 30, 35, 40, 45, 50, 55 and 60 km. These average annual cycles was obtained by averaging of all monthly mean profiles, separately for each month of the year. The annual cycles for lidar data are in very good agreement with that for NCEP for the altitudes 30, 35, and 50 km as relative difference is smaller than 1%. The values obtained by lidar are higher than NCEP data in altitudes 40 and 45 km for all the months of the year. However, the relative difference remains smaller than 2%. The annual cycles of the temperature show highest levels occur in late spring and early summer – May to June at all presented altitude. All the features temperature's annual cycles are typical for Northern Hemisphere.

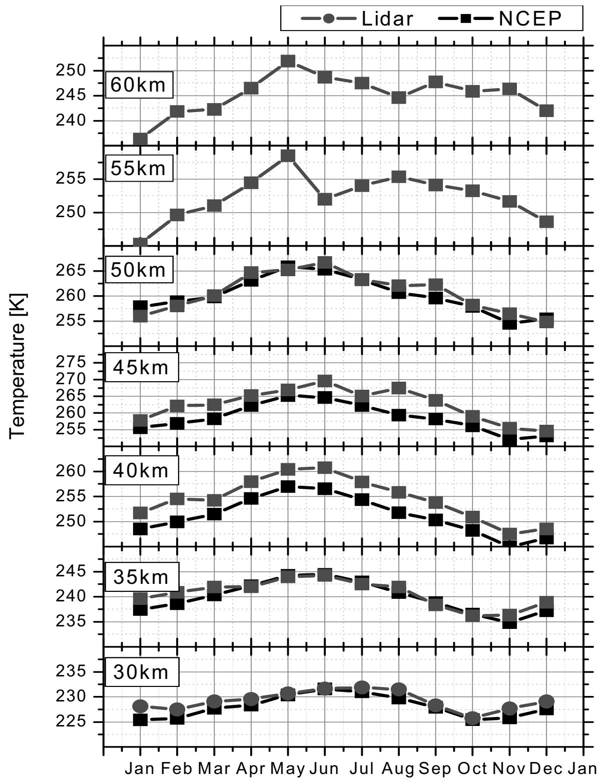


Figure 6. Annual cycles of temperature obtained with the NIES ozone lidar and NCEP.

## CONCLUSIONS

Long-term variations of stratospheric ozone concentration over Tsukuba, Japan were observed with the NIES ozone DIAL system. Comparison of the climatological mean ozone profiles measured by lidar and the SAGE II showed agreement within 4% in altitude range from 16 km to 37 km and within 15% up to 45 km. The annual cycles of the ozone concentration show highest ozone concentration in spring at altitude 20 km. In the middle stratosphere (30 and 35 km), a maximum of the ozone concentration was observed in summer.

Comparison of the climatological mean temperature profiles measured by lidar and NCEP showed agreement within ±1.5% in altitude range from 30 km to 53 km and within 3% up to 55 km. The annual cycles of the temperature show highest temperature values in late spring at all altitudes.


## ACKNOWLEDGMENTS

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## REFERENCES


1. MCGEE T.J., et al., 1991, STORZ LITE: Stratospheric Ozone Lidar Trailer Experiment, Optical Engineering **30**, 31–39.
2. NAKANE H., et al., 1992, Comparison of ozone profiles obtained with NIES DIAL and SAGE II Measurements, Journal of Meteorological Soc. Japan, **71**, 153–159.
3. NAKANE H., et al., 1992, Vertical profiles of temperature and ozone observed during DYANA campaign with NIES ozone lidar system at Tsukuba, Journal of Geomagnetism and Geoelectricity, **44**, 1071–1083.
4. PARK C. B., et al., 2006, Algorithm improvement and validation of National Institute for Environmental Studies ozone differential absorption lidar at the Tsukuba Network for Detection of Stratospheric Change complementary station, Applied Optics **45**, 3561-3576.
5. SCHOTLAND R. M., 1974, Errors in the lidar measurements of atmospheric gases by differential absorption, Journal of Applied Meteorology, **13**, 71–77.
6. CHANIN M. L. and HAUCHECORNE A., 1981, Lidar observations of gravity and tidal waves in the stratosphere and mesosphere, Journal of Geophysical Research, **86**, 9715–9721.
7. MCCORMICK M. P., et al., 1989, An Overview Of SAGE I And II Ozone Measurements, Planetary and Space Science, **37**, 1567–1586.
8. STEINBRECHT, W., et al., 2006, Long-term evolution of upper stratospheric ozone at selected stations of the Network for the Detection of Stratospheric Change (NDSC), Journal of Geophysical Research, **111**, D10308, doi:10.1029/2005JD006454.
9. NEWCHURCH M. J., YANG E.-S., CUNNOLD D. M., REINSEL G. C., ZAWODNY J. M., and RUSSELL III J. M., 2003, Evidence for slowdown in stratospheric ozone loss: First stage of ozone recovery, , **108**(D16), 4507, doi:10.1029/2003JD003471
10. STEINBRECHT W., CLAUDE H., and WINKLER P., 2004, Enhanced upper stratospheric ozone: Sign of recovery or solar cycle effect?, Journal of Geophysical Research, **109**, D02308, doi:10.1029/2003JD004284