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Atmospheric Excitation of Time Variable Length-of-Day on Seasonal Scales *

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Abstract We use the method of wavelet transform to analyze the time series of the Earth's rotation rate of the EOP (IERS) C04. The result shows that the seasonal (annual and semiannual) variation of the length-of-day (LOD) has temporal variability in its period length and amplitude. During 1965.0–2001.0, the periods of the semiannual and annual components varied mainly from 175-day to 190-day and from 360-day to 370-day, respectively; while their amplitudes varied by more than 0.2 ms and 0.1 ms, respectively. Analyzing the axial component of atmospheric angular momentum (AAM) during this period, we have found that time-variations of period lengths and amplitudes also exist in the seasonal oscillations of the axial AAM and are in good consistency with those of the seasonal LOD change. The time variation of the axial AAM can explain largely the change of the LOD on seasonal scales.

Key words: Earth rotation — seasonal variation — wavelet transform

1 INTRODUCTION

Theoretical studies and astronomical observations have already testified that the Earth's rotation is variable. The variability of the Earth-rotation vector is caused by the gravitational torque exerted by the Sun, the Moon and some planets, by mass redistributions in different parts of the Earth system, and by some other excitation mechanisms. The principle of conservation of angular momentum requires different variations taking place in different layers of the whole Earth system. The oscillations of the Earth's rotation reflect the interactions between the solid Earth, atmosphere and oceans, indicating the complexity of overall dynamical motion of the Earth system. The observed oscillations can be interpreted in terms of mantle elasticity, Earth flattening, structure and properties of the core-mantle boundary, rheology of the core, continental water, oceanic variability and atmospheric variability on time scales of weather or climate (Lambeck 1980; Wahr 1988; Dickey 1995). With the development of astronomy and Earth science, the relation between the variation of the Earth's rotation and some geophysical phenomena is subjected to broad attention of astronomers and geophysicists (Dehant et al. 2002). The Earth's variable rotation includes variation of its rotation rate or equivalently of the length-of-day (LOD), polar motion, precession and nutation. Variations of the rotation rate occur over a wide range of time scales from hours to the geological age. Some studies showed that nontidal changes in the Earth's rotation rate on timescales from a few days to a few years are closely related to changes in the atmospheric angular momentum (AAM) (Barnes 1983; Gross 2004; Zhou 2001; Liao 1999; Zhong 2002).

In recent decades, some space geodesic techniques with high precision began to contribute to long-term monitoring of the Earth's rotation. Improved data and advanced data processing

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method have enabled a deeper understanding of the characteristics of the Earth's rotation. The geodynamical theory of the variation of the Earth's rotation has correspondingly advanced. It has been revealed that the variation in the Earth's rotation is more complex than imagined before. Here, seasonal oscillations including semiannual and annual changes, detected since the beginning of 20th century, are the main components of the LOD change and are relatively stable. The LOD change during 1983.5–1993.6 was studied using the method of band-passing filtering and modified harmonic analysis, and the period and amplitude of its seasonal oscillations were found to be not strictly stationary (Höpfner 2000). As an adaptive time-frequency analysis tool, wavelet transform has been successfully applied in geodesy and geophysics. Compared with the classical methods, the wavelet transform has remarkable advantages: the wavelet function adapts itself to the signals to be analyzed by shifting it along the time axis and scaling it along the frequency axis. Some authors have used wavelet transform to analyze periodic signals in LOD and AAM and obtained good results (Liao 1999; Abarca del Rio 2000). In this paper we shall use wavelet transform to examine the LOD and the atmospheric excitation of the LOD on seasonal scales, in an effort to further our understanding of the characteristics of the LOD change and the coupling between the solid-earth and the atmosphere.

2 SEASONAL CYCLES OF LOD CHANGE

Variations of the Earth's rotation rate are usually described as changes in the LOD. When the Earth's rotation becomes quicker (slower) the LOD gets shorter (longer). Components of the LOD signals already examined have periods from several hours to dozens of years, according to high precision observations of space geodetic techniques, such as very long baseline interferometry (VLBI), satellite laser ranging (SLR) and global positioning system (GPS). Change of the LOD is usually divided into long-term fluctuations, periodic and irregular variations, with dominant signals in annual and semiannual periods. So, here, we analyze the seasonal variations of the LOD with emphasis on the semiannual and annual components.

The LOD data set analyzed in the paper is the combined LOD series (in EOPC04) released by the International Earth Rotation Service (IERS). The daily LOD data series covers from January 1962 to March 2005. The part during the 1960–1970s was derived from observations of optical astrometry. Since the 1980s the data were mainly derived from the modern space geodesic techniques and are therefore far more accurate than before. Data pre-processing includes removing of the zonal tide effects from 5 days to 18.6 years and obtaining the signals in periods of 100–500 days by an FFT-Band-Pass filter. First, we use the Fast Fourier Transform to obtain the frequency spectrum of the LOD series. Two prominent peaks clearly correspond to the annual and semiannual components. Their amplitudes are found by harmonic analysis; the results: 0.35 ms for the annual component, 0.28 ms for the semiannual component.

3 TIME-VARYING CHARACTERISTICS OF THE SEASONAL VARIATIONS OF LOD AND AAM

3.1 Wavelet Transform

Fourier transform is a tool widely used for many scientific fields, but it is well suited only to analysis of stationary signals where all frequencies have an infinite coherence time generally. The Fourier analysis only brings out global information but not compact patterns, i.e., it cannot characterize signals whose frequency contents change with time. Compared with the Fourier transform, wavelet transform has some desirable properties. It is based on a wavelet matrix, which can be computed more quickly than the Fourier matrix. For a 1-Dimension signal $f(x) \in L^2(\Re)$, the Morlet-Grossmann definition of the continuous wavelet transform is,

$$W(a,b) = a^{-\frac{1}{2}} \int f(x)\psi^*(\frac{x-a}{b})\ \mathrm{d}x, \tag{1}$$

where $\psi(x)$ is analyzing wavelet, $\psi^*(x)$ denotes the complex conjugate of $\psi(x)$, a (>0) is the scale parameter and b is the position parameter. The purpose of the wavelet transform is to separate a signal into its frequency components. This much is like the Fourier transform. The difference is that we also obtain the frequency components over the time domain with the wavelet transform. When an adapted wavelet function is chosen, we can analyze oscillation by shifting cycle along the time axis and scaling cycle along the frequency axis. The transform allows the time localization analysis of an unstable quasi-harmonic signal in the given data series. Using wavelet transform, we can obtain the characteristics of a signal in both frequency and time domains at the same time, and, in other words, it provides us not only the amplitudes (or power) at different frequencies but also information about their time dependence. Thus, wavelet transform is an excellent tool for analyzing signals with time-varying periods and amplitudes (Cui 1995; Kumar & Foufoula-Georgiou 1997).

3.2 Wavelet Transform of Seasonal Variations of LOD Signals

In order to understand seasonal variations of LOD signals in detail, wavelet transform is used to study the LOD variations obtained in Section 2. The results of the time-varying characteristics of the seasonal components of the LOD in both time and frequency domains are shown in Figure 1(a). To illustrate the seasonal oscillations more clearly, we draw in Figure 1(b) the amplitude spectrum for the period 1990.0–2000.0.

Considering the end-effects of wavelet transform, we use the results during 1965.0–2001.0 to analyze the time-variation of the seasonal components. The periods and amplitudes of the annual and semiannual components in the specific date are obtained, and their variations are shown in Figure 2 in red lines. Figures 2(a) and 2(b), 2(c) and 2(d) display the variations of the periods and amplitudes of the semiannual and annual oscillations. We can see the time-varying characteristics of the annual and semiannual oscillations of the LOD from Figure 1. Combining Figures 1 and 2, we can acquire more information about the time-varying characteristics of the two components. During 1965.0–2001.0, there exist complicated changes in the periods and amplitudes of seasonal oscillations. Almost all periods have different lengths and amplitudes. The overall averages of period length and amplitude of the semiannual oscillation are 182 days and 0.29 ms. According to Figures 2(a) and 2(b), the period length varies mainly from 178-day to 188-day during 1965.0–1972.0. After that period, the variation of period length is about 5 days until 1978.0. From that time to 2001.0, the period varies by more than 10 days. The amplitude of the semiannual component varies mainly from 0.25 ms to 0.35 ms, with minimum of about 0.13 ms. According to Figures 2(c) and 2(d), the period length of the annual component varies from about 350-day to about 373-day, most from 365 days to 370 days. Especially, the period is close to 350-day in about 1983 and 1999. Before 1977.0 the amplitude changes by about 0.08 ms. The change approaches 0.15 ms from 1977.0 to 2001.0. The mean period of the annual oscillation is 365 days and the mean amplitude is 0.35 ms.

3.3 Wavelet Transform of Seasonal Variations of AAM Signals

The influence of the atmosphere on the Earth's rotation is described by the effective atmospheric angular momentum (EAAM) vector. The equatorial components χ_1 and χ_2 of EAAM are related to the excitation of polar motion, the axial component χ_3 is associated with changes in the LOD, and all three components are composed of a wind term and a mass term (Barnes 1983). Seasonal variations of the axial AAM are thought to be the main cause of the seasonal variations of the LOD. In this paper, we define whether there are time variations in the axial AAM and, in exist, whether they are consistent with those in seasonal LOD signals. Again we use wavelet transform to examine seasonal variations of the axial AAM. We use the data series of the axial AAM spanning from 1948.0 to 2004.0 at 6^{h} steps from National Centers for Environmental Prediction (NCEP) reanalysis project. The data set is first re-sampled at the same interval (1 day) as of the LOD by simple averaging, then the trend term is removed and band-pass filtering is applied to obtain the seasonal components in the range of 100–500 days, to which wavelet transform is finally applied.

The result indicates clear time variations in the seasonal variations of the axial AAM. Based on the results, the periods and amplitudes of the annual and semiannual components are obtained for the specific dates when the amplitudes of the wavelet spectrum reach their extrema. See Figure 2. To avoid the end-effects of wavelet transform and compare with LOD change, the curves in Figure 2 show only the results during 1965.0–2001.0. In Figure 2, panels (a) and (b) refer to the semiannual oscillations (c) and (d), to the annual oscillations, (a) and (c) refer to the period, (b) and (d),

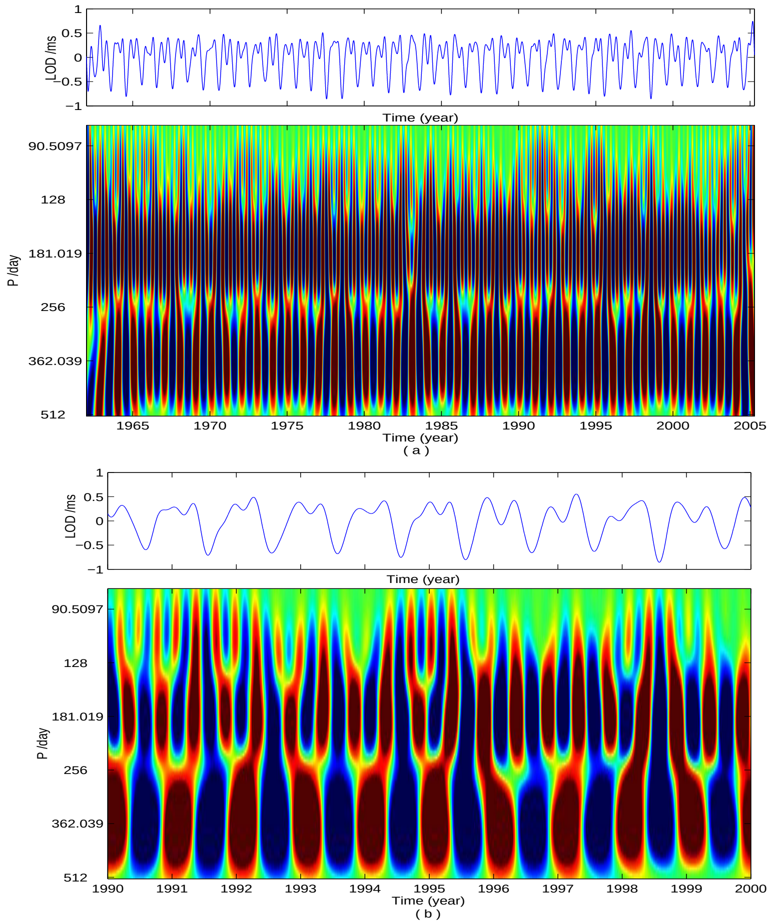

Fig. 1 Wavelet spectrum of the Earth's variable rotation rate. (a) during 1962.0–2005.2; (b) during 1990.0–2000.0. The top panels show the time curve of the LOD after the FFT-Band-Pass filter. The bottom panels display the oscillating amplitude (represented by the depth of color, red for the peaks, green for the valleys) as a function of the oscillating period (y-axis, in days) and epoch (x-axis).

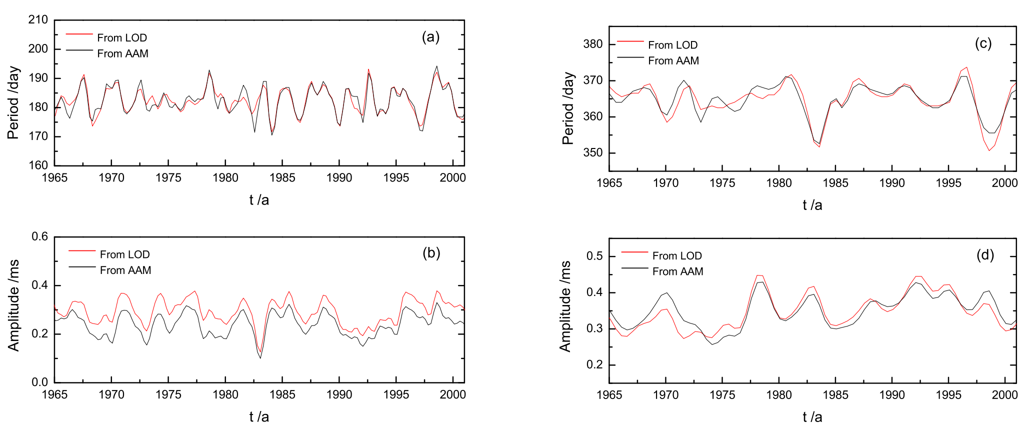

Fig. 2 Variations of the period length (panels (a), (c)) and amplitude ((b), (d)) of the semiannual ((a), (b)) and annual ((c), (d)) oscillations from the LOD and the axial AAM.

to the amplitude. And in each panel, one curve is the result from LOD, the other is that from axial AAM. The results from the axial AAM can be seen to be are in good agreement with the results from LOD. There is good synchronism between their variations in period and amplitude. Variations on seasonal scales in the axial AAM could explain largely those in the LOD.

4 CONCLUSIONS AND DISCUSSION

Results from wavelet analysis indicate that seasonal oscillations of the LOD change are complex: the periods and amplitudes of the annual and semiannual components of the LOD change functions of the epoch. The seasonal variations of the axial AAM are time variable, too, and are in step with the variations in LOD. Over the years 1965.0 to 2001.0, seasonal oscillations of the axial AAM can explain largely those of the LOD. From the results, we know that the axial AAM is the key excitation source of the changes in the LOD on the seasonal time scales. It suggests that variations of the seasonal axial AAM can efficiently drive the variations of the seasonal LOD both in its amplitude and its period length. The variations of LOD change and the axial AAM are almost at the same time, and their changes in amplitude are nearly equal. A few differences can be found between the magnitudes of their seasonal variations. This fact indicates that additional contributions to the seasonal LOD excitation are likely from other geophysical processes, such as global oceanic angular momentum and continental water storage, etc.

Some authors have suggested that the seasonal oscillations of LOD change could be related to the ENSO (El Niño events and Southern Oscillation) phenomena and strong earthquakes in some regions (Gross 1996; Han 2003). Some studies have shown that there exists global connection of the variation of LOD change to the global seismicity on time scale and regional difference at the space scale (Zheng 1995). Zharov (1996) argued that seasonal oscillations of the LOD can induce occurrence of strong earthquakes in some regions. In fact, the Earth's rotation rate is possibly affected by various factors, such as the atmosphere, continental water, oceans and dynamical processes in the Earth's inner. Among these exciting sources, the axial AAM is the main factor to affect the seasonal oscillations of the LOD. Therefore, we believe that one should pay more attention to the time-varying characteristics of the Earth's variable rotation rate and its relation to various geophysical phenomena.

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