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Interannual and seasonal variations of diurnal tide, gravity wave, ozone, and water vapor as observed by MLS during 1991–1994

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Abstract

The diurnal tide in the mesosphere and lower thermosphere (MLT) shows large seasonal and interannual variations. Despite recent modeling investigations, the underlying physical mechanisms for causing these variations remain unclear. This paper provides further observational constraints to tide-sensitive variables (H_2O, O_3, and gravity wave variances) used by the models, which are obtained simultaneously by upper atmosphere research satellite microwave limb sounder at altitudes below the MLT region. The strong quasi biannual oscillation and semiannual oscillation variations in these measurements reveal good correlations between the diurnal tide with other tide-sensitive variables, which should be taken into account for further modeling studies.

Keywords: Diurnal tide; Gravity wave; Water vapor; Ozone; Microwave satellite observations

1. Introduction

Despite the improved understanding of tidal variability in the mesosphere and lower thermosphere (MLT), physical mechanisms for the strong seasonal and interannual tidal variations remains unclear. Plausible causes include variations in mean zonal winds, forcings due to ozone and water vapor, and gravity wave (GW) drag. However, the model sensitivity studies reached different conclusions on what might control the tidal amplitude variations in the MLT region (Hagan et al., 1999; McLandress, 2002a,b), partly because of lacks of observations on tidal variability in relation to ozone, water vapor and gravity waves. This paper provides further observational constraints to these tide-sensitive variables using three-year upper atmosphere research satellite microwave limb sounder (UARS MLS) measurements of temperature, gravity wave variances, ozone and water vapor in the stratosphere and mesosphere. Among the observed variabilities, the quasi biannual oscillation (QBO) and semiannual oscillation (SAO) associated with the diurnal tide and related variables are of particular interest for understanding the underlying physical mechanisms.

2. Diurnal tide

The method to deduce the diurnal amplitude from MLS temperature can be found in Wu et al. (1998) where the MLS data were only available up to 0.46 hPa. In this study, we apply the same method to a new MLS dataset from a special retrieval where the temperature measurement covers altitudes between ~20 and ~85 km (Wu et al., 2003). As shown in Fig. 1, MLS diurnal amplitude at 0.01 hPa (~82 km) exhibits strong seasonal and interannual variations that are similar to those observed with the UARS high resolution

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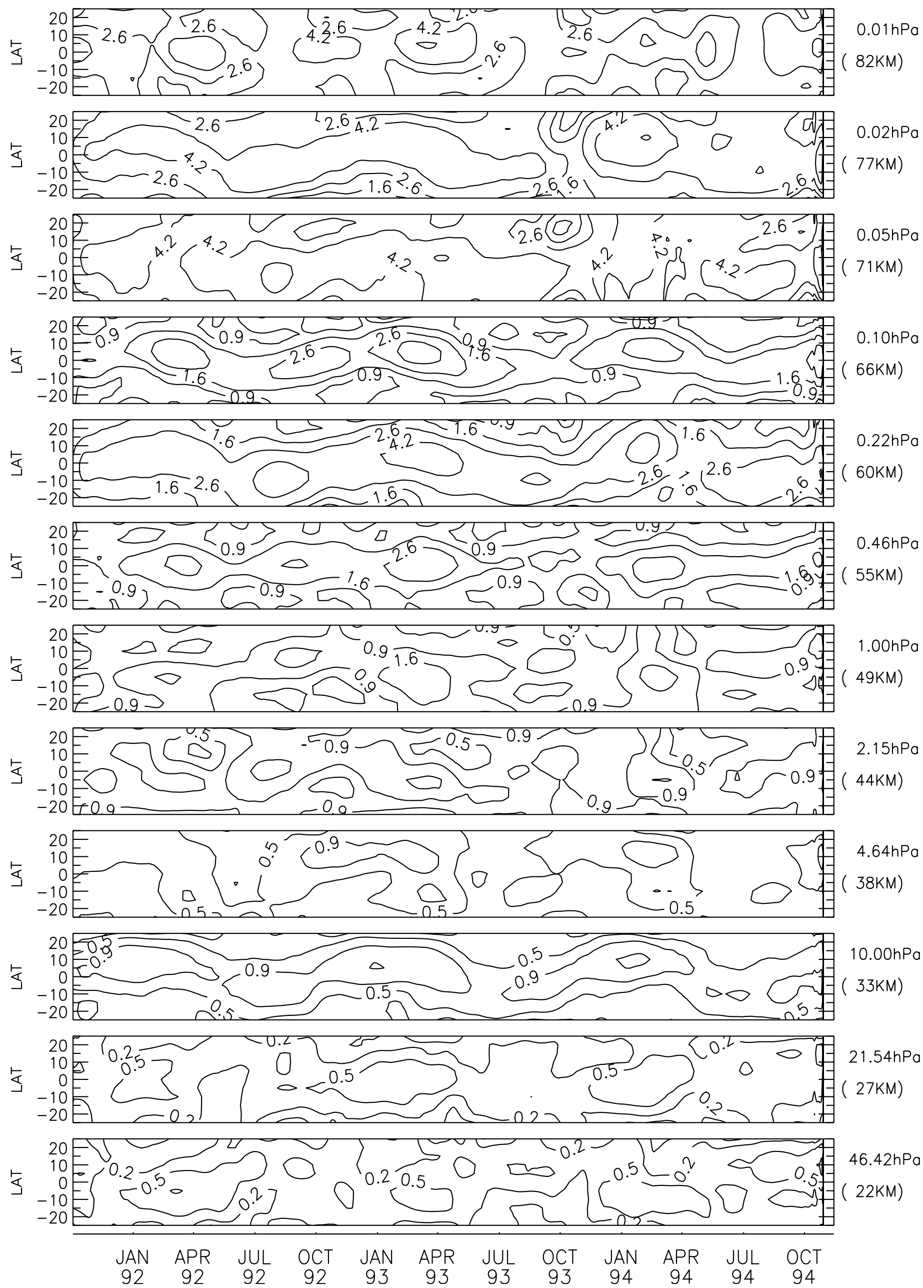

Fig. 1. Diurnal amplitude of MLS temperature from the lower stratosphere to the mesosphere during 1991–1994 when MLS sampling was quite uniform. The contour levels are increased exponentially as $0.2*1.5^n$ K (n = 1,2,...,10) to cover the large range of the tidal variability.

doppler imager (HRDI) winds in the mesosphere and lower thermosphere (MLT) during the same period (Burrage et al., 1995). Near the stratopause the seasonal maxima (in February–March and in August–September) during the period of October 1991–April 1993 are generally larger than those during October 1993–October 1994. These QBO and SAO variations exhibit good coherency over altitudes of 49–82 km despite the mixed patterns at 71 and 77 km.

At 10 hPa (33 km) the diurnal temperature variability is dominated by an annual variation peaking in January/July over the northern/southern subtropics. In between, the peak of the diurnal tide varies within 5°S and 5°N. The peak in January 1993 is stronger than ones in other years. This annual variation pattern disappears at 38–55 km but reappears at 60–77 km. It is interesting to note that this variation pattern of the diurnal temperature tide is anti-correlated with the tropospheric water vapor that always peaks in the summer hemisphere (Fig. 2). On the other hand, the diurnal amplitude at 46 hPa (~22 km) shows weak correlation with the summertime subtropical H_2O peak but is quickly replaced

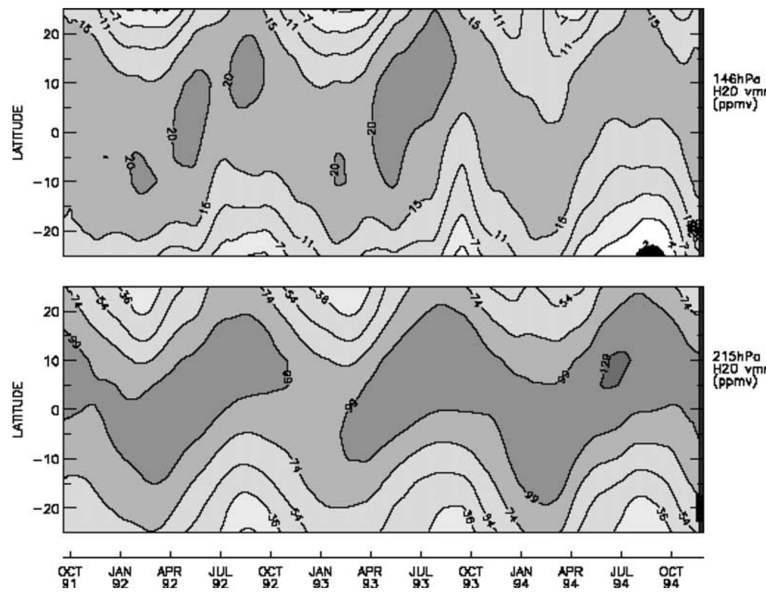

Fig. 2. MLS v5 H_2O vmr at 147 and 215 hPa averaged with a 30-day running window. Contours are in unit of ppmv.

by an equatorial annual variation peaked in January at 27 km.

3. MLS upper-tropospheric H_2O

Water vapor in the troposphere is an important forcing for the diurnal tide and the peak of the heating rate is near 8 km (Chapman and Lindzen, 1970). Here, we use MLS 147 and 215-hPa H_2O as the proxy for the intensity of H_2O radiative forcing in the troposphere to examine seasonal variations of the tidal heating due to this component. Fig. 2 shows a time series of upper-tropospheric H_2O from MLS v5 retrieval (Livesey et al., 2000). The H_2O volume mixing ratios (vmr) at 147 and 215 hPa are dominated by a strong annual variation with peaks in the summertime subtropics (~10°N in August and ~5°S in February). However, the diurnal temperature amplitude at 10 hPa (Fig. 1) shows a seasonal variation very different from upper-tropospheric H_2O with peak in the wintertime subtropics. As a note of caution, the upper-tropospheric H_2O may not reflect variations of latent heat release from clouds, which is another source for diurnal tide generation and requires further observational and modeling studies (e.g. Hagan et al., 1997).

4. MLS O_3

Ozone radiative heating in the upper stratosphere is another important forcing for the diurnal tide, and MLS O_3 can be used to accurately monitor the variation of this forcing source. The v5 of O_3 is greatly improved from its earlier versions with better measurements in the mesosphere and upper stratosphere (Livesey et al., 2000), where the O_3 heating rate is expected to peak. As shown in Fig. 3, MLS O_3 vmr exhibits a strong semi-annual oscillation (SAO) at pressures $\leqslant$10 hPa. At 4.6 and 2.2 hPa the SAO peaks slightly earlier in time than those at lower altitudes, showing a downward progression in the SAO phase. Good correlation can be found between 10-hPa O_3 and the diurnal temperature amplitudes at 0.46 and 2.2 hPa for both seasonal and interannual variations. There is a significant QBO-like variation in the 10-hPa O_3 that also correlates well with the variability of the MLT diurnal tide both in amplitude and in timing.

Annual O_3 variations become dominant at 46, 1 and 0.46 hPa. At 46 hPa the mixing ratio peaks near the equator in the month of July with the weakest peak in July 1993 and shifted to 10°N. At 1 hPa the low O_3 occurs in January, and similar to the SAO variation, there is a download progression in phase.

5. MLS gravity wave variances

Gravity waves (GWs) may interact with the tidal waves causing variations in tidal amplitude. The interactions are expected to become more effective in the mesosphere as both GW and the tidal amplitudes are large (e.g. Fritts and Vincent, 1987). Roughly speaking, GWs and the tidal wave are destructive to each other at these altitudes. The vertically oscillating winds due to the tidal wave tend to filter out GWs in all directions as a result of the spiral tidal wind. The GW drag from

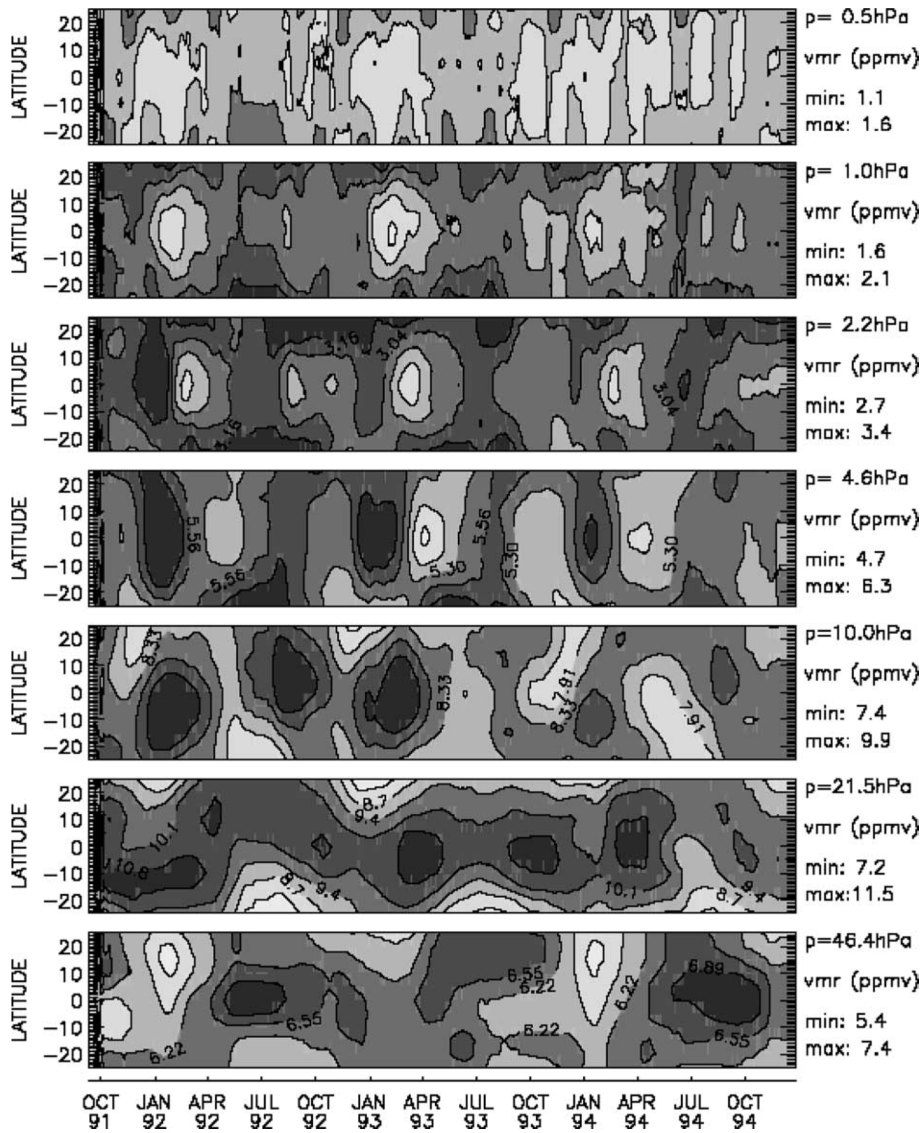

Fig. 3. Time series of MLS O3 vmr at 46–0.5 hPa. Maximum and minimum values in the time series are indicated in the right of each panel.

the GW–tide interactions, on the other hand, tend to reduce overall tidal amplitude.

MLS stratospheric GW variances developed by Wu and Waters (1996) can be used as an indicator of the GW flux available for GW–tide interactions in the mesosphere. In the stratosphere, larger MLS GW variances suggest more waves from the lower atmosphere, and increasing GW variances with height indicate that these waves are propagating and growing in amplitude. The seasonal/annual variation of GW forcing in the subtropics can become important for the diurnal tide as the tidal meridional wind from the (1, 1) mode peaks at these latitudes. As shown in Fig. 4, the subtropical GW variance at 38 and 43 km peaks in January–February (20°S) and July–August (20°N) during the onset of the diurnal tide intensification, not during the period of the lowest diurnal amplitude. Most of the variations in MLS GW variances are strongly correlated with the background wind. As also shown in Fig. 4, they are correlated well with the UKMO winds at 10 km below the variance altitude. In addition to the direct interactions between GWs and the tide, GWs can affect the tidal propagation indirectly through tidal-mean flow interactions (Miyahara et al., 1991). The timing of the interplays of these interacts is an interesting subject to investigate in the future observational and modeling studies.

At 28 and 33 km, the GW variances are correlated with the seasonal variations of upper-tropospheric H_2O or deep convection. As discussed in Alexander (1998), the filtering by the background winds dominates the variabilities of the MLS GW variances in the lower stratosphere. This filtering effect can also explain the QBO-like interannual variation seen in the GW vari-

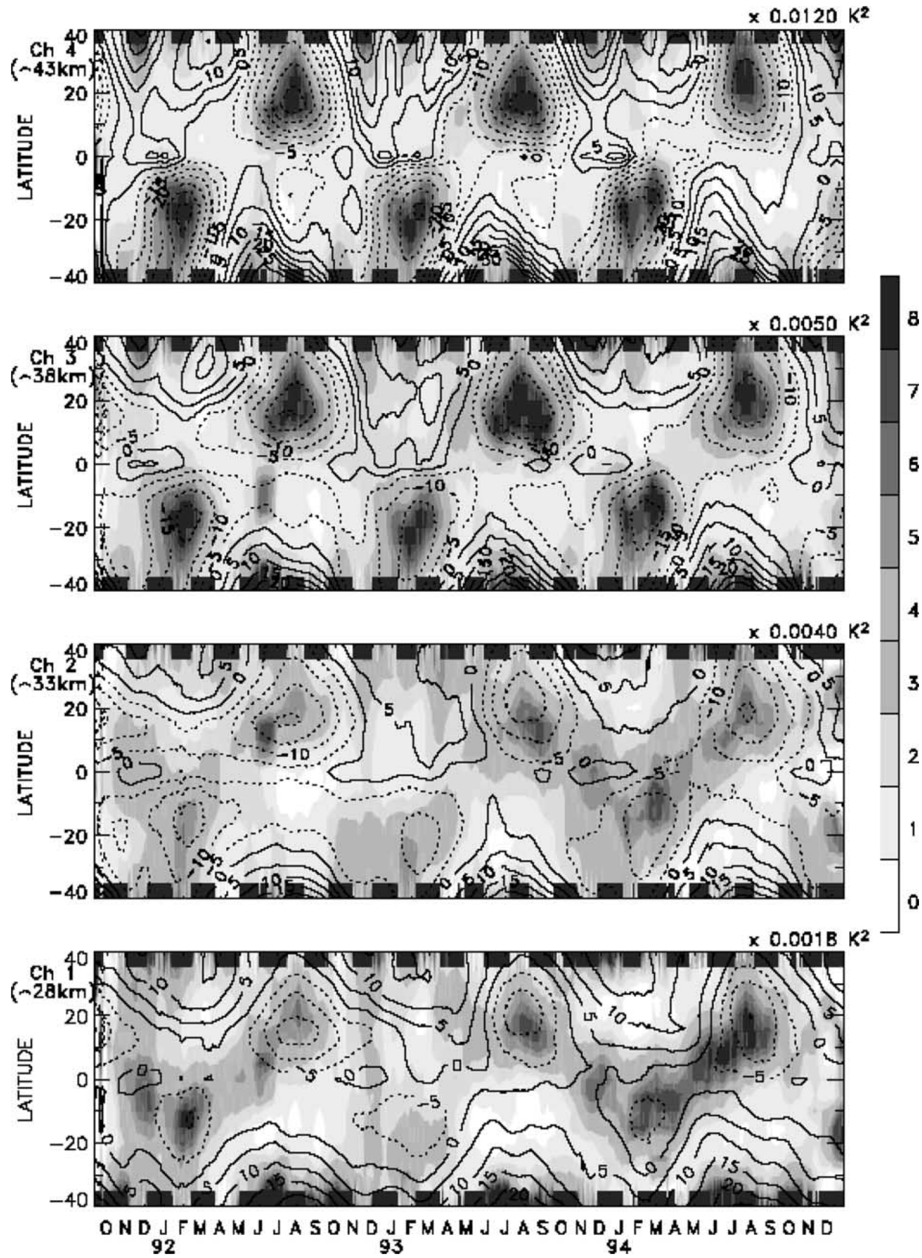

Fig. 4. Time-latitude plot of MLS GW variances at 28-43 km in grey scales (with the multipler for each panel) overlaid by UKMO zonal winds (in m/s) at 10 km below.

ance. The variance in January 1993, when the tropical zonal wind is mostly eastward, is noticeably weaker than in other years.

6. Conclusions

We here presented further observations of the diurnal tide in the new MLS temperature data and its seasonal and interannual variations. Other simultaneous MLS measurements (H_2O, O_3 and GW variances) are also shown to help better understand these tidal variations during 1991–1994. Some important conclusions are summarized as follows.

- MLS observations reveal a strong correlation between the variabilities of the MLT diurnal tide and 10-hPa O_3, suggesting the important role of O_3 heating in modulating the diurnal tide at higher altitudes.
- MLS GW variances in the upper stratosphere maximize during the onset of the MLT tidal intensification where the MLT winds are expected to play an important role in modulating the diurnal tidal amplitude.

Nevertheless, the role of the enhanced GW activity in coupling to the mean winds and interacting with the tidal winds remains to be quantified.
- The variability in upper-tropospheric H_2O heating is likely responsible for the seasonal and interannual variations of the diurnal temperature amplitude at 10 and 22 hPa levels although detailed forcing and filtering mechanisms remained to be explored by modeling studies.

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