Strong longitudinal variations in the OH nightglow

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[1] Airglow from the hydroxyl Meinel bands, originating from about 87 km, gives a signature of the atmosphere that can be observed remotely. Analysis of long term global observations of the 2.0 \( \mu \)m OH Meinel brightness observed by the TIMED/SABER satellite instrument presents some striking patterns that appear in the Meinel airglow. The analysis shows that migrating and nonmigrating tides have large effects on the nighttime OH airglow emission in the upper mesosphere. The OH airglow emission rate is positively correlated with temperature below 94 km and negatively correlated above. Variations with longitudinal wavenumbers 1 and 4 are shown to result from the impacts of the stationary (D0), westward wavenumber 2 (DW2), and eastward wavenumber 3 (DE3) nonmigrating diurnal tides. Citation: Xu, J., A. K. Smith, G. Jiang, H. Gao, Y. Wei, M. G. Mlynczak, and J. M. Russell III (2010), Strong longitudinal variations in the OH nightglow, Geophys. Res. Lett., 37, L21801, doi:10.1029/2010GL043972.

1. Introduction

[2] A prominent airglow system that can be observed by satellite is the infrared Meinel bands, caused by vibrationally excited hydroxyl (OH). Satellite observations indicate that the airglow in the mesopause region can be obviously modulated by atmospheric waves. The migrating diurnal tide, which is a dominant dynamical feature of the mesosphere, affects the nighttime airglow. The \( \text{O} \left( ^1\text{S} \right) \) and OH airglow emission observed by the Wind Imaging Interferometer (WINDII) on the Upper Atmosphere Research Satellite (UARS) is stronger near the equator than at other latitudes due to modulation by the diurnal tide (e.g., Shepherd et al., 1998; Ward, 1999; Zhang et al., 1998; Zhang and Shepherd, 1999; Melo et al., 1999; Russell et al., 2005; Liu et al., 2008). The OH Meinel airglow measured by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) also shows the modulation by the migrating diurnal tide (Marsh et al., 2006).

[3] Besides the equatorial enhancement of airglow due to diurnal migrating tide, the UARS satellite airglow observations indicated that there was substantial longitudinal variability in airglow signatures in the mesopause region [Shepherd et al., 1993; Burrage et al., 1994; Yee et al., 1997; Hays et al., 2003] that was attributed to planetary scale waves [Shepherd et al., 1993; Hays et al., 2003].

[4] Recent research shows that nonmigrating tides have notable effects on the upper atmosphere. Signatures of nonmigrating diurnal tides have been reported for the OI 135.6 nm emission in the ionosphere [e.g., Sagawa et al., 2005; Immel et al., 2006; England et al., 2006], the \( \text{CO}_2 \) 15 \( \mu \)m emission in the thermosphere [Mlynczak et al., 2010], and the thermospheric nitric oxide densities [Oberheide and Forbes, 2008].

[5] The current study highlights two new results: the impact of nonmigrating diurnal tides on the Meinel airglow in the mesosphere and the strong correlation of the airglow variations with those of atmospheric temperature. Standard SABER products include vertical profiles of temperature and three volume emission rates: the \( \text{O} \left( ^1\Delta \right) \) 1.27 \( \mu \)m emission, the 2.0 \( \mu \)m Meinel band emission, which has contributions from the OH (9–7) and (8–6) vibrational transitions, and the 1.6 \( \mu \)m Meinel band emission, which has contributions from the OH (5–3) and (4–2) vibrational transitions. In this paper, we analyze temperature and the 2.0 \( \mu \)m OH volume emission rate profiles from SABER version 1.07 from February 2002 to December 2008.

[6] Section 2 presents the global distribution of the OH airglow brightness near midnight and the temperature in the mesopause region. The mechanism for the correlation between the nightglow and temperature is given in Section 3. A summary is given in Section 4.

2. Seasonal Variation of the OH Airglow Brightness Map

[7] The TIMED satellite precesses slowly in an annually repeating orbit. During six intervals per year the local time of the measurements are near local midnight. To focus on the midnight variations, we use 40–d windows of data and select all profiles whose local time is within 2 hours of midnight (from −2:00 to 2:00 h local time). At low and mid latitudes, the periods are centered at days 15, 75, 135, 200, 260, and 320. These will be referred to by the months corresponding to the center of the period: January, March, May, July, September, and November. Observations are averaged over seven years (2002–2008). Within the latitude range 53°S to 53°N there is a high density of observations (∼15 orbits per day). Higher latitude data, which are available in alternate hemispheres for periods of 56–65 days, are not included in the analysis. A spline interpolation is used to create a grid with spacing of 5° latitude and 10° longitude.

[8] The brightness is defined as the vertical integral of the emission, which for the Meinel bands extends from 75 to
100 km. This brightness is equivalent to what a ground-based observer or nadir viewing satellite would see,

\[ B(\varphi, \lambda) = \int_{75 \text{ km}}^{100 \text{ km}} I(\varphi, \lambda, z)dz. \tag{1} \]

\( I \) is the vertical profile of the airglow emission rate (a retrieved Level 2 SABER product) and \( \varphi \) and \( \lambda \) are latitude and longitude.

[9] The midnight OH airglow brightness map is shown in Figure 1. Figure 1 shows that, in the equatorial region, the OH airglow brightness in the March and September periods is much higher than that in the other periods. The OH airglow brightness in January and July is the weakest and, at the equator, is only about half of that in March. The stripe of high brightness near the equator in March and September is a factor of 2–2.5 higher than that at \( \pm 35^\circ \).

[10] At the equator, the longitudinal variation of the brightness (Figure 1, right) is dominated by wavenumber 1 and has a minimum near 180°. There also are wavenumber 4 signatures in the airglow at the equator, especially in July and September. At \( \pm 20^\circ \), wavenumber 4 is dominant. In most of the periods, the brightness in the two hemispheres is out of phase. At 20°N, there is also a wavenumber 3 structure, most apparent in May.

[11] The altitude of the peak emission rate varies from 84 to 90 km, with an average of about 87 km. Figure 2 shows the global distribution of the midnight temperature at 87 km. From comparison of Figures 1 and 2, it is clearly evident that the OH airglow brightness and the temperature have very similar structures. A wavelike variation in longitude is also evident in Figure 2 and, again, the wavenumber 1 and 4 components are dominant. The longitude structures are very similar to the OH nightglow shown in Figure 1. Near the March equinox, the equatorial temperature is much higher than that at midlatitudes. Near the September equinox, the situation is similar except that the peak temperature near the equator is slightly smaller. At solstices, the equatorial enhancement in temperature is weaker than at equinoxes. The migrating diurnal tide in temperature near the equator has a strong semiannual variation with maxima near equinoxes [Xu et al., 2009]. The phase of the tide is such that the maximum temperature occurs close to midnight at 87 km.

[12] Our analysis of the OH brightness maps and the global maps of the temperature at 87 km from individual years (not shown) indicate that the wavelike patterns in
these two maps and are a regular feature and that the phases persist over the years.

3. Mechanism of the Correlation Between Nightglow and Temperature

[13] The vibrationally excited OH that gives rise to the airglow is a product of the exothermic reaction of ozone with atomic hydrogen. During night, the ozone production R1: \( \text{O} + \text{O}_2 + \text{M} \rightarrow \text{O}_3 + \text{M} \) is approximately balanced by destruction through reaction R2: \( \text{H} + \text{O}_3 \rightarrow \text{OH}^* + \text{O} \) and R3: \( \text{O} + \text{O}_3 \rightarrow 2\text{O}_2 \). However, R3 is smaller than R2 by several orders of magnitude below \( \sim 95 \text{ km} \). Therefore, the production rate of excited hydroxyl \( P_{\text{OH}^*} \) is approximately linearly proportional to the atomic oxygen mixing ratio, which is [Smith et al., 2008]:

\[
P_{\text{OH}^*} = k_2 \cdot q_{\text{OH}} \cdot q_{\text{O}_2} \cdot \rho^2 \approx k_1 \cdot q_{\text{O}} \cdot q_{\text{O}_2} \cdot \rho^3,
\]

\( k_1 = 6.0 \times 10^{-34} \left( \frac{300}{T} \right)^{2.4} \) \( \text{cm}^6 \text{ molecule}^{-2} \text{ s}^{-1} \) (2)

\( \rho \) is the atmospheric number density and \( q_i \) is the volume mixing ratio of chemical species \( i \). The asterisks indicate that the product is in an excited state. The reaction rate \( k_1 \) is from http://jpldataeval.jpl.nasa.gov; Evaluation Number 15.

[14] We separate the production rate of \( \text{OH}^* \) into a mean (overbar) and perturbation (primed) components. On a specified pressure level, the total production rate is

\[
P_{\text{OH}^*} = \bar{P}_{\text{OH}^*} + P'_{\text{OH}^*}
\]

\[
\approx 6.0 \times 10^{-34} \left( \frac{300}{T} \right)^{2.4} \cdot q_{\text{O}} \cdot q_{\text{O}_2} \cdot \left( \frac{P}{kT} \right)^3
\]

\[
= \bar{P}_{\text{OH}^*} \left[ 1.0 + \frac{q_0}{q_{\text{O}} - 5.4 \frac{T'}{T}} \right] (3)
\]

where \( \bar{P}_{\text{OH}^*} = 6.0 \times 10^{-34} \left( \frac{300}{T} \right)^{2.4} \cdot q_{\text{O}} \cdot q_{\text{O}_2} \cdot \left( \frac{P}{kT} \right)^3 \). We have taken advantage of the ideal gas law to express \( \rho \) as \( (\rho/kT) \). Equation (3) indicates that the perturbations in the production rate of the excited hydroxyl are caused by perturbations in the atomic oxygen mixing ratio and the temperature. We have neglected perturbations in \( \text{O}_2 \), which are expected to be only a few percent.

[15] Because of the long (months) chemical lifetime in the upper mesosphere, it is appropriate to assume that perturbations in atomic oxygen on time periods of hours or days are due almost exclusively to transport. Observations and modeling studies have shown large perturbations to the airglow due to the migrating diurnal tide [Ward, 1999;
Zhang et al., 1998]. Because the vertical gradient is much larger than the horizontal gradient, the variation of the atomic oxygen mixing ratio is quite sensitive to the vertical tidal motion. In regions where the tidal vertical velocity is large (it depends on latitude and altitude), the tidal variation of atomic oxygen (which can be obtained by equations (8) and (9) of Smith et al. [2008]) is:

\[
\frac{d\tilde{q}_O'}{C_{22}} = \frac{1}{S} \frac{\partial}{\partial z} T' \quad (4)
\]

where \( S \) is the static stability. Therefore, from equation (3) and (4), we obtain,

\[
\frac{P'_T}{P'_T} = \left[ \frac{d\ln(\tilde{q}_O)}{C_{22}} \frac{1}{S} - \frac{5.4}{T'} \right] T'\equiv \varepsilon T' \quad (5)
\]

Equation (5) indicates that perturbations in the production of excited OH are predicted to be linearly proportional to perturbations in temperature. The formula indicates that two factors contribute to the correlation between the temperature and the airglow: the transport of atomic oxygen, which is a precursor to the formation of excited OH, and the dependence of reaction rates and number density on temperature. The sign is positive (emission and temperature perturbations are in phase) when the transport of O by vertical motions dominates and the sign is negative when the temperature dependence of photochemical reactions and/or the atmospheric density dominates. A plot of the vertical profile of \( \varepsilon \) calculated by using NRLMSIS-00 input is shown in the auxiliary material that accompanies this paper.1 \( \varepsilon \) changes from positive to negative near the altitude of 94.5 km.

Scatter plots of OH airglow intensity versus temperature observed by TIMED at the equator at several altitudes (Figure 3) indicate that the intensity and temperature are positively correlated below about 94 km and negatively correlated above, consistent with the NRLMSIS-00 prediction.

The enhanced OH nightglow brightness at the equator compared to that at midlatitudes during the equinoxes can be attributed to the impact of the diurnal tide; see also analysis of UARS/WINDII observations by Ward [1999] and Zhang and Shepherd [1999]. The tidal phase at 87 km is such that, at midnight, tidal perturbations to temperature at the equator are warm while those around 30° are cool. The tidal amplitude is much larger at equinoxes [Xu et al., 2009] so the impact is most apparent in March and September. The equatorial enhancement and its seasonal variation have been seen in other analyses [Shepherd et al., 2006; Baker et al., 2007], although Baker et al. [2007] assumed that this structure had a photolytic origin.

Forbes et al. [2008] investigated the nonmigrating tides at altitudes between 100 and 116 km using temperature measurements made with TIMED/SABER. Here, we analyze nonmigrating tides in the temperature near the OH airglow emission peak (87 km). We use a two dimensional (UT and longitude) spectral least squares fitting method [Wu et al., 1995; Oberheide et al., 2006] to extract the tides from SABER temperature data. The analysis is performed over data in incremental 60-day windows in order to cover the full range of local times. The calculations indicate that the prominent non-migrating tides are the westward-propagating diurnal tide with wavenumber 2 (DW2), the standing or zonally-symmetric (wavenumber 0) diurnal oscillation (D0), and the eastward-propagating diurnal tide with zonal wave-

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1Auxiliary materials are available in the HTML. doi:10.1029/2010GL043972.

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Figure 3. Scatter plots of the OH airglow at 2.0 µm vs. temperature and a linear regression fit for different altitude at the equator.
number 3 (DE3). Modeling of non-migrating tides [Hagan and Forbes, 2002] also finds that these modes are strong near the equator. In a fixed local time map such as Figures 1 and 2, the DW2 and D0 tides will produce a zonal wavenumber 1 structure and the DE3 tide will produce a zonal wavenumber 4 structure.

The averaged seasonal variations of the amplitudes and phases at the local time of 0:00 (the longitude at which the tide reach maximum) of the DW2 tide is very weak around the Jun/Jul solstice but is strong in the other 3 seasons. See the auxiliary material for seasonal amplitudes and phases of DW2, D0, and DE3. The seasonality agrees with that of UARS wind observation analyzed by Forbes et al. [2003]. DW2 is weaker in midlatitudes than at the equator. The D0 tide reaches maxima at the equinoxes and is weak during solstices. Its amplitude at 87 km is weaker than that of the DW2 tide. These two non-migrating tides both contribute to the wavenumber 1 oscillation in temperature near the equator seen in Figure 2. The amplitude of the DE3 tide reaches maximum near the September equinox and minimum near the December solstice at the equator. The DE3 is appreciably weaker at mid-latitudes than at the equator. This seasonality is consistent with the tide in the UARS wind [Forbes et al., 2003; Talaat and Lieberman, 1999]. The result of DE3 also shows that the phase at 87 km is around 65° at the equator. The DE3 at 20°N and 20°S are nearly out of phase except during May and July. The out of phase pattern of wavenumber 4 between 20°N and 20°S can also be seen in Figures 1 and 2. Additional analysis of the temperature fields (not shown) indicates that stationary wavenumber 4 at 87 km has small amplitude compared to the DE3 tide and therefore confirms that the pattern observed at 87 km is tidal. Figures 1 and 2 show that in July, at 20°N, there is also an obvious wavenumber 3 variation. This is a signature of the non-migrating DE2 tide (eastward-propagating diurnal tide with zonal wavenumber 2), which reaches about 2 K in July (not shown).

The very similar wave structure in the OH airglow brightness and the temperature in Figures 1 and 2 indicating that modulation by the migrating and nonmigrating diurnal tides is the primary driver of the OH airglow emission variability. We could in principle extract the tides directly from the SABER OH airglow emissions using the same algorithm as used for temperature. However, the emissions have large photolytically driven day–night differences. In the extracted diurnal “tides,” this photochemical signal would mask the emission variations due to interactions with the temperature and transport variations due to the dynamical tide. Therefore we have used the similarities in the amplitude variations, phases, and horizontal structure at midnight to interpret the observed patterns.

4. Summary

In this paper, we present SABER observations of the global distribution and seasonal variation of the OH airglow brightness and use tidal analysis of temperatures to show the mechanism for the structure and variability. The longitudinal variations of the OH airglow at midnight have a linear relationship with those of temperature, which are associated with the migrating and nonmigrating diurnal tides. Below 94 km, the OH airglow emission rate increases with temperature; above there, it decreases with temperature.

Near the equinoxes, the maximum OH airglow brightness is located near the equator and is much brighter than that in midlatitudes. Near solstices, the brightness of the airglow is weak in all latitudes. This is mainly caused by the seasonal and latitude variations of the migrating diurnal tide.

There are obvious wave patterns in longitude in the airglow emission and the brightness. Zonal wavenumber 1 is the dominant wave near the equator, especially during the equinoxes, although wavenumber 4 is also prominent at the equator in September. Analysis of the tidal components of the temperature indicates a longitudinal wave pattern that is very similar to the one in the airglow, indicating that these variations are due to modulations by nonmigrating tides. The tides that are important are DW2, D0, and DE3. The calculations show that these non-migrating tides have fixed phases so the wave pattern in the airglow emission is similar in every year.

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References


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