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Global observations of thermospheric lunar tidal winds

R.S. Lieberman [a,*], D.C. Fritts [a], N. Pedatella [b], E. Doornbos [c], D.A. Ortland [d]

[a] G&A Technical Software, Inc. (GATS), Boulder Division, Boulder, CO, USA
[b] UCAR, Boulder, CO, USA
[c] Aerospace Engineering, Delft University of Technology, The Netherlands
[d] Northwest Research Associates, Redmond, WA, USA

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ABSTRACT

We present direct observations of the semidiurnal lunar tide zonal winds at 260 km and 350 km during low solar activity in 2007–2008, and 2010–2011. The migrating semidiurnal lunar tide, or M_2, is a global feature with amplitudes of about 10 m s^{-1} at equatorial latitudes, and 20 m s^{-1} at high latitudes. Amplitude maxima appear twice yearly, between February and April and between August and November. M_2 amplitudes during 2007–2008 are about 20% stronger than those during 2010–2011. These magnitudes are consistent with numerical predictions in WACCM-X. However, only one annual global-scale maximum is simulated during January–March.

1. Introduction

Atmospheric lunar tides are global-scale oscillations driven by the gravitational force exerted by the moon (Chapman and Lindzen, 1970), and by tidally induced vertical motions of the ocean and solid earth (Vial and Forbes, 1994). Variations in the moon's orbit, along with the motion of the earth relative to the moon give rise to a spectrum of lunitidal frequencies (Siebert, 1961). The most significant of these is the M_2 lunar semidiurnal tide, with a zonal wavenumber of 2 and a period of 12.42 solar hours, or one-half of a lunar day. Dynamically speaking, lunar tides are global scale, vertically propagating inertia-gravity waves whose amplitudes increase with altitude up to about 10 m s^{-1} at meteor heights (70–110 km). The predicted vertical wavelength of the classical main M_2 mode is about 100 km (Chapman and Lindzen, 1970).

Interest in the lunar tides has intensified in recent years owing to their apparent role in linking sudden stratospheric warming events (SSW) to ionospheric variability. Several studies have associated SSW with enhanced lunar tidal variability in the equatorial electrojet and vertical plasma drifts (Fejer et al., 2010, 2011), and in the geomagnetic field (Yamazaki et al., 2012). Pedatella et al. (2012) reported global lunar tide amplification of 50–60% in the NCAR Whole Atmosphere Community Climate Model (WACCM) during SSW simulations. Forbes and Zhang (2012) observed lunar tidal enhancements in the mesosphere and thermosphere during January 2009, when significant SSW occurred. Using the Global Scale Wave Model (GSWM), they showed that with zonal mean winds and temperatures attending SSW, a resonant peak appears at 12.43 h that would enhance the M_2 12.42-h response.

Because of the close proximity between lunar and solar tidal frequencies, and the weaker amplitudes of the lunar tides, isolating M_2 in data presents a challenge. Very long records of ground-based observations are required in order to effectively resolve lunar and solar tides. M_2 winds have been inferred from mesospheric radar measurements spanning intervals ranging from 10 to 20 years (Stening et al., 1987; Stening and Vincent, 1989; Stening and Jacobi, 2001; Sandford et al., 2006; Niu et al., 2007). M_2 wind amplitudes maximize near 10 m s^{-1} in the lower thermosphere. Observed vertical wavelengths ranged between 17 and 80 km.

The separation between solar and lunar tidal periods becomes more pronounced when these phenomena are observed from a satellite frame of reference (Forbes et al., 2013). A wave with zonal wavenumber m and frequency σ (in radians per day) with respect to the Earth is viewed from a low Earth orbiting satellite as an oscillation with an aliased frequency:

$$k_s = \frac{|c_0|m - \sigma}{\sqrt{1 + c_0^2}} \quad (1)$$

(Salby, 1982). c_0 is the rate at which observations drift around a latitude circle, and is -2π rad day^{-1} for satellites in a sun-synchronous orbit. When viewed from this platform, the migrating solar semidiurnal tide with $m=2$ and a period of 12 h (0.5 days) registers as an invariant feature ($k_s = 0$), while the lunar

* Corresponding author.

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semidiurnal tide (with $m=2$ and a period of 12.42 h) will have an apparent period of roughly 15 days ($k_s = 0.067$). Thus, polar- and low-orbiting satellite data are particularly well-suited to the study of global lunar tides. Forbes et al. (2013) exploited these properties to document lunar tides in mesospheric and lower thermospheric temperatures, and in thermospheric densities during the solar minimum period of 2007–2010. Zhang and Forbes (2013) examined M_2 winds between 80 and 100 km from the UARS High Resolution Doppler imager (HRDI).

Thermospheric winds play an important role in ionosphere–thermosphere coupling, through dynamo generation and transport of plasma along magnetic field lines. Motivated by the apparent significance of the lunar tide for stratosphere–ionosphere coupling, the purpose of this paper is to document the contribution of M_2 to thermospheric zonal winds. We analyze winds from the CHAllenging Minisatellite Payload (CHAMP) and Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) missions during the years surrounding the 2009 solar minimum. Monthly mean M_2 behavior is presented in CHAMP and GOCE zonal winds, and compared with simulations of M_2 in the extended WACCM model, or WACCM-X. Our findings indicate that M_2 is a climatological feature of the thermospheric wind near solar minimum that exhibits interannual variability and possible sensitivity to the underlying background wind.

2. Data and analysis

2.1. CHAMP

CHAMP was a 10-year mission managed by the GeoForschungsZentrum (GFZ) in Germany. The primary mission goals were mapping of Earth's magnetic and gravity fields, and the collection of refraction data for characterizing the troposphere and the ionosphere. Although CHAMP was not designed for studies of the thermosphere, it carried a Spatial Triaxial Accelerometer for Research (STAR) that measured nongravitational forces acting on the spacecraft, among which the drag is dominant (Bruinsma et al., 2004). While the recovery of wind products was never part of CHAMP's mission, cross-track winds were derived from acceleration values by Liu et al. (2006) and Doornbos et al. (2010). This study uses the "Legacy" wind dataset derived by Doornbos et al. (2010), distributed at http://thermosphere.tudelft.nl/acceldrag/data.php?cat=CH_PN_R02.

CHAMP was stabilized in a near-circular orbit starting at about 450 km in 2000 and descending to 265 km by September 2010. Between roughly 65°S and 65°N, CHAMP ground-relative orbit tracks are aligned north–south, implying that the crosswind orientation is east–west, or zonal. Daily measurements are fixed in local solar time, with a separation of approximately 12 h between the ascending and descending node observations. The orbital precession of CHAMP ($c_0 \sim -6.3$ rad day^{-1}) results in 12 h of lunar local time coverage within 13.3 days.

Useable CHAMP winds are available between 2003 and 2008. This study utilizes winds in 2007 and 2008, the available years closest to the 2009 solar minimum (see Fig. 1). Our analysis begins with the formation of daily longitudinal averages of the east–west crosswind, binned in 5° wide latitude bins and segregated by ascending and descending parts of the orbit. We follow the strategy described by Forbes et al. (2013), which is based on the property that according to (1), M_2 is viewed by CHAMP as an oscillation of the zonal mean zonal wind ($\overline{U}$) with a period of roughly 13.3 days. It is important to bear in mind that the M_2 tide is considerably weaker than the time-mean and the solar migrating tidal winds, which are also represented in the daily longitudinal averages (Lieberman et al., 2013). We therefore filter these components by subtracting 14-day averages of the zonal mean zonal wind from each daily value. The "residual" zonal mean zonal winds, denoted $\overline{U}_{res}$, are binned in lunar local time, and composited over 54-day blocks slid by one day, in order to average over 18–24 h of local solar time. At each latitude, a 12-h harmonic (M_2) is fit to the lunar local time composites.

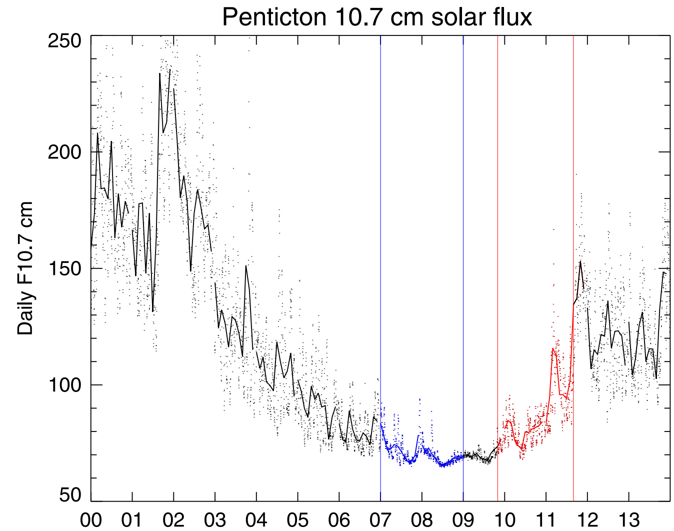

Fig. 1. 10.7 cm solar radio flux ($F_{10.7}$) spanning 2000–2013. Dots are daily values, solid lines are monthly mean values. Thin vertical lines bracket the intervals of CHAMP (blue) and GOCE (red) sampling. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

2.2. GOCE

The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) was a European Space Agency (ESA) satellite intended to map the Earth's gravity field in unprecedented detail. The mission commenced on March 17, 2009 and ended November 11, 2013 when the spacecraft re-entered Earth's atmosphere. We examined M_2 GOCE winds between November 2009 and July 2011, when solar flux conditions were fairly similar to the CHAMP data analysis period. (See Fig. 1.) Data are distributed at https://earth.esa.int/web/guest/missions/esa-operational-missions/goce/goce-thermospheric-data.

The primary onboard instrumentation was a highly sensitive gravity gradiometer consisting of three pairs of accelerometers which measured gravitational gradients along three orthogonal axes. To gain the best possible measurements, the satellite was stabilized in an extremely low orbit (255 km above Earth), where it was subjected to air drag. This drag was compensated by an electric ion engine that generated carefully calculated thrust. Accelerometer and thrust activation data were used to detect the aerodynamic force on the satellite. Cross-winds and density were determined by iterating wind and density inputs to an aerodynamic model of the satellite, until the modeled aerodynamic accelerations matched the observations (Doornbos, 2013).

GOCE was launched in a nearly sun-synchronous orbit, with equatorial local time crossings of 18.0 (6.0) LST on the ascending (descending) portions of the orbit. (Over the lifetime of the mission, these crossing times increased by one hour and 36 min.) However, the lunar local time precessed by approximately 52 min per day, tracing out a full 12-h cycle over a 15-day period. The analysis of GOCE data was therefore very similar to the CHAMP data. Daily longitudinal averages of the east–west crosswind are formed, binned in 5° wide latitude bins and segregated by ascending and descending parts of the orbit. A 15-day average of the zonal mean zonal wind is then subtracted from each daily value to