Lunar tidal winds in the upper atmosphere over Collm

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Received: 10 April 2000 / Revised: 5 October 2000 / Accepted: 11 October 2000

Abstract. The lunar semiannual tide in winds measured at around 90 km altitude has been isolated with amplitudes observed up to 4 m s⁻¹. There is a marked amplitude maximum in October and also a considerable phase variation with season. The average variation of phase with height indicated a vertical wavelength of more than 80 km but this, and other results, needs to be viewed in the light of the considerable averaging required to obtain statistical significance. Large year-to-year variations in both amplitude and phase were also found. Some phase comparisons with the GSWM model gave reasonable agreement but the model amplitudes above a height of 100 km were much larger than those measured. An attempt to make a comparison with the lunar geomagnetic tide did not yield a statistically significant result.

Key words: Meteorology and atmospheric dynamics (middle atmosphere dynamics; waves and tides)

Introduction

The lunar atmospheric tide is generated in the lower atmosphere primarily as a result of the moon’s gravitational attraction on the atmosphere and of the vertical motion of the oceans at the lower boundary of the atmosphere. The theory of the lunar tide in the atmosphere and descriptions of early measurements of it are given in Chapman and Lindzen (1970).

Lunar effects in the upper atmosphere were first seen in the daily geomagnetic variations as early as 1850 (Kreil, 1850). Even now, however, puzzles still remain concerning some aspects of the seasonal behaviour of these variations (Stening and Winch, 1979).

In order to understand the lunar geomagnetic variations we needed to study the lunar tides in the winds which drive these variations by dynamo action in the ionosphere. The present work is part of an effort to analyse suitable wind data sets for the lunar tide. We believe that this is the first time that winds measured by the D1 method have been analysed extensively in this way. Most of the data analysed hitherto have been gathered by the partial reflection drift method which gives data in the 80 to 100 km height region just below the dynamo region of the ionosphere (e.g. Stening et al., 1994).

Another focus has been to simulate the lunar tide in the upper atmosphere from first principles. Vial and Forbes (1994) provided a much improved model which showed reasonable agreement with observations. This model was extended to greater heights using the Global Scale Wave Model (GSWM) of Hagan et al. (1995) (see Stening et al., 1997a). Results from the extended model gave fair agreement with analysed data at the near equatorial site of Christmas Island (Stening et al., 1997b). This same GSWM model is used for comparisons in this work.

Description of the Collm wind measurements

Winds in the mesosphere/upper thermosphere region have been measured at Collm (52°N, 15°E) for many years using low frequency transmitters and the D1 method (Kürschner and Schminder, 1986; Schminder and Kürschner, 1988; Jacobi et al., 1997). The ionospherically reflected sky waves of three commercial radio transmitters at 177, 225 and 270 kHz are recorded using the closely spaced receiver technique. A modified form of the similar-fade method is used to automatically interpret the wind measurements (Kürschner, 1975; Schminder and Kürschner, 1994). The procedure is based on the estimation of time differences between corresponding fading extrema for three measuring points forming a right angled triangle over the ground with small sides of 300 m in the north and east.
directions. The pairs of time differences which allow the calculation of individual wind vectors are measured with a temporal resolution of 0.25 s.

Half-hourly zonal and meridional mean wind values are obtained after averaging over 30–60 data points. The standard deviation of a half-hourly mean is in the order of 20 m s\(^{-1}\), caused by the real wind variations and by the resolution and number of the individual wind measurements. After including the results of the individual measurements on each of the three frequencies combined with a weighting function based on an estimate of the “chaotic velocity” (Sprenger and Schminder, 1969; Schminder and Kürschnier, 1992), mean values are calculated referring to a reflection point at 52°N, 15°E. During the daytime the low frequency radio waves are mostly absorbed in the ionospheric D region so the observations are confined to nighttime. This results in a total of about 700 half-hourly mean values per month in summer and about 1200 in winter and in a coverage of 11–12 h per day in summer and about 20 h per day in winter.

The virtual reflection height is measured on 177 kHz using phase differences between the ground wave and the reflected sky wave. The differences are obtained in the modulation frequency range near 1.8 kHz (Kürschnier et al., 1987). The height resolution of each individual reflection height measurement is close to 1 km. Half-hourly means consist of 6000 individual values on average. The standard deviation of these mean reflection height values is in the order of 3 km below 95 km and 5 km near 100 km height.

A recent study has been made using these data by Rawer and Harnischmacher (1999). They examined the lunar tides in the daily mean winds and in the amplitudes and phases of the solar semidiurnal tides. Our analysis is different from this in that we seek the amplitude and phase of the lunar semidiurnal tide itself.

**Lunar analysis**

In order to analyse these data for a lunar tidal periodicity, the method of Malin and Schlapp (1980) is used. The half-hourly data points are first averaged in pairs to give hourly means. Each of the hourly mean values in the data set under consideration is then randomly assigned to one of ten subsets. The data in each of these ten subsets is then fitted by least squares to a mean, a 12 h solar tide and a lunar semidiurnal tide, where each tidal component has sine and cosine terms enabling the calculation of the phase. The lunar tide varies as \( A \sin (2\pi t + \phi) \) where \( A \) is the amplitude, \( \tau \) is the lunar time and \( \phi \) is the phase. The lunar time \( \tau = t - v \) where \( t \) is the local solar time and \( v \) is the lunar age (\( v = 0 \) corresponds to new moon). In the analysis the lunar tide is derived by calculating the lunar age \( v \) of each data point and the phase of the tide is presented as the lunar hour of maximum \( \tau_{\text{max}} \). \( \tau_{\text{max}} \) is related to the phase \( \phi \) (in degrees) by \( \tau_{\text{max}} = 3 - \phi/30 \). The relation of these quantities, measured as angles, may be seen in Fig. 2L.2 of Chapman and Lindzen (1970). However \( \tau \) is more usually measured in solar hours and \( \tau \) in lunar hours.

The accuracy (standard deviation) of the resulting amplitude and phase is determined from the variance of the results from the ten separate determinations from the ten subsets. This method employed is useful in that the presence of gaps in the data, as is the case here, is not a problem. The main drawback is that a somewhat large number of data points need to be included in each data set in order to get significant results.

Some calculations were made when the solar 24 h tide was also included in the fit, but unreasonably large amplitudes for this tide were sometimes produced and the phase of the solar semidiurnal tide did not always agree with earlier determinations (Jacobi et al., 1997). In these earlier analyses the tides were fitted by a multiple regression analysis in which a polynomial dependence of amplitude on height is assumed and the eastward and northward winds are assumed to have the expected quadrature phase relationship usually found for high-latitude observations. We shall see that the phase of the eastward wind is indeed normally 90° or 3 h ahead of the northward phase but this is not always exactly so for the lunar tide. It should particularly be noted, in passing, that this phase difference may not be 3 h for low latitude stations (Stening et al., 1997b).

We use data from the years 1985 to 1997 and we will examine the variations of the lunar tide with season, with year and with altitude.

Our results will be compared with simulations derived from the Global Scale Wave Model (GSWM) of Hagan et al. (1995). In this model we use zonal wave number 2 and the tide is assumed to be a small perturbation of a shallow, compressible, hydrostatic, perfect gas atmosphere. The momentum, mass continuity, ideal gas law and thermal energy equations are solved in their linearized form. Molecular and eddy diffusion, Newtonian cooling and ion drag are included. A zonal mean atmosphere and the resulting zonal winds are taken from Hedin et al. (1991) as the background. The lunar tide is introduced both as a gravitational force on the lower atmosphere and as a movement of the lower ocean and land boundaries (Vial and Forbes, 1994). Further information on the model may be found in the cited references.

**Seasonal variation**

The average seasonal variation of the amplitude and phase of the tide is shown in Fig. 1. In this analysis data are taken from 1985 to 1997, 80 to 150 km and data from one month are analysed together. It should be emphasised here that all heights quoted are virtual heights. The true heights are not known but will be, on the average, about two to three kilometres lower than the virtual heights at the levels where the bulk of the reflections occur.

There is a clear maximum in the amplitude centred on October where over 3 m s\(^{-1}\) is reached. A maximum occurs near the September equinox also in the solar