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The two-day wave in EOS MLS temperature and wind measurements during 2004–2005 winter

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[1] Two-day wave observations during January–March 2005 are reported using the recently launched Microwave Limb Sounder (MLS) aboard NASA's Earth Observing System Aura mission. Wave-induced disturbances in temperature, water vapor, carbon monoxide, and MLS line-of-sight wind appear in early January, peak near the end of January, and persist until late February. Temperature and wind amplitudes as large as 9 K and 50 m/s are observed near 90 km. The wave disturbance is initially confined in the mid to low summer latitudes where the climatological summer easterly jet exhibits strong shear. The wave then develops features akin to the third Rossby-gravity global normal mode, with a weak temperature disturbance in the winter hemisphere (anti-symmetric about the equator) and wind disturbance over the equator. Strong wind perturbation episode around 17–23 January 2005 in the mid-latitude Southern hemisphere coincides with a particularly intense solar proton event. **Citation:** Limpasuvan, V., D. L. Wu, M. J. Schwartz, J. W. Waters, Q. Wu, and T. L. Killeen (2005), The two-day wave in EOS MLS temperature and wind measurements during 2004–2005 winter, *Geophys. Res. Lett.*, *32*, L17809, doi:10.1029/2005GL023396.

1. Introduction

[2] Readily observed after the solstice above 40 km, the two-day wave is a recurring dynamical feature in the terrestrial atmosphere. The phenomenon is dominated by a westward propagating disturbance of zonal wavenumber 3 with a period of about 2.1 days, (3, 2.1) [*Andrews et al.*, 1987]. It is also accompanied by smaller variances with wavenumber and period combinations, like (1, 6.7), (2, 3.5) and (4, 1.8), that tend to have similar phase speed (60–70 m/s) [*Burks and Leovy*, 1986; *Garcia et al.*, 2005]. As such, the two-day wave appears to be an instability outgrowth of the mesospheric summer easterly jet [*Plumb*, 1983]. Likewise, the wave exhibits characteristics of an amplifying global normal mode under suitable supporting wind conditions [*Salby*, 1981; *Randel*, 1994; *Salby and Callaghan*, 2001].

[3] Satellite observations (e.g., NIMBUS 7 LIMS (Limb Infrared Monitor of the Stratosphere); UARS (Upper Atmosphere Research Satellite) MLS (Microwave Limb Sounder) and HRDI (High Resolution Doppler Imager); and TIMED (Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics) SABER (Sounding of the Atmosphere using Broadband Emission Radiometry)) report that wave-induced perturbations tend to be largest above the stratopause ($\sim$50 km) (*Burks and Leovy* [1986], *Limpasuvan and Wu* [2003], *Wu et al.* [1993], and *Garcia et al.* [2005], respectively). Near the upper mesosphere, temperature wave amplitude can exceed 5 K in the mid-latitude summer hemisphere [e.g., *Garcia et al.*, 2005]. Two-day water vapor variation larger than 0.3 parts per million by volume (ppmv) can exist in regions of strong meridional gradient in water vapor distribution [*Orsolini et al.*, 1997; *Limpasuvan and Wu*, 2003]. In low latitudes, meridional and zonal wind perturbations contribute significantly to the mesospheric flow, with maximum observed wave amplitude of nearly 60 and 20 m/s, respectively [*Wu et al.*, 1993].

[4] Here, the most recent two-day wave episode is reported using observations by the Earth Observing System (EOS) MLS aboard NASA's Aura satellite, launched in July 2004 (J. W. Waters et al., The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura satellite, submitted to *IEEE Transactions on Geoscience and Remote Sensing*, 2005). In addition to two-day wave variations in temperature and water vapor (H_2O), the present study provides a first glimpse at the wave signature in carbon monoxide (CO) and an offline-retrieved MLS wind product. As such, this study provides further evidence and insight on this remarkable phenomenon, whose global structures in the mesosphere/lower thermosphere are becoming more into focus with new measurements from NASA's Aura and TIMED spacecrafts. Additionally, as a recurring dynamical feature, the two-day wave presence serves to further validate the wind observing techniques in the mesosphere.

2. Data and Analysis

[5] This study uses EOS MLS temperature, H_2O, and CO profiles from an off-line research retrieval for the period during December 2004 through March 2005. The along-track data product covers approximately 85°S to 85°N with useful vertical range of 300–0.001 hPa for temperature and CO, and 300–0.1 hPa for H_2O. Vertical resolution for temperature is $\sim$4 km the middle stratosphere, decreasing

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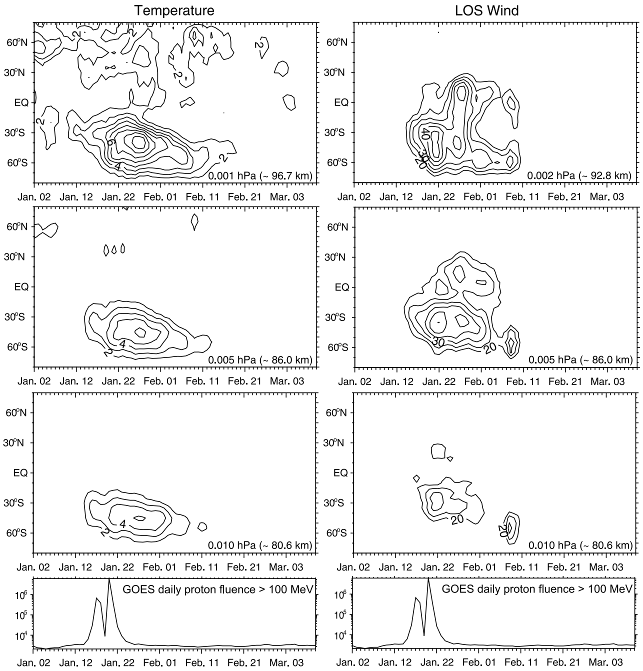

Figure 1. (top) The 2005 latitude-time evolution of the two-day wave amplitude in temperature (every 2 K) and line-of-sight (LOS) wind (every 5 m/s). The LOS wind is computed from profiles along the ascending tracks (see Section 2). (bottom) Concurrent values of NOAA GOES daily proton fluence (in Protons/cm^2-day-sr).

to $\sim$10 km above 0.1 hPa. For CO and H_2O, the vertical resolution is $\sim$3 km.

[6] Additionally, this study uses preliminary retrievals of mesospheric line-of-sight (LOS) wind from EOS MLS in the spacecraft's moving direction. The wind retrieval is based on the Doppler shift of the 118-GHz Zeeman-split O_2 lines, which can be resolved with 128 100-kHz-wide channels (M. J. Schwartz et al., MLS forward model for polarized mesospheric signals, submitted to *IEEE Transactions on Geoscience and Remote Sensing*, 2005; D. L. Wu and M. J. Schwartz, Mesospheric wind measurements from EOS MLS 118 GHz radiometer, manuscript in preparation, 2005). Reported here for the first time, the MLS LOS wind is a special MLS product, now under development. It typically has a (1/6-second integration time) single-measurement precision of $\sim$15 m/s at 83–92 km to $\sim$70 m/s at 70 km, which is the height range used in this study. For the polar-orbiting Aura satellite, the MLS LOS wind is dominated by the meridional component in the tropics, and therefore, winds derived from the northward (ascending) and southward (descending) tracks are out-of-phase. While only the ascending LOS wind is presented in this paper, results from descending LOS wind are very similar.

[7] To extract the two-day wave, the least-squared-fitting method is applied to the data [*Wu et al.*, 1993, 1996], which has been successfully used to identify the two-day wave in UARS measurements. Based on an *a priori* assumption of the two-day wave recurring presence, the along-track profiles at each pressure levels are regressed onto a linear combination of cosine and sine functions of zonal wavenumber 3 of 0.48 cycles per day ($\sim$2.1 day period).

3. Results

[8] Figure 1 (left) illustrates the evolution of the temperature two-day wave amplitude at 3 different pressure levels. A well-defined wave disturbance appears in the summer (Southern) hemisphere in early January and persists until near the end of February. At each level, peak amplitude exits around January 28, with largest amplitude ($\sim$9 K) found near the highest level ($\sim$97 km).

[9] The evolution of the two-day wave signature in the LOS wind differs from that in temperature (Figure 1, right). At each level, the primary peak amplitude occurs about 9 days earlier (January 19) in the mid summer latitudes. Then, around January 28, as the temperature wave matures, a weaker secondary peak in the LOS wind occurs with significant extension into the equatorial region at higher levels.

[10] In the period of strongest temperature wave activity (Jan. 24–27), the cross-section of the temperature wave exhibits an inverted wedge-like shape in amplitude that ranges from 50 km to the upper observational limit (Figure 2a). Below 80 km, the axis of maximum amplitude leans toward the summer pole as the amplitude latitudinal extent grows with increasing altitude (see also Figure 1). The wave phase tilts westward (overlaid black contours in Figure 2a) and the wave appears to have a very long vertical wavelength (>40 km). A relatively weaker wave signature is evident in the winter (Northern) hemisphere near the stratopause and above 80 km. The associated disturbances are out-of-phase with those found in the summer hemisphere, and are also present in Figure 1 (top left). Overall, the described characteristics and magnitude are strikingly similar to temperature observations discussed by *Limpasuvan and Wu* [2003] using UARS MLS data and by *Garcia et al.* [2005] using the TIMED SABER data.

[11] Cross-section of the LOS wind amplitude during January 24–27 shows a strong peak value of $\sim$40 m/s near 40°S at 90 km (Figure 2b). A relatively weaker peak appears over the equatorial region at similar altitudes (see also Figure 1, right). Like the temperature structure, the overall double-peak amplitude takes on an inverted wedge shape and the wave tilts westward with height (increasing phase line with altitude).

[12] As the two-day wave signature is larger in the meridional wind than in the zonal wind, the LOS wind is expected to exhibit significant disturbance (see also Section 2). Indeed, the LOS wind amplitude structure and values are comparable to satellite observations by *Wu et al.* [1993], local station measurements [e.g., *Fritts et al.*, 1999], and numerical model calculations [e.g., *Palo et al.*, 1999]. Likewise, the wave amplitude distribution during January 23–27 is analogous to the third Rossby-gravity global normal mode during solstice condition [*Salby*, 1981].

[13] Figure 3 demonstrates the concurrent evolution of the two-day wave amplitudes in H_2O and CO. Largely confined in the summer hemisphere, the H_2O maximum amplitude of $\sim$0.42 ppmv exists near 45°S and 56 km and is nearly simultaneous with the temperature wave maximum (see Figure 1). The evolution of CO tends to parallel the LOS wind response, peaking around 50°S prior to January

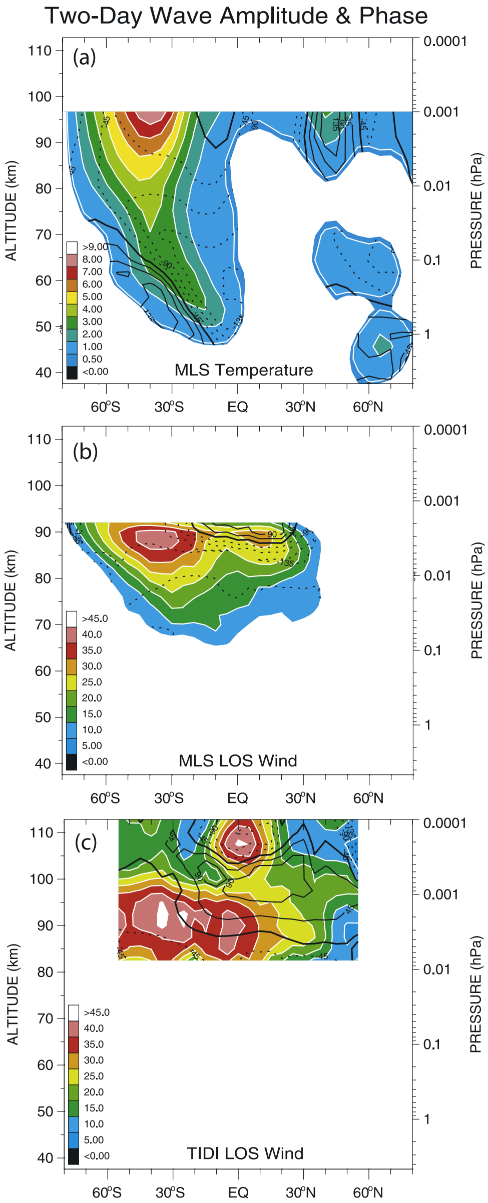

Figure 2. January 24–27 meridional structure of the two-day wave amplitude (filled contours) for (a) temperature in K and (b) LOS wind in m/s from ascending MLS data, and (c) ascending cold side TIDI profiles in m/s. Phase lines (every 45°) are in black.

22 then at lower summer latitude around January 25. The maximum CO amplitude (~2.4 ppmv) is found above 90 km. *Limpasuvan and Wu* [2003] suggests that wave-induced wind perturbations can elicit a notable H_2O response through meridional advection in regions of strong meridional gradient in H_2O distribution. While further investigation is needed, a similar dynamical mechanism may be at work, given CO's distribution and relatively long photochemical lifetime compared to horizontal transport timescales [e.g., *Solomon et al.*, 1985].

4. Summary and Discussion

[14] This study presents the first observations of the two-day wave in temperature, water vapor, carbon monoxide, and LOS wind during December 2004–March 2005. The wave appears in early January, peaks near the end of January, and persists until late February. The temperature and wind amplitudes as large as 9 K and 50 m/s are observed near 90 km.

[15] Pronounced wave amplitude appears at mid to low summer latitude in the region where the summer easterly jet tends to have strong vertical and meridional shear (e.g., CIRA [*Fleming et al.*, 1990]). As such, wave growth from jet instability is a possible generating mechanism. Likewise, the anti-symmetric (about the equator) temperature amplitude in the winter hemisphere, the simultaneous presence of equatorial wind disturbance, and the apparent large vertical wavelength are consistent with the third Rossby-gravity global normal mode [*Salby*, 1981; *Garcia et al.*, 2005]. Thus, the observed two-day wave is consistent with previous interpretation that the wave arises from the excitation of normal modes by instability outgrowth of the easterly jet [*Randel*, 1994; *Norton and Thuburn*, 1996; *Salby and Callaghan*, 2001; *Garcia et al.*, 2005].

[16] Near the upper observational level, the evolution of wind and temperature amplitude suggests the normal mode excitation process (Figure 1, top). The early peaking of the LOS wind amplitude over a deep layer in the mid summer latitude (also mimicked by CO; see Figure 3) may be related to instability growth prior to January 22. This growth is followed by the characteristic wave features of the third Rossby-gravity global normal mode around Jan. 25–27, with winter temperature disturbance and equatorial wind enhancement.

[17] During January 16–22, a strong solar proton event was observed with numerous medium and large solar flares from a single sunspot cluster. This event may have considerable impact on the upper stratosphere and mesosphere dynamics [e.g., *Orsolini et al.*, 2005; *Seppala et al.*, 2005]. On January 22, the NOAA GOES-11 observed an in-flux of highly energetic solar protons (>100 MeV) to be 6.1×10^6 Protons/cm^2-day-sr, on the same order as the famous

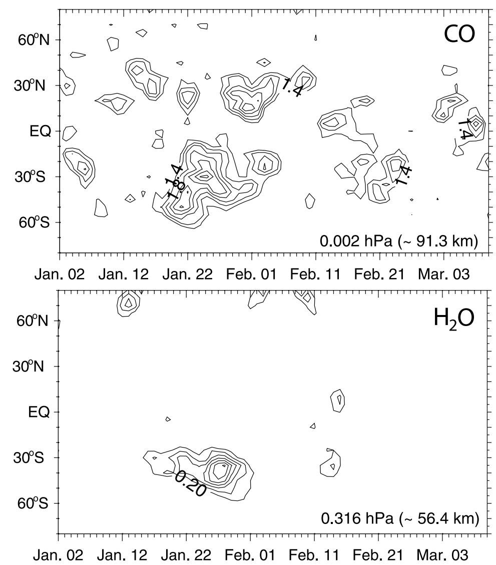

Figure 3. The 2005 latitude-time evolution of the two-day wave amplitude in carbon monoxide (top; every 0.5 ppmv) and water vapor (bottom; every 0.2 ppmv).

October 1989 solar proton event (see Figure 1, bottom). The roles of upper-air local instability and strong solar activity in the two-day wave excitation warrant further investigations.

[18] While the LOS wind product is preliminary, comparisons with concurrent TIMED Doppler Interferometer (TIDI [*Killeen et al.*, 1999]) measurements reveal general correspondence in the wind structures. By projecting TIDI horizontal wind components (using the cold-side profiles along the ascending tracks) onto the MLS LOS, resulting LOS wind wave exhibits amplitude and phase grossly similar to those observed by MLS (compare Figures 2b and 2c, where they overlap). In fact, the LOS wind amplitude in Figure 2c greatly resembles the two-day wave in TIDI *meridional* wind below 105 km (not shown).

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References

Andrews, D. G., J. R. Holton, and C. B. Leovy (1987), *Middle Atmospheric Dynamics*, 489 pp., Elsevier, New York.
Burks, D., and C. B. Leovy (1986), Planetary waves near the mesospheric easterly jet, *Geophys. Res. Lett.*, *13*, 193–196.
Fleming, E. L., et al. (1990), Zonal mean temperature, pressure, zonal wind, and geopotential height as function of latitude, *Adv. Space Res.*, *10*(12), 11–59.
Fritts, D. C., J. R. Isler, R. S. Lieberman, M. D. Burrage, D. R. Marsh, T. Nakamura, T. Tsuda, R. A. Vincent, and I. M. Reid (1999), Two-day wave structure and mean flow interactions observed by radar and high resolution Doppler imager, *J. Geophys. Res.*, *104*, 3953–3970.
Garcia, R. R., et al. (2005), Large-scale waves in the mesosphere and lower thermosphere observed by SABER, *J. Atmos. Sci.*, in press.
Killeen, T. L., et al. (1999), TIMED Doppler Interferometer (TIDI), *Proc. SPIE Int. Soc. Opt. Eng.*, *3756*, 289–301.
Limpasuvan, V., and D. L. Wu (2003), Two-day wave observations of UARS Microwave Limb Sounder mesospheric water vapor and temperature, *J. Geophys. Res.*, *108*(D10), 4307, doi:10.1029/2002JD002903.
Norton, W. A., and J. Thuburn (1996), The two-day wave in the middle atmosphere GCM, *Geophys. Res. Lett.*, *23*, 2113–2116.
Orsolini, Y. J., V. Limpasuvan, and C. B. Leovy (1997), The tropical stratopause in the UKMO stratospheric analyses: Evidence for a 2-day wave and inertial circulations, *Q. J. R. Meteorol. Soc.*, *123*, 1707–1724.
Orsolini, Y. J., G. L. Manney, M. L. Santee, and C. E. Randall (2005), An upper stratospheric layer of enhanced HNO_3 following exceptional solar storms, *Geophys. Res. Lett.*, *32*, L12S01, doi:10.1029/2004GL021588.
Palo, S. E., R. G. Roble, and M. E. Hagan (1999), Middle atmosphere effects of the quasi-two-day wave determined from a general circulation model, *Earth Planets Space*, *51*, 629–647.
Plumb, R. A. (1983), Baroclinic instability at the summer mesosphere: A mechanism for the quasi-two-day wave?, *J. Atmos. Sci.*, *40*, 262–270.
Randel, W. J. (1994), Observations of the 2-day wave in NMC stratospheric analyses, *J. Atmos. Sci.*, *51*, 306–313.
Salby, M. L. (1981), Rossby normal modes in nonuniform background conditions. part II: Equinox and solstice conditions, *J. Atmos. Sci.*, *38*, 1827–1840.
Salby, M. L., and P. F. Callaghan (2001), Seasonal amplification of the 2-day wave: Relationship between normal mode and instability, *J. Atmos. Sci.*, *58*, 1858–1869.
Seppala, A., et al. (2005), The high energy proton fluxes of January 2005: Impact on middle atmosphere, paper presented at 2005 Scientific Assembly, Int. Assoc. of Geomagn. and Aeron., Toulouse, France.
Solomon, S., et al. (1985), Photochemistry and transport of carbon monoxide in the middle atmosphere, *J. Atmos. Sci.*, *42*, 1072–1083.
Wu, D. L., P. B. Hays, W. R. Skinner, A. R. Marshall, M. D. Burrage, R. S. Lieberman, and D. A. Ortland (1993), Observations of the quasi 2-day wave from the High Resolution Doppler Imager on UARS, *Geophys. Res. Lett.*, *20*, 2853–2856.
Wu, D. L., et al. (1996), Excitation and evolution of the quasi-2-day wave observed in UARS/MLS temperature measurements, *J. Atmos. Sci.*, *53*, 728–738.

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