SABER observations of mesospheric ozone during NH late winter 2002–2009

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1. Introduction

The Northern Hemisphere winters of 2004, 2006, and 2009 had dynamical events in the middle atmosphere that were similar to one another but different from the long-term average. Manney et al. [2005, 2008b, 2009] described the stratospheric dynamics during these years. Hoffmann et al. [2007] used radar observations to characterize the NH dynamics during the January 2006 sudden stratospheric warming. Siskind et al. [2007] discussed the role of gravity waves during January-February 2006. In all three of these winters, there was a sudden stratospheric warming in mid-winter, followed by a period with low planetary wave activity. During these quiet periods, a strong, stable, and cold vortex developed in the upper stratosphere and lower mesosphere and the stratosphere was above 80 km. The high altitude of the maximum has led Manney et al. [2005] and others to call this phenomenon the “elevated stratopause”.

The unusual dynamics also affected downward transport of trace species from the upper mesosphere or thermosphere during these periods. Observations indicating enhanced descent of mesospheric air into the upper stratosphere after the sudden warming during one or more of these winters have been reported for NOx [Randall et al., 2006, 2009], NO2 [Hauchecorne et al., 2007], CO [Jin et al., 2005; Manney et al., 2008a; Funke et al., 2009], and H2O [Manney et al., 2008a]. Winick et al. [2009] found a sharp enhancement in OH airglow emission and a lowering of the peak of the emission layer, both of which are closely tied to atomic oxygen. None of these studies show the upper limit of the downwelling region. Thus, there has not yet been published evidence indicating how far into the upper mesosphere or lower thermosphere the anomalous conditions extended.

In this paper, we will refer to the periods after the sudden stratospheric warmings in 2004, 2006, and 2009 as anomalous periods, and to those winters as being anomalous winters, in order to distinguish them from the other winters for which we have observations. For convenience, the other winters will be called normal. We use observations of temperature, ozone and atomic oxygen from the mid-January to mid-March period of eight winters beginning in 2002. The temperature and ozone observations span from the lower stratosphere to above the mesopause; atomic oxygen data are available for the middle to upper mesosphere. This work shows how ozone at the secondary (mesopause) and tertiary (mid-mesosphere) maxima in the anomalous winters differs from that in other years.

2. SABER Data

This study uses version 1.07 data from the SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) instrument on the TIMED (Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics) satellite. Each year, the SABER viewing direction is towards the north for a period in NH winter beginning around 12–15 January (25 January in 2002) and lasting for two months. We focus on the high latitudes (70–83°N) during this winter period of 2002–2009. The data used are Level 2 temperature, nighttime ozone, and Meinel band volume emission rate (used to retrieve atomic oxygen). CO2 emission data from two 15 μm channels are used for the non-LTE retrieval of temperature; see Remsberg et al. [2008] for a detailed description and error analysis. The nighttime retrieval uses a specified distribution of CO2, which could be a source of systematic error in dynamical periods that are strongly perturbed. The retrievals of nighttime ozone, atomic oxygen, and atomic hydrogen use measurements from two additional SABER channels, detecting emissions of ozone at 9.6 μm and OH Meinel band at 2.0 μm. The O and H retrievals assume that ozone is in chemical equilibrium. Both rely on temperature and pressure information; the nighttime O retrieval is weakly dependent on ozone while the H retrieval is strongly dependent.

Recent careful analysis of the v1.07 retrievals has shown that some profiles of temperature and ozone do not
fit the quality screening. The primary screening criterion is a consistency between the LTE and non-LTE temperature retrievals, which overlap in the altitude range 60–70 km. In particular, there are a number of unsatisfactory retrievals during NH winter at latitudes greater than 80°N. These are no longer included in the data set posted at http://saber.gats-inc.com but were in the v1.07 data until recently and have been widely disseminated. In our analysis, profiles that do not satisfy the quality screening (see http://saber.gats-inc.com/screened/ for a list) are not included.

Here, we derive the nighttime O using an algorithm based on that recently developed by the SABER project, including the same parameters (rate coefficients, etc.). Papers giving details of the retrieval are in preparation by M. G. Mlynczak et al. and A. K. Smith et al. The method assumes that ozone is in photochemical equilibrium so that its losses by reaction with H (which gives rise to the observed Meinel emission) and O are in balance with its production from the reaction O + O₂.

3. Results

Figure 1 shows an altitude-time series of the daily averaged night temperature extending from 30 to 100 km, averaged over all profiles poleward of 70°N. The anomalous dynamics in 2004, 2006, and 2009 can be seen in the elevated position of the stratopause, which is more than 20–30 km above the climatological stratopause height. During 2004, the elevated stratopause already existed at the time SABER high latitude observations began; it persisted until about day 60. In 2006, there was a striking discontinuity in the stratopause; the warm temperatures disappeared from ~50 km after day 25 and reappeared at 80 km around day 30. The elevated position of the stratopause descended with time but the location was still above 50 km at the time the TIMED satellite yawed around and pointed SABER toward the SH. In 2009, SABER again was observing the NH when the discontinuity and upward displacement of the stratopause occurred in late January/early February.

Figure 2 shows the nighttime ozone in the middle and upper mesosphere as in Figure 1. The most prominent climatological feature is the ozone secondary maximum, around 90–95 km. In the period following the sudden warmings of all three of the anomalous winters, the magnitude of the secondary ozone maximum decreased to less than 10 ppmv and its short-term variability was lower. For 2006 and 2009, when the observations span the onset of the unusual structure, the timing of the ozone decrease coincided with the appearance of the elevated stratopause. Prior to the dramatic discontinuities in January 2006 and 2009, the ozone in the secondary maximum was particularly high and coincided with low temperatures. The ozone tertiary maximum is visible as a weak maximum at 70–75 km. In the anomalous winters its position was displaced downward by 3–5 km.

In exploring aspects of the ozone chemistry that would contribute to the observed interannual variability, we first look at the photochemical lifetime. The lifetime is defined as the inverse of the photochemical loss rate, including all kinetic and photolytic reactions. If it is short, the ozone concentration is governed by local photochemistry; if it is long, the ozone can also be directly affected by transport. Figure 3a shows the 24-hour average chemical lifetimes of ozone and odd oxygen (Oₓ = O₃ + O) for two latitudes for 1–20 February 2004, calculated with the ROSE model. The model simulates realistic temperatures and chemical transport and includes the photochemical reactions in the hydrogen, chlorine, nitrogen, and hydrocarbon families that are important for ozone chemistry in the middle atmosphere [Smith and Marsh, 2005]. The 87.5° profiles are completely within the polar night while those at 67.5° include both daylight and darkness. With the large difference in the ozone lifetime between the secondary maximum near 90 km and the tertiary maximum near 70–75 km, we will consider the ozone in these two regions separately.

3.1. Secondary Ozone Maximum

Ozone at the secondary maximum is formed by the reaction combining the abundant and long-lived atomic oxygen with molecular oxygen. At night, it is destroyed
is illustrated by the coincident high ozone and low temperature at around 90 km during January 2006 and 2009 (Figures 1 and 2), just before the discontinuities in both fields. Changes in H could also contribute to the ozone variability. On short timescales (hours to days), mesospheric temperature and O are positively correlated; downward motion increases both. The evolution of H is less easy to predict. The mean gradient of hydrogen in the mesosphere is not as strong as those of potential temperature and atomic oxygen so its variability due to vertical motions is less. In the lower and middle mesosphere, its lifetime is short so its concentration can be affected by local photochemistry. The seasonal cycle of hydrogen responds to the seasonal transport of water; the normal downwelling in the winter high latitudes brings air that has a low concentration of water. Downwelling may also bring air with lower molecular oxygen.

From equation (1), we would expect lower O₃ to be accompanied by one or more of the following: higher T, lower O, or higher H. Figures 3b–3d shows SABER observations of nighttime ozone, temperature, and atomic oxygen for high northern latitudes of February for the eight years covered in this study. During the anomalous winters, concentrations of atomic oxygen that are substantially higher than those normally seen appear over much of the mesosphere from the lowest level shown (70 km) to about 90 km. Above there, atomic oxygen is within the normal range. Temperatures are also high through most of the mesosphere. High values of either atomic oxygen or temperature are signatures of downward motion; these are therefore consistent with other observational evidence of enhanced downward transport during the three anomalous winter periods cited in the Introduction. Using the differences in temperature and atomic oxygen between the anomalous and other winters as a signature of enhanced downwelling, it appears that the perturbation to the vertical motion no longer plays a role above about 90 km.

The accumulated effect of these observations indicates that there is a discrepancy at altitudes above ~90 km. The T there is slightly higher than average but not enough so to explain the O₃ perturbation. Likewise, O is within the range seen in the other years. Although H has not been independently measured, a higher concentration is not expected; in fact, the strong descent of air with low values of water measured by MLS in the lower mesosphere during 2006 [Manney et al., 2008a] suggests instead H would be lower than normal. Possible causes of the discrepancy between the observed O₃ and the other fields are errors in the retrieved fields (T, O₃, or O), larger than expected perturbations in other fields that have not been retrieved (H or O₂), or errors in the terms of equation (1) (ozone not in equilibrium, neglect of additional processes, incorrect rate coefficients). We are aware of approximations that could affect the retrieved fields and their interannual variability: the use of specified rather than observed CO₂ mixing ratio in the temperature retrieval; the use of climatological rather than retrieved O in the nighttime non-LTE temperature and ozone retrievals [Remsberg et al., 2008] or large uncertainties in some of the OH vibrational quenching rates used in the retrieval of O.

Species production varies linearly with O; loss also depends on O although, below about 95 km, the H loss reaction is strongly dominant. O₃ has a strong negative dependence on temperature due to the reaction rates \( k_1, k_2, k_3 \), [Sander et al., 2006] and the number density \( n = p/(kT) \), where \( T \) is temperature, \( p \) is pressure and \( k \) is Boltzman’s constant. This
indicating a downward displacement of the ozone layer. During 2006 and 2009, the contour is first displaced upward during the sudden warming in mid-January and then descends rapidly at the same time that the stratopause altitude is displaced upward.

3.2. Tertiary Ozone Maximum

At the location of the ozone maximum near 73 km (the tertiary ozone maximum, or TOM), the lifetimes of both ozone and $O_x$ in the polar night (solid lines) are in transition from long below 65 km to extremely short at 75–80 km. Analysis presented by Marsh et al. [2001] showed that the TOM near the polar night terminator is the result of the limited penetration of solar ultraviolet radiation at high solar zenith angles at an altitude where molecular oxygen and water are beginning to be optically thick. The wavelengths that photodissociate water, and hence generate the reactive hydrogen species responsible for destroying $O_x$, have been absorbed while the wavelengths that photodissociate $O_2$, and hence generate $O_x$, have not. The TOM is a maximum not only in ozone but also in $O_x$.

The results shown in Figure 3 indicate that the altitudes of both the TOM and the minimum near 80 km are displaced downward during 2004, 2006, and 2009. The difference in ozone at 80 km can also be seen in Figure 2. The magnitude of the TOM is enhanced during these three years but is smaller than that in 2002. Also see Sofieva et al. [2009] for GOMOS observations of the TOM from 2003 through 2006. Since the photochemical lifetime of ozone in the polar night becomes long below 80 km, it is likely that direct transport of ozone is a major contributor to the observed downward displacement of the TOM by several kilometers. The downward transport of $O$ also contributes to the higher overall amount of $O_x$. A third contribution may be a reduction in mesospheric reactive hydrogen ($HO_x$) associated with the strong downward transport of dry air [Manney et al., 2008a].

The ozone mixing ratio minimum normally occurs around 80 km, where the lifetimes of ozone and atomic oxygen are both short. During night, when there is no production of $O_x$, the concentrations of both ozone and atomic oxygen will drop to low values unless they are replenished by transport. In the high latitude winter, the transport takes the form of poleward and downward advection by the wave-driven mean residual circulation. During the three anomalous winters, the ozone was enhanced at the normal position of the minimum, associated with the much higher atomic oxygen at that altitude. An enhanced supply of atomic oxygen due to downward transport can also increase the nighttime loss of $O_x$, normally the $HO_x$ catalytic cycles that destroy $O_x$ in the lower mesosphere slow down in darkness because of a lack of atomic oxygen.

4. Summary

We present SABER observations showing the mesospheric ozone during the NH winter period of mid-January

![Figure 3](image-url)

**Figure 3.** (a) Chemical lifetime of ozone (black) and $O_x$ (blue) calculated by the ROSE chemical transport model (solid: 87.5°N; dashed: 67.5°N); average over latitudes 70°–83°N of SABER (b) ozone volume mixing ratio, (c) temperature, and (d) atomic oxygen number density. In Figures 3b–3d black solid lines are for 2002, 2003, 2005, 2007, and 2008; red lines are for 2004 (dotted); 2006 (dashed), and 2009 (solid). Lifetime is defined as the inverse of the photochemical loss rate. All profiles are averages over days 1–20 February.

![Figure 4](image-url)

**Figure 4.** Height of the ozone 2 ppmv contour at the base of the secondary maximum for days 15–75 of each winter 2002–2009 for latitudes 70N–83N.
to mid-March of 2002–2009. The winters of 2004, 2006, and 2009 have received much attention due to anomalous dynamics and transport in the middle atmosphere. During the periods of these three winters with a cold stratopause and warm middle mesosphere, the SABER ozone also differed from that seen in the five other winters. The anomalies were 1) downward displacement of the altitude of the tertiary ozone maximum; 2) enhanced magnitude of the tertiary ozone maximum; 3) downward displacement of the ozone minimum normally near 80 km; 4) lower ozone mixing ratio at the secondary maximum; and 5) temperature and atomic oxygen profiles consistent with downwelling in the range 65–90 km. The changes in ozone at the tertiary maximum (73 km) are explained by enhanced production due to more abundant O, reduced loss due to reduced HO\(_x\) production, and direct transport of ozone downward. The differences at the tertiary maximum and at the ozone minimum are consistent with enhanced downwelling during the anomalous years and the associated warmer temperature and higher O in the middle mesosphere. The changes in ozone at the secondary maximum (95 km) are not associated with consistent perturbations in either T or O and, at this point, remain unexplained.

[20] The SABER ozone observations show clearly that the perturbed state of the middle atmosphere in these unusual recent NH winters extends into the upper mesosphere, to almost 100 km. At the same time, there is evidence of dynamical anomalies (temperature) only below about 90 km although perturbations to the CO\(_2\) concentration that are not accounted for (and not known) could affect the temperature retrievals. While these results highlight the importance of the stratospheric dynamics in controlling the upper mesosphere structure and composition, they also point to inconsistent observations and/or incomplete understanding of mesopause ozone.

[21] Acknowledgments. The authors acknowledge the outstanding ongoing work by the SABER instrument, algorithm, and data processing teams. The National Center for Atmospheric Research is sponsored by the National Science Foundation. Any opinions, findings and conclusions or recommendations expressed in the publication are those of the authors and do not necessarily reflect the views of the National Science Foundation. The IAA team was supported by the Spanish project ESP2004-01556 and EC FEDER funds.

References

Funke, B., et al. (2009), Carbon monoxide distributions from the upper troposphere to the mesosphere inferred from 4.7 \(\mu m\) non-local thermal equilibrium emissions measured by MIPAS on Envisat, Atmos. Chem. Phys., 9, 2387–2411.


