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Seasonal Variation of Ozone in The Upper Mesosphere at High Latitudes

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1. Abstract

Ozone in the upper mesosphere and lower thermosphere (20-105 km) has been measured by The Solar Occultation for Ice Experiment (SOFIE) instrument on the Aeronomy of Ice in the Mesosphere (AIM) satellite. The ozone measurements at 0.292 μm were made over 9 years (2007-2016) in the latitude range of 65°-85° in both hemispheres at a high vertical resolution (1.8 km). In the upper mesosphere (~80-87 km), large seasonal variation can be noticed where the ozone mixing ratio observed at the winter solstice is 3-4 times higher than summer solstice. What controls this seasonal variation of ozone is still up for much debate. These variations are annual in nature and occur every year in both hemispheres. The characteristics of the variations also change with altitude. In this study we use water vapor, also measured by SOFIE and atomic oxygen inferred from ozone measurements to understand the cause of the observed variability in ozone. Preliminary analysis indicates that the driving force for the seasonal variation of ozone is the variability of atomic oxygen and water vapor in the upper mesosphere, with ozone positively correlated with atomic oxygen and negatively correlated with water vapor. In the upper mesosphere, the photochemical reactions are fast enough that ozone is in equilibrium with odd oxygen, our study suggests that the seasonal variation is caused by dynamics through species like water vapor, atomic oxygen and temperature.

2. Introduction

In the upper mesosphere, odd hydrogen compounds are the main source of destruction for ozone which is primarily produced from photolysis of water vapor at this altitude. On the other hand, atomic oxygen is the main source of ozone at the upper mesosphere, which is transported downwards from the thermosphere. In this study we use water vapor, also measured by SOFIE and atomic oxygen inferred from ozone measurements to understand the cause of the observed variability in ozone. SOFIE orbit (65° -85° latitude in both hemisphere) gives us a great opportunity to investigate the seasonal behavior of ozone at high latitudes. In this study, we investigate the ozone variability in the upper atmosphere (~75-95 km) in the northern hemisphere (NH). The mean ozone profile for NH 2007-2016 is shown in Figure 1.

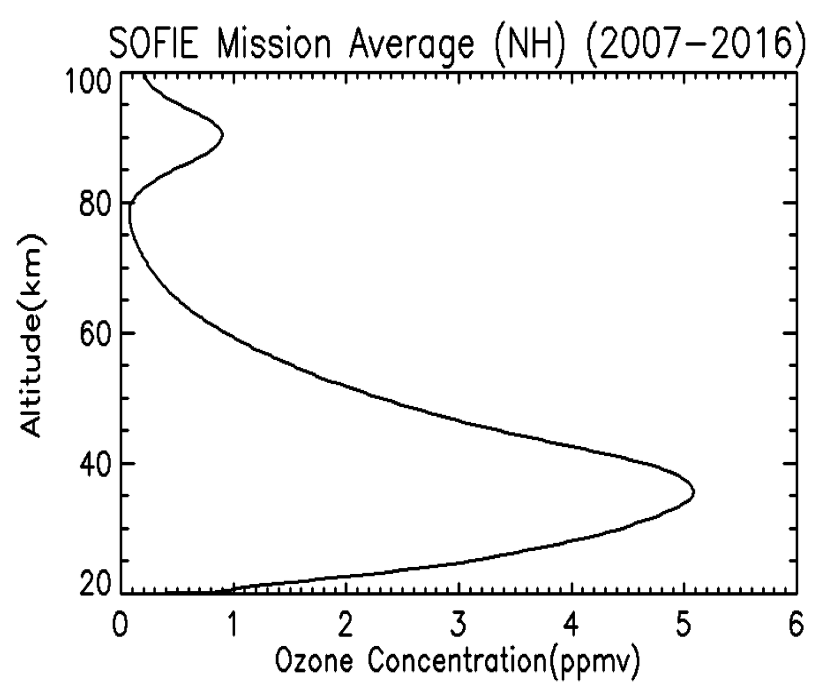

Figure 1: Zonal mean ozone profile averaged over all latitudes (65° -85° North) and over 9 years (2007-2016) in the northern hemisphere

3. Data & Methods

SOFIE ozone, water vapor, pressure and temperature profile are used in this study. Atomic oxygen is derived from SOFIE ozone and is based on SABER atomic oxygen derivation by Smith et al. [2010]. The determination of atomic oxygen in the upper mesosphere is based on ozone photochemistry at day and night. The relevant photochemical equations are,

$$O + O_2 + \mathrm{M} = O_3^{*} + M \qquad \left(k_1 = 6\times10^{-34}\left(\frac{300}{T}\right)^{2.4}\right) \qquad (1)$$

$$\mathrm{H} + O_3 = OH^{*} + O_2 \qquad (k_2 = 1.4\times10^{-10}\exp(-470/T)) \qquad (2)$$

$$O + O_3 = O_2 + O_2 \qquad \left(\mathrm{k}_3 = 8.0\times10^{-12}\exp\left(-\frac{2060}{\mathrm{T}}\right)\right) \qquad (3)$$

$$O_3 + hv = O_2^{*} + O^{*} \qquad (J_{O_3}) \qquad (4)$$

Ozone is produced from atomic oxygen by reaction (1) and is destroyed by reaction (2),(3) and (4). The lifetime of ozone above 80 km is very short so the assumption of photochemical equilibrium between O_3 and O is valid . During the day, the loss rate due to photolysis is so rapid that loss due to kinetic reactions can be ignored. Equating daytime production and loss yields,

$$k_1\cdot[O]\cdot[O_2]\cdot n = J_{O_3}\cdot[O_3]$$

And therefore,

$$[O]_{day} = \frac{J_{O_3}\cdot[O_3]}{k_1\cdot[O_2]\cdot n}$$

Where n is number density,

$$n = \frac{P}{kT}$$

SOFIE uses solar occultation to measure sunset and sunrise profile of ozone. Satellite occultation sunset (local sunrise) is measured in the southern hemisphere and satellite occultation sunrise (local sunset) is measured in the northern hemisphere. The daytime atomic oxygen formula is applied on the satellite occultation sunrise (local sunset) data to retrieve atomic oxygen in the northern hemisphere.

4. Results

4. 1. Seasonal Variation

Figure 2 shows the seasonal variation of ozone, atomic oxygen and water vapor at the upper mesosphere. Positive correlation can be observed between ozone and atomic oxygen at this altitude which is expected because above 80 km in the upper mesosphere, ozone is essentially a tracer for atomic oxygen. Negative correlation can be seen between water vapor and ozone because odd hydrogen compound is the main source of destruction for odd oxygen in the upper mesosphere which is produced from photolysis of water vapor. Overall this figure indicates a high negative correlation between ozone and water vapor, and a high positive correlation between ozone and atomic oxygen.

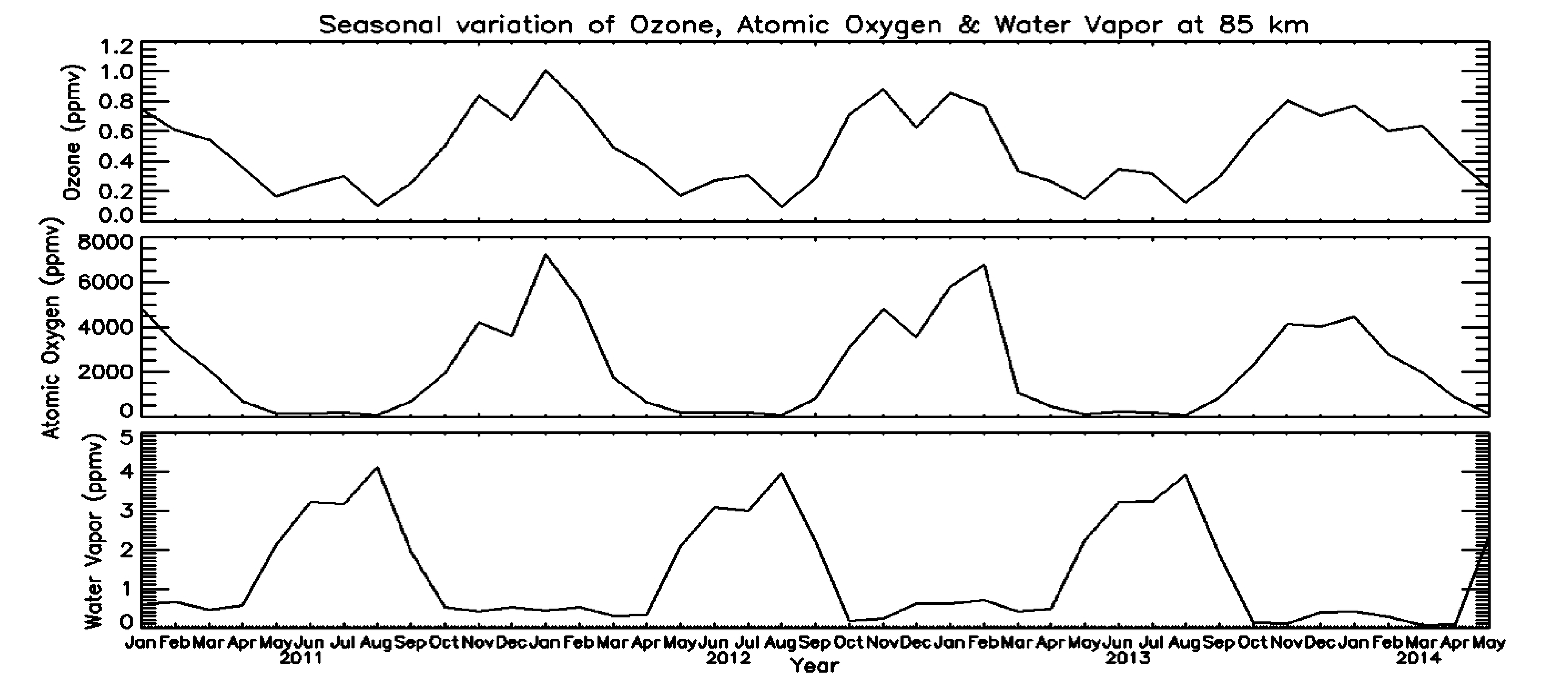

Figure 2: Monthly mean mixing ratio of Ozone, Atomic Oxygen & Water vapor are plotted for 2011- 2014 at 85 km for the northern hemisphere.

4.2. Correlation between Ozone, Water Vapor and Atomic Oxygen

In Figure 3, the correlation coefficient between ozone and water vapor & ozone and atomic oxygen is plotted as a function of altitude for the year 2011. Between 80-87 km, high positive correlation can be observed between ozone and atomic oxygen. High negative correlation can be observed between ozone and water vapor at this altitude range. These two factors produce the seasonal variation of ozone in the upper mesosphere.

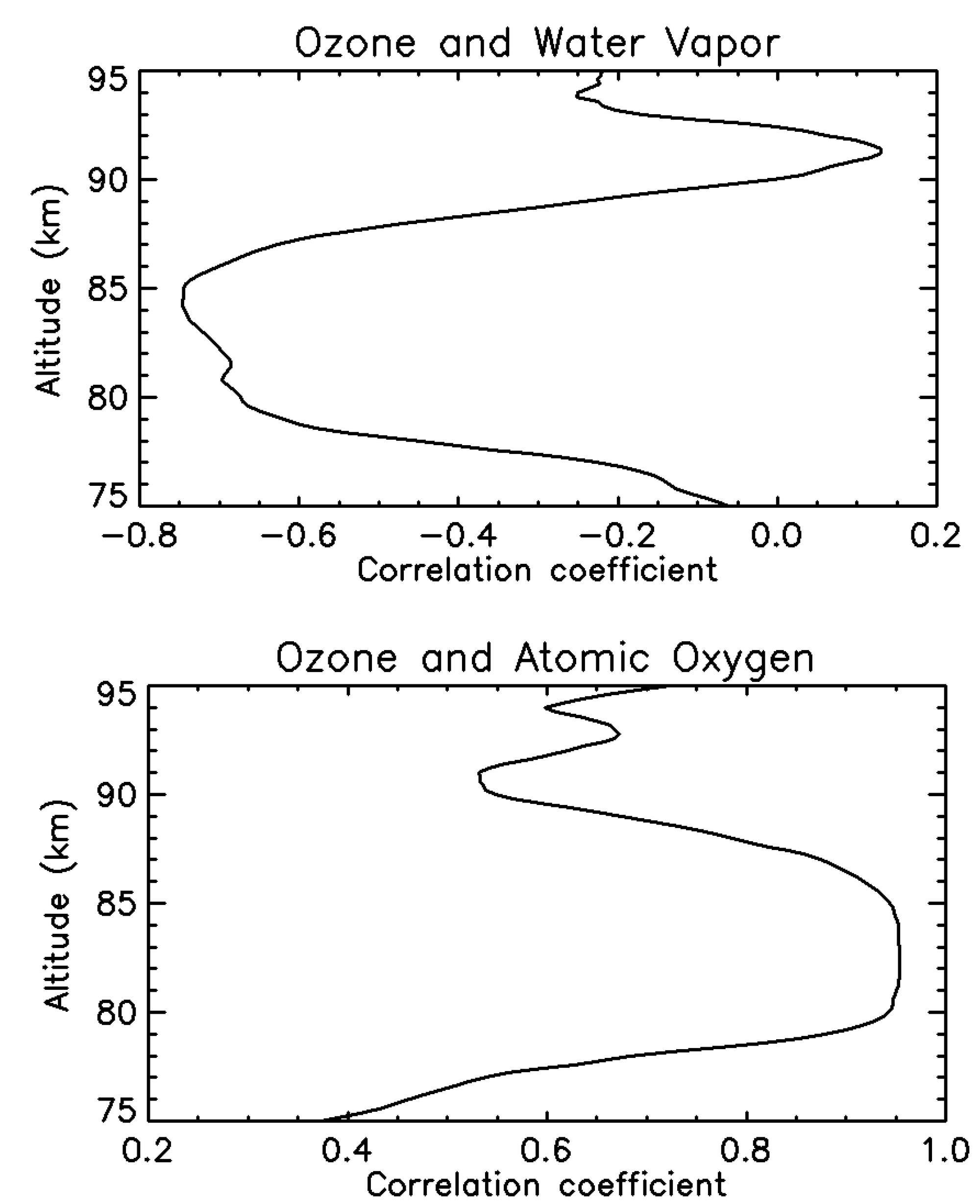

Figure 3: Correlation between ozone and water vapor (upper panel) & ozone and atomic oxygen (lower panel) NH 2011 as a function of altitude.

4.3. Vertical Transport

Figure 4 shows SOFIE observations of water vapor mixing ratio and atomic oxygen mixing ratio for the year 2011. For water vapor, a large vertical transport can be seen from stratosphere to the upper mesosphere every summer. PMC evaporation is another component in water vapor enhancement in the summer. The amount of water vapor can be increased by 8 times which causes destruction of ozone which sets motion to the seasonal variation of 0zone. There is a sharp drop off in active H production after 85 km, so we don't see much seasonal variation of ozone above 87 km. Enhanced downwelling of atomic oxygen can be observed in winter due to gravity waves. At summer when there's an abundance of water vapor in the upper mesosphere, a large cavity can be seen in the atomic oxygen profile. This indicates how water vapor is responsible for odd oxygen destruction in the upper mesosphere.

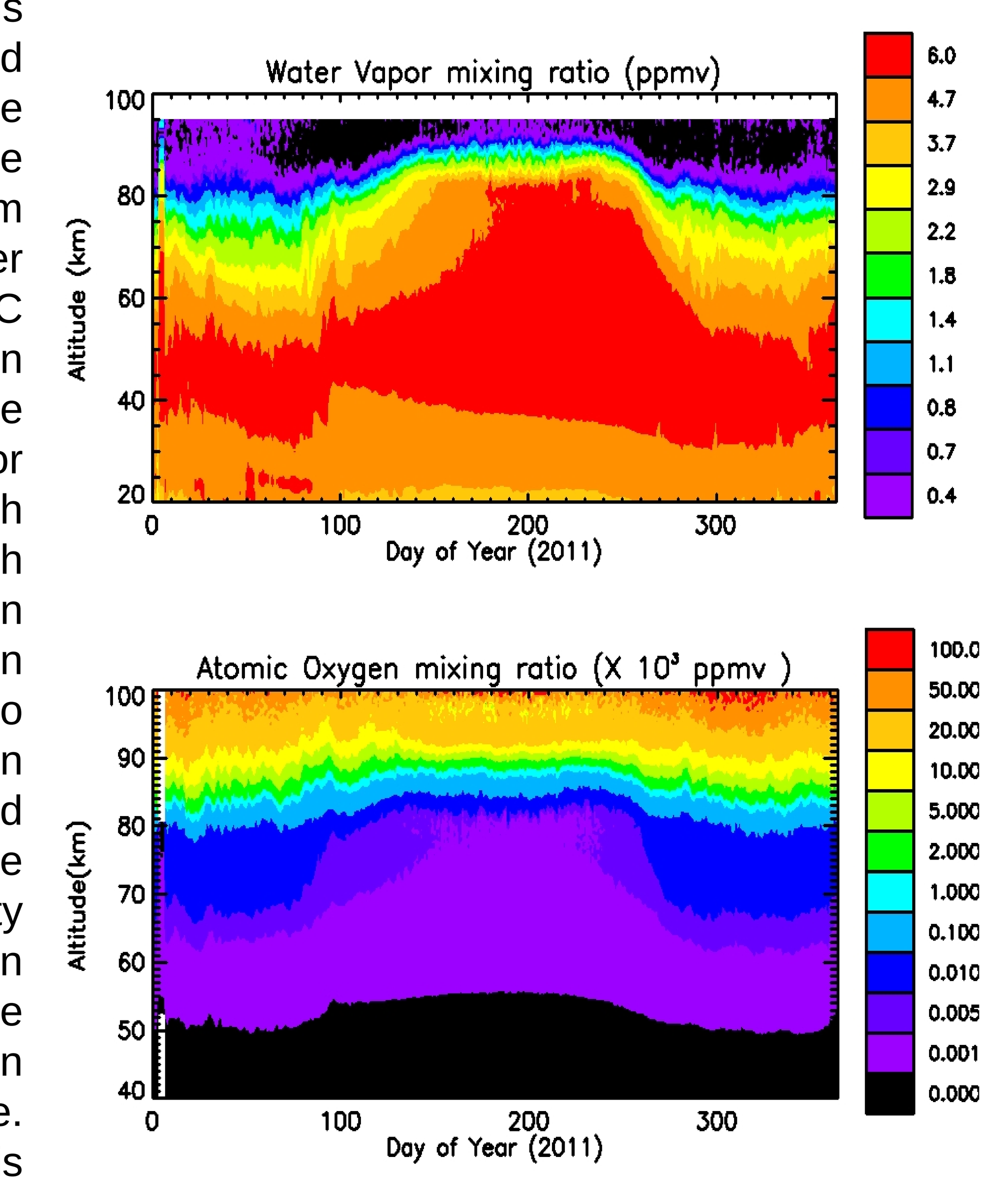

Figure 4: Contour image of mixing ratio vertical profile for water vapor (upper panel) and atomic oxygen (lower panel for the year 2011 at the northern hemisphere

5. Conclusion

1. In the upper mesosphere, the photochemical reactions are fast enough that ozone is in equilibrium with odd oxygen, So the seasonal variation is caused by dynamics through species like water vapor, atomic oxygen and temperature.

2. The driving force for the seasonal variation of ozone is the variability of atomic oxygen and water vapor, with ozone positively correlated with atomic oxygen and negatively correlated with water vapor.

3. Vertical Transport of water vapor upwards from the stratosphere in summer is the primary factor. H_2O enhancement due to PMC evaporation is also a major component.

4. Enhanced downwelling of atomic oxygen from lower thermosphere due to gravity waves in the winter may be another contributing factor.

6. References

Smith, A. K., D. R. Marsh, M. G. Mlynczak, and J. C. Mast (2010), Temporal variations of atomic oxygen in the upper mesosphere from SABER, J. Geophys. Res., 115, D18309, doi:10.1029/2009JD013434.