Seasonal and Short-Period Fluctuations of Earth Rotation Investigated by Wavelet Analysis

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Summary

When compared with classical Fourier or spectral analysis there are several remarkable advantages of the wavelet analysis. In particular, it allows the time localisation of an unstable quasi-harmonic signal within a given data set. This paper concentrates on seasonal variations and on the short-period, i.e. subseasonal fluctuations of Earth rotation. The analysis of length of day (lod) series yields in the high frequency range periods of 28 days, 14 days down to 5.6 days caused by the lunisolar tides and irregular periodic variations between 40 and 150 days. These are mainly excited by global zonal winds. For the semi-annual variations of lod a correlation with El Niño events and with the antarctic circumpolar current can be seen. The main seasonal components of polar motion are the prograde annual and semi-annual variations. Both get maximal amplitudes one to two years after strong El Niño events. Additionally, variable periods in polar motion with periods between two and five months and even down to periods of 8-10 days can be seen in the wavelet spectrum of the short-period range.

1. Introduction

The Earth rotation vector is variable with time, both in its direction and in its length. The directional change of the rotation axis with respect to an Earth-fixed reference system is called polar motion and has a magnitude of several meters on the Earth' surface. Polar motion consists mainly of two periodic components, one is the Chandler wobble with a period of about 1.18 years and the other one is the annual wobble. The Chandlerian part of polar motion is caused by the deviation of the rotation axis from the Earth's polar axis of inertia whereas the annual variation and variations with periods shorter than one year are mainly due to the interactions between the atmosphere, the hydrosphere and the solid Earth. The length of a mean solar day (length of day, lod) depends on the rotation of the Earth, i.e. changes of the Earth' rotational velocity with respect to a quasi constant velocity derived from atomic clocks cause small changes of lod. The lod time series consist mainly of a secular trend, long-period variations and seasonal variations with an annual and a semi-annual period. In the last years the short-period variations of lod with periods down to a few hours have become an important scientific subject.

As the total angular momentum vector of the Earth, the atmosphere and the hydrosphere (including oceans) is temporally constant (apart from minor torques of the sun and the moon), there is a close relation between meteorological and hydrological processes and the rotational behaviour of the Earth. The atmospheric perturbations of polar motion can be expressed by the equatorial components of the atmospheric angular momentum (AAM) excitation functions χ_1, χ_2 and those of the length of day (lod) by the zonal component χ_3, respectively (Barnes et al., 1983).

It has been shown in several publications that a strong correlation exists between lod and the total AAM (Nastula et al., 1992; Rosen, 1993; Kolaczek, 1995; Zatman, 1997). The atmospheric contribution to the variations of polar motion in time scales between several weeks and a few months has also been demonstrated by many authors (Brzezinski, 1987; Eubanks et al., 1988; Eubanks, 1993; Kuehne et al., 1993; Kosek, 1995; Kosek et al., 1995; Kosek and Kolaczek, 1997; Nastula, 1997; Nastula et al. 1997). In recent time the important contribution of the oceans on the Earth rotation parameters has been reported, too, e.g. by Chao et al. (1995), Chao et al. (1996) and by Chao and Zhou (1999).

In the last years, the wavelet transform as an adaptive time-frequency analysis has been success- fully applied in geodesy and geophysics. Examples are given by Gambis (1992), Popinski and Kosek (1994), Chao and Naito (1995), Baudin et al. (1996), Schmidt (1996), Praveen (1997), Gibert et al. (1998), Schmidt and Schuh (1999), Schmitz-Hübsch (1999), Schuh and Titov (1999). In our investigations the Morlet Wavelet transform will be used to study the time-variability of the instable quasi-periodic oscillations of the Earth rotation parameters for periods shorter than one year. The time-variable wavelet covariance (e.g. Torrence and Compo, 1998; Whitcher, 1998) between the geodetic signals and the atmospheric excitation functions will be regarded, too.

2. Data

We analysed the EOP(IERS) C 04 data series of the pole coordinates and of lod from 01.01.1962 till 31.03.1999 provided by the International Earth Rotation Service (IERS), Paris. These are equidistant daily values with the very short periods filtered out (below 8d till 1988, below 3d till 1993, below 2d since 1994). Atmospheric Angular Momentum (AAM) series were also analysed which were derived from global meteorological data (series *aam.ncep.reanalysis.1958.1999* computed by NCEP, National Center for Environmental Prediction and published by IERS). They represent the atmospheric influence on x_p, y_p and lod due to global wind forcing and global air pressure variations. In our computations both the pole coordinates x_p, y_p and the equatorial atmospheric excitation χ_1, χ_2 were treated in the complex plane $(x_p - i \cdot y_p)$, $(\chi_1 + i \cdot \chi_2)$, respectively.

3. Method of Analysis

The Fourier transform is a suitable tool for analysing periodic signals like ocean tides or Earth tides. The signal is compared with harmonic oscillations of different frequencies. The Fourier transform gives the information about the frequency content of the signal without any time localisation. Thus, time-varying amplitudes and/or periods can hardly be detected.

There are several remarkable advantages of the wavelet transform when compared with 'classical' methods based on the Fourier transform. In the wavelet transform the harmonic oscillation is replaced by a wavelet function which is adapted to the signal to be analysed by shifting it along the time axis and scaling it along the frequency axis. It allows the time localisation of an unstable quasi-harmonic signal within a given data set. Hence, the wavelet transform is an excellent tool for analysing signals with time-varying amplitudes and/or periods. The wavelet transform was introduced by Grossmann and Morlet (1984). With respect to a wavelet by which the data are analysed it has the form:

$$W_\psi \left[f(t)\right](a,b) = \frac{1}{\sqrt{|a|}} \int f(t) \cdot \overline{\psi\left(\frac{t-b}{a}\right)} \, dt$$

$$a \neq 0, \; a, b \in \mathbb{R}$$

with
Ψ (t) – non-stationary part of a wave (= wavelet) and the wavelet basis a and b:

a – dilation (scale parameter)
b – translation (shift parameter)

The analysing wavelet Ψ (t) is a localised oscillating function defined on the real line. Here, the complex

Morlet wavelet will be used:

$$\psi(t) = \frac{1}{\sqrt{2\pi}} \cdot e^{ipt} \cdot \left[e^{-t^2/\left(2\sigma_0^2\right)} - \sqrt{2} \cdot e^{-t^2/\sigma_0^2 - (p\cdot\sigma_0)^2/4} \right]$$

with
p - variable (usually $p > 5$; in this paper $p = 2\pi$ was used),
σ_0 - parameter which describes the decay of the Morlet wavelet.

The wavelet cross-spectrum will also be regarded. As it is a complex function, we will compute the *squared* wavelet cross-spectrum between the lod-series f(t) and the AAM-series g(t) according to Schmidt (1999):

$$\left| W_\psi \left[f(t), g(t) \right](a,b) \right|^2 = W_\psi \left[f(t) \right](a,b) \cdot \overline{W}_\psi \left[f(t) \right](a,b) \cdot W_\psi \left[g(t) \right](a,b) \cdot \overline{W}_\psi \left[g(t) \right](a,b)$$

This is equivalent to the cross-wavelet power (Torrence, 1998).

The Morlet wavelet is well-suited for the analysis of Earth rotation parameters which - depending on the excitation mechanism - partly show very clear and stable periods but contain also unstable, spurious, quasi-periodic variations. As described above, the wavelet transform allows the exact localisation by time which usually cannot be seen by the classic Fourier analysis. Furthermore, the choice of different wavelets offers a lot of flexibility for the analyst. Generally it can be said that the localisation by time can only be improved by worsening the localisation by frequency and vice versa. The choice of the wavelet transform and of the specific decay parameter σ_0 to be used depends on the data to be analysed and on the information we are interested in. It's the task of the analyst to find the best compromise.

4. Results

4.1 Variations of length of day (lod)

1. The two time series of lod and of AAM plotted in fig. 1a are analysed by the wavelet transform. In fig. 1b the main components of lod can be seen which are the well-known annual variation and the semi-annual variation, the second one being considerably smaller than the first one.

2. These seasonal variations of lod are strongly correlated with variations of the angular momentum due to the global zonal wind and air pressure field (fig. 1c). A comparison of the energies of the wavelet spectra shows that the annual period of lod is almost totally excited by the global wind and pressure field whereas the semiannual period must be additionally excited by sources other than the winds and the pressure.

3. The main other cause for the semi-annual variation in lod is the Antarctic Circumpolar Current (ACC) (e.g. Dickey et al., 1993). It is responsible for the variation of the semi-annual oscillation of lod because it feeds the cold Humboldt current from South to North along the West coast of South America. During strong El Niño events (marked by thin vertical lines in fig. 1b,c) the Humboldt current is being disturbed by the warm water of the El Niño moving from North to South along the South American West coast. There are many interferences in the currents and as a consequence the semi-annual variation in lod almost vanishes. This is clearly visible on fig. 1b, e.g. during the very strong El Niño event in 1982/83.

4. In the period range shorter than 150 days down to 30 days, the transient variations of lod can be clearly assigned to those related to the global wind and pressure field, i.e. they are almost exclusively caused by atmospheric excitation as can be seen on fig. 2a,b,. The wavelet cross-spectrum (fig. 2c) nicely displays the strong correlation between the two processes in that period range. The average coorelations have increased since 1983 as a consequence of the improved accuracy of lod-measurements by using modern space geodetic techniques.

5. The periods below 30 days in lod are mainly due to the solid Earth tides (Yoder et al., 1981). The strongest variations are those with periods of 13.63 and 13.66 days (fortnightly variations) with a modulation period of 18.6 years and those around 27.6 days (monthly variations) what can be seen on fig. 2a and also on fig. 2d, which is a 3d-representation of fig. 2a rotated by 180°.

6. We have also looked on the very short periods in lod, i.e. on periods between 5 and 8 days. These were not filtered out from the EOP(IERS) C 04 series since 1988. For this period range, the wavelet spectrum shows very clearly the tidally induced variations around 7 days for the *whole* data set (fig. 3). Even the two periods at 6.86 days and at 7.10 days can be separated. This proves that it was not the time-interval of 5 days and 7 days, respectively, between subsequent VLBI-sessions which caused the peaks around 5 and 7 days in lod-spectra (plotted on fig. 3, left side) as was assumed by some authors in the past (e.g. Dehant et al., 1999). If such an effect existed, it would have been made visible by the wavelet analysis with a clear 'step' from 5 to 7 days in April, 1991 when the VLBI observing interval was changed from 5 to 7 days. On fig. 3 we can also see a thin horizontal line at the 5.6 days period till 1991 corresponding to the small tidally induced variation with that period. Later than 1991 this period could not be resolved any more because the time interval between the VLBI sessions had been increased to 7 days.

4.2 Variations of polar motion

The variations of the energy of the Chandler motion and that of the annual term can only be seen by the wavelet analysis if one of the two is filtered out first from the original data series. Then, the following results are obtained from the wavelet analysis (see also Schmitz-Hübsch, 1999):

1. The annual wobble of the pole (with the Chandler wobble removed before) is dominantly a prograde circular motion; their retrograde part is very small (fig. 4a). By contrast, the corresponding annual variation of the angular momentum due to the global air pressure and wind gets a strongly elliptic shape, i.e. with prograde *and* retrograde components of about the same magnitude (fig. 4b).

2. The energy of the annual polar motion is not constant by time. In particular there are strong maxima of the annual variations one to two years after the strongest El Niño events (fig. 4a). Such time lags cannot be seen in the corresponding wavelet spectra of the global AAM excitation functions (fig. 4b). This indicates the important role of the global oceans in the excitation of the annual polar wobble as was also reported by Furuya and Hamano (1998) when looking at the Pacific Ocean, only.

3. For the short periods of polar motion, i.e. below 200 days, we see strong semi-annual prograde circular variations of polar motion (fig. 5a). The maxima of the semi-annual prograde variations are delayed by about one year after the strong El Niños in 1982/83, 1987/88 and 1994/95, respectively. There is no such an effect in AAM (fig. 5b) which contains only weak semi-annual variations. This is an indication that the semi-annual polar motion is mainly caused by the oceans rather than by the atmosphere.This shows again the influence of the global ocean currents and in particular of El Niño events on the Earth rotation parameters.

4. The wavelet spectrum of the very short periods of polar motion, i.e. below 60 days is plotted in fig. 6a. It should be mentioned that whereas the seasonal variations of the pole (annual and semi-annual) are mainly prograde motions (see fig. 4a, 5a), the very short periods of the pole, i.e. below 30 days (as can be seen on fig. 6a), are mainly retrograde motions. A comparison with the corresponding

AAM variations (fig. 6b) shows that the relative energy of the variations from 60 down to 30 days is higher in polar motion than in AAM but the situation gets inverse for the extremely short periods below 30 days. It should be noted that periods shorter than 30 days in polar motion are not visible in the spectrum before the end of 1983. The investigation of the very short periods then became possible due to the increased accuracy of the VLBI results which was achieved by adding the Wettzell station to the international VLBI network in autumn 1983.

5. High-frequency variations with periods shorter than 12 days are visible in polar motion (fig. 7a). These very short periods are also contained in AAM (fig. 7b), they are due to the atmospheric modes in the period range of 8-10 days (Eubanks et al., 1988; Eubanks, 1993). On fig. 7a it can be seen even clearer than on fig. 6a that the very short periods in polar motion are dominantly retrograde motions.

5. Conclusions

The wavelet transform was successfully applied for the investigation of variations in length of day (lod) and polar motion. By the Morlet analysing function transient, quasi-periodic effects could be exactly localised and be brought into relation with other geophysical phenomena such as variations of global wind and pressure and the global oceanic tides and currents.

The seasonal variations of lod are dominated by the variations of the global zonal wind field. An interaction between strong El Niño events, the Antarctic Circumpolar Current and the semi-annual period of lod could be shown. Irregular short-period variations in lod could also be localised and could be clearly brought into relation with AAM variations. The tidally induced lod variations with periods between 5 and 35 days could also be made visible. By the wavelet analysis it could be proved that the variations around 7 days are due to the tides, too, and had not been caused by the time interval of 7 days between subsequent VLBI sessions.

The annual wobble of the pole is mainly a prograde circular motion. Epochs when small elliptic 'deformations' of these usually circular polar motions occured can be identified by the wavelet analysis. The seasonal atmospheric excitation due to variations of the global air pressure and wind contains both prograde and retrograde terms corresponding to an elliptic motion.

Influences of strong El Niño events on polar motion could also be made visible for different periods which demonstrates the important effect of oceanic currents on the pole.

The very short-period variations of the pole are mainly retrograde motions. It can nicely be seen in the wavelet spectra that the increased accuracy of the observed polar motion has allowed since the end of 1983 to detect the periods shorter than 30 days, too.

6. References

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Figure Captions

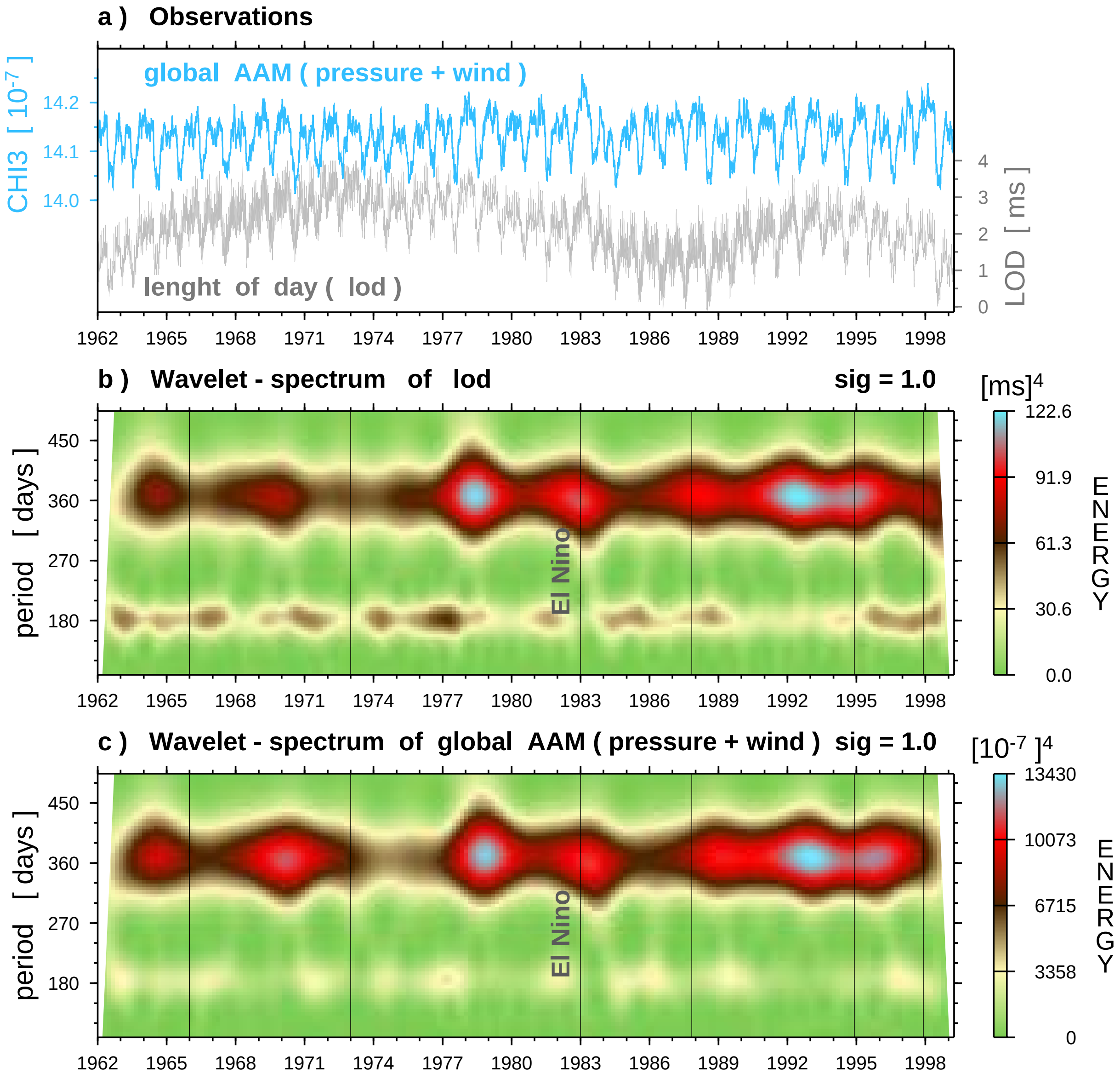

Fig. 1: Observed length of day (lod) from 1962 till 1999 and atmospheric angular momentum (AAM) excitation functions due to global pressure and wind (a) and wavelet spectra of the two series showing the seasonal variations (b,c)

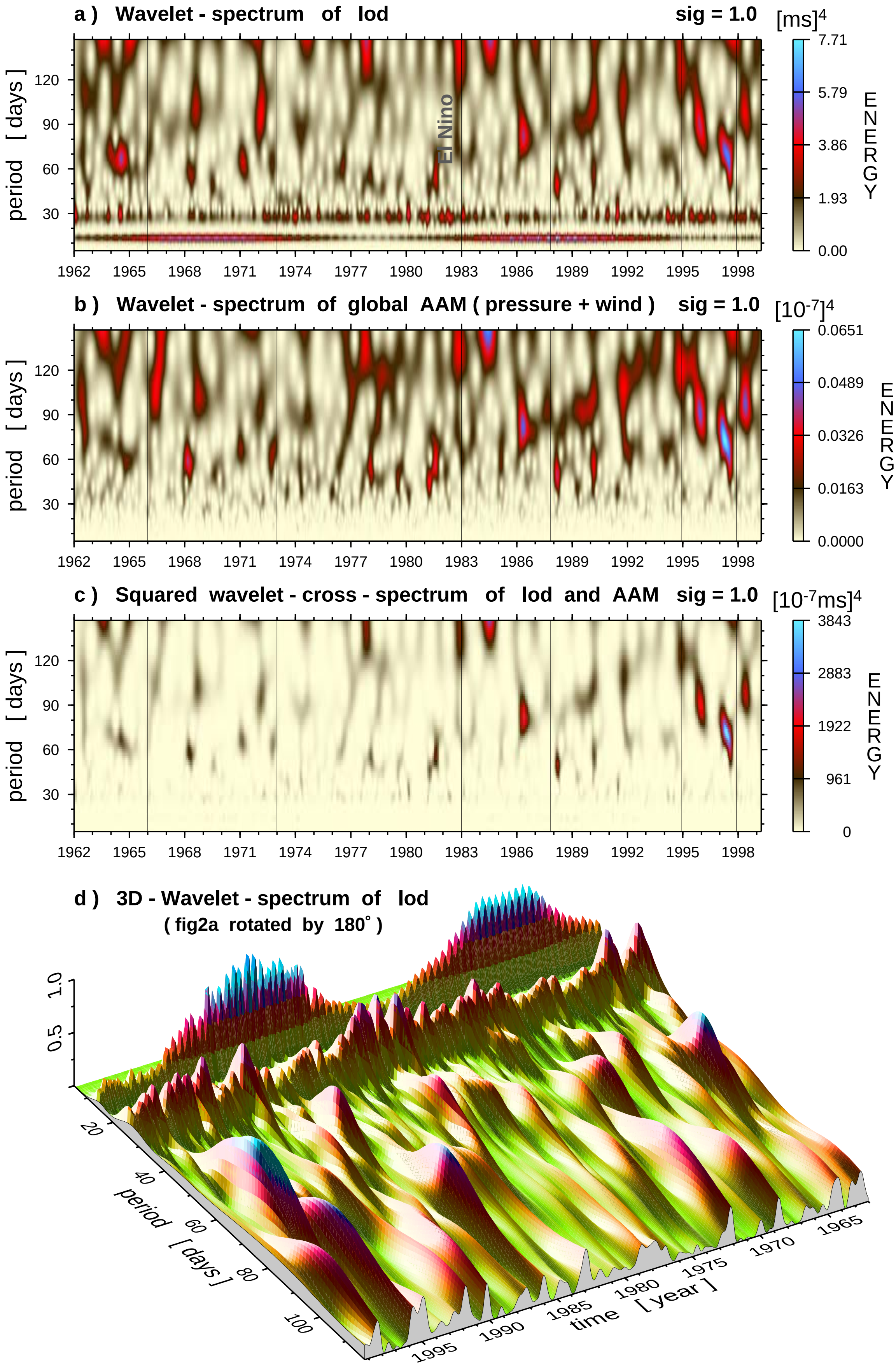

Fig. 2: Wavelet spectra of lod and of AAM for periods from 10 to 150 days (a,b), the wavelet cross spectrum (c) and a 3D-representation of fig. 2(a) rotated by 180° (d)

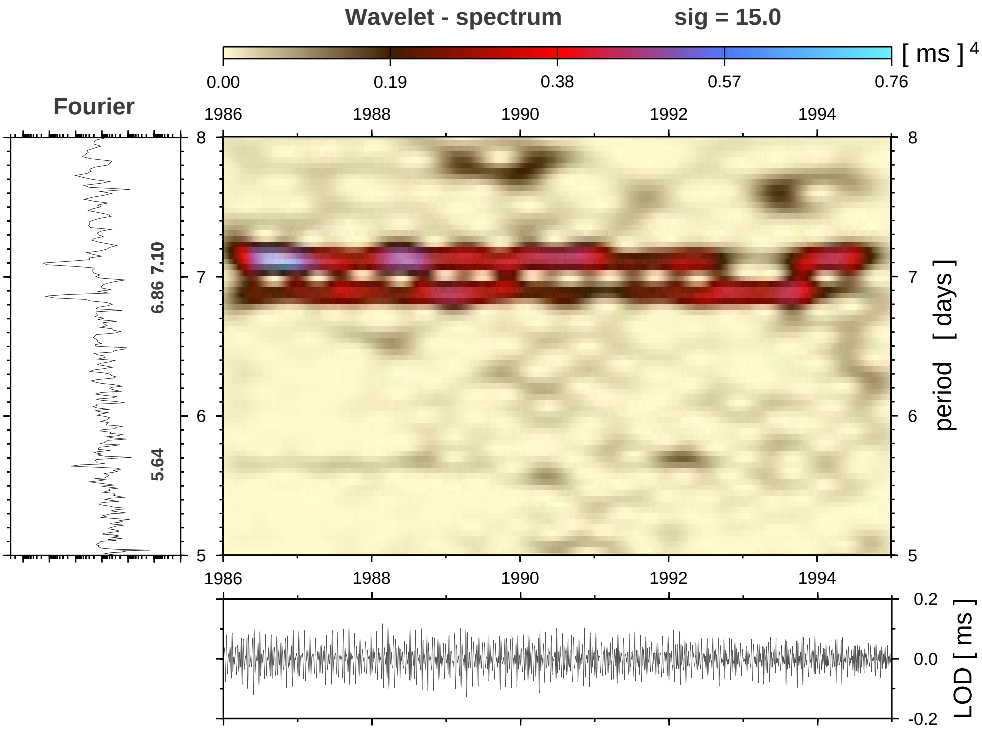

Fig. 3: Wavelet spectrum of lod for the very short periods between 5 and 8 days. The tidally induced variations around 7 days can be seen clearly

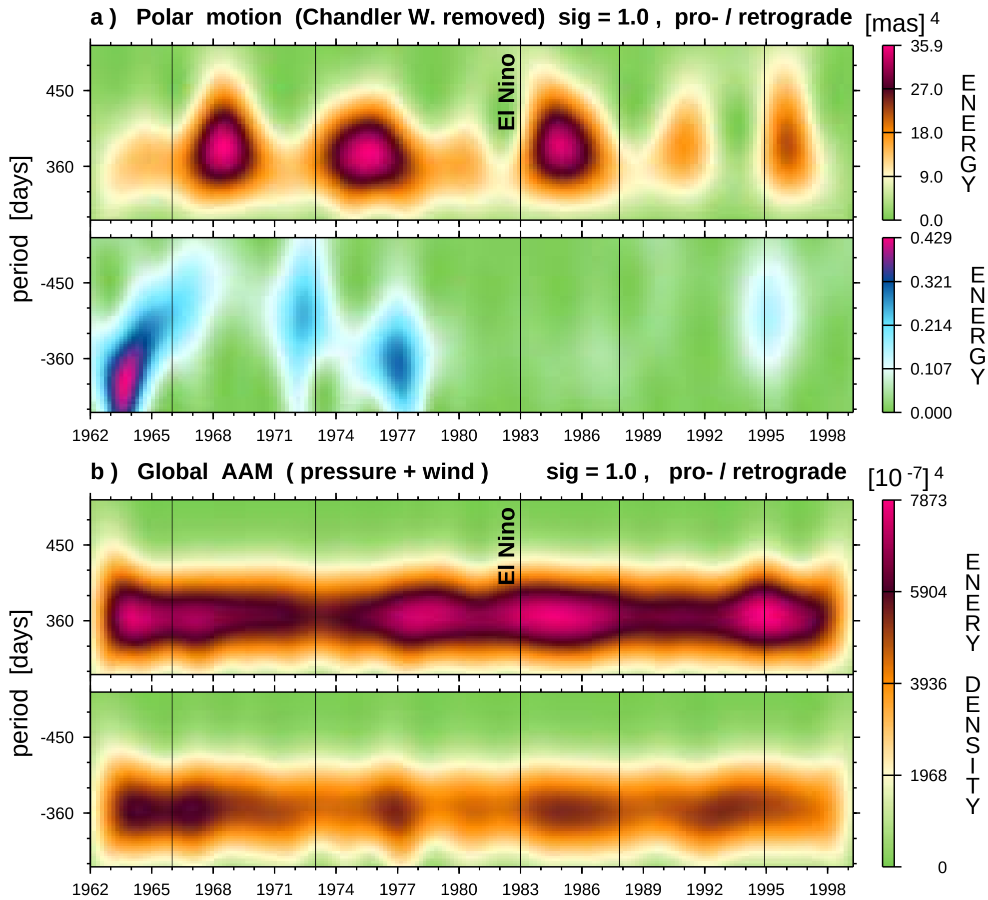

Fig. 4: Wavelet spectra of polar motion (a) and of the global AAM excitation functions (b) around the annual period (the Chandler Wobble at 1.18 years had been removed before)

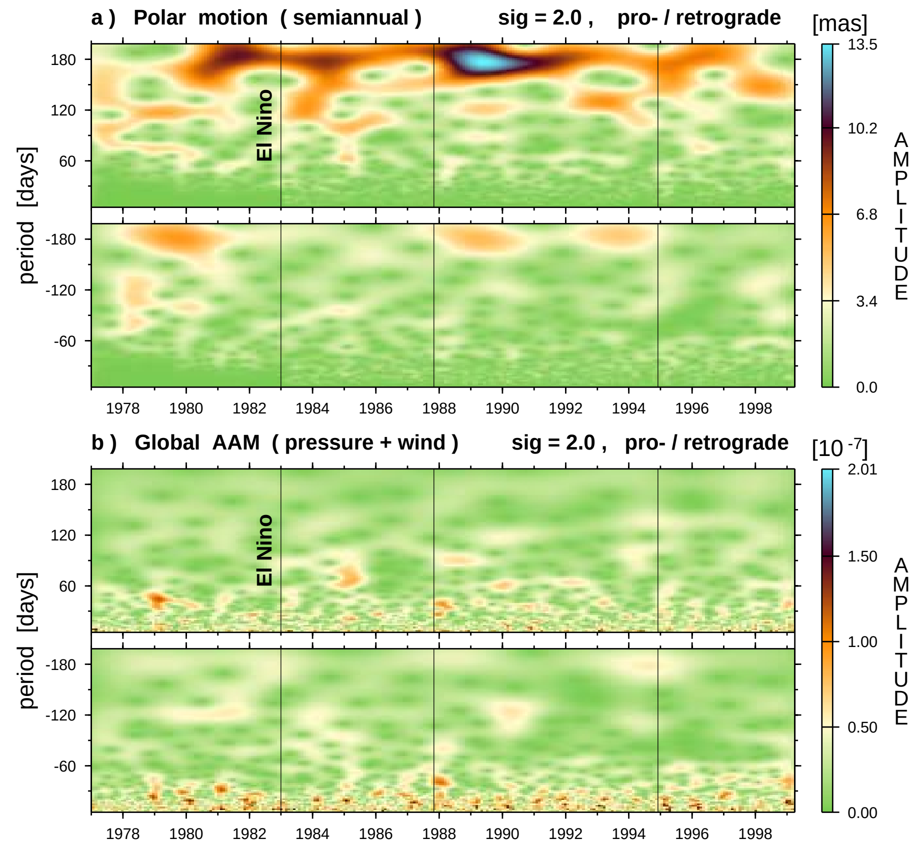

Fig. 5: Wavelet spectra of polar motion (a) and of AAM (b) for periods shorter than 200 days

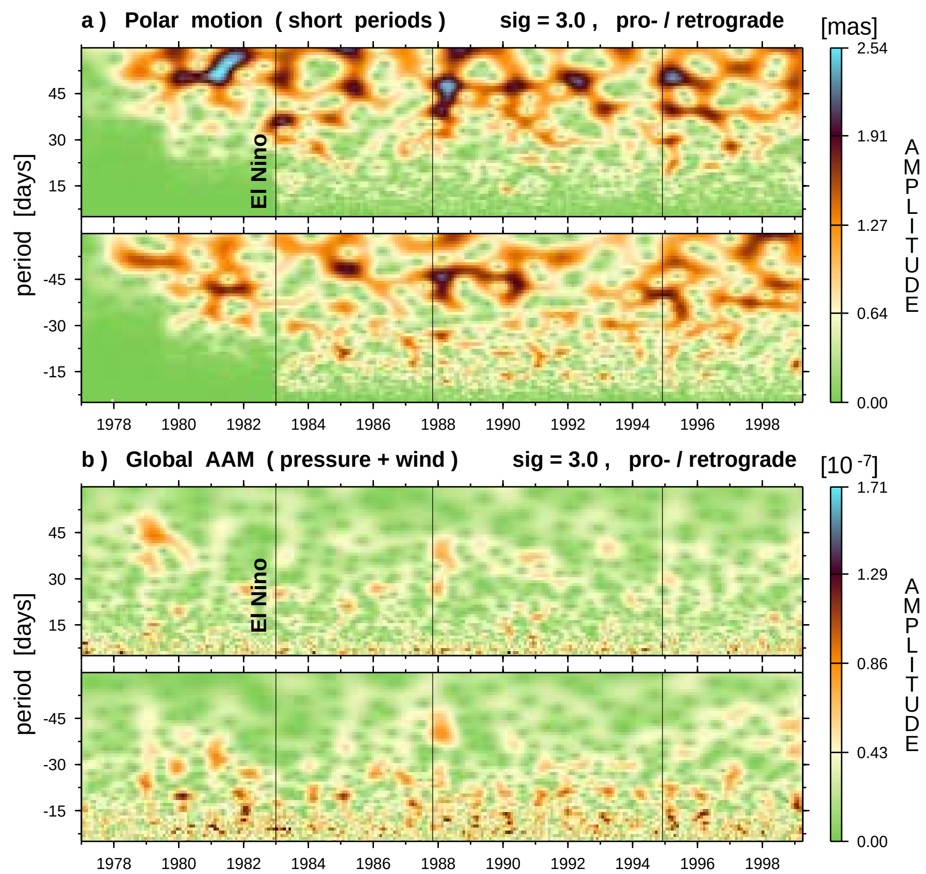

Fig. 6: Wavelet spectra of polar motion (a) and of AAM (b) for periods shorter than 60 days

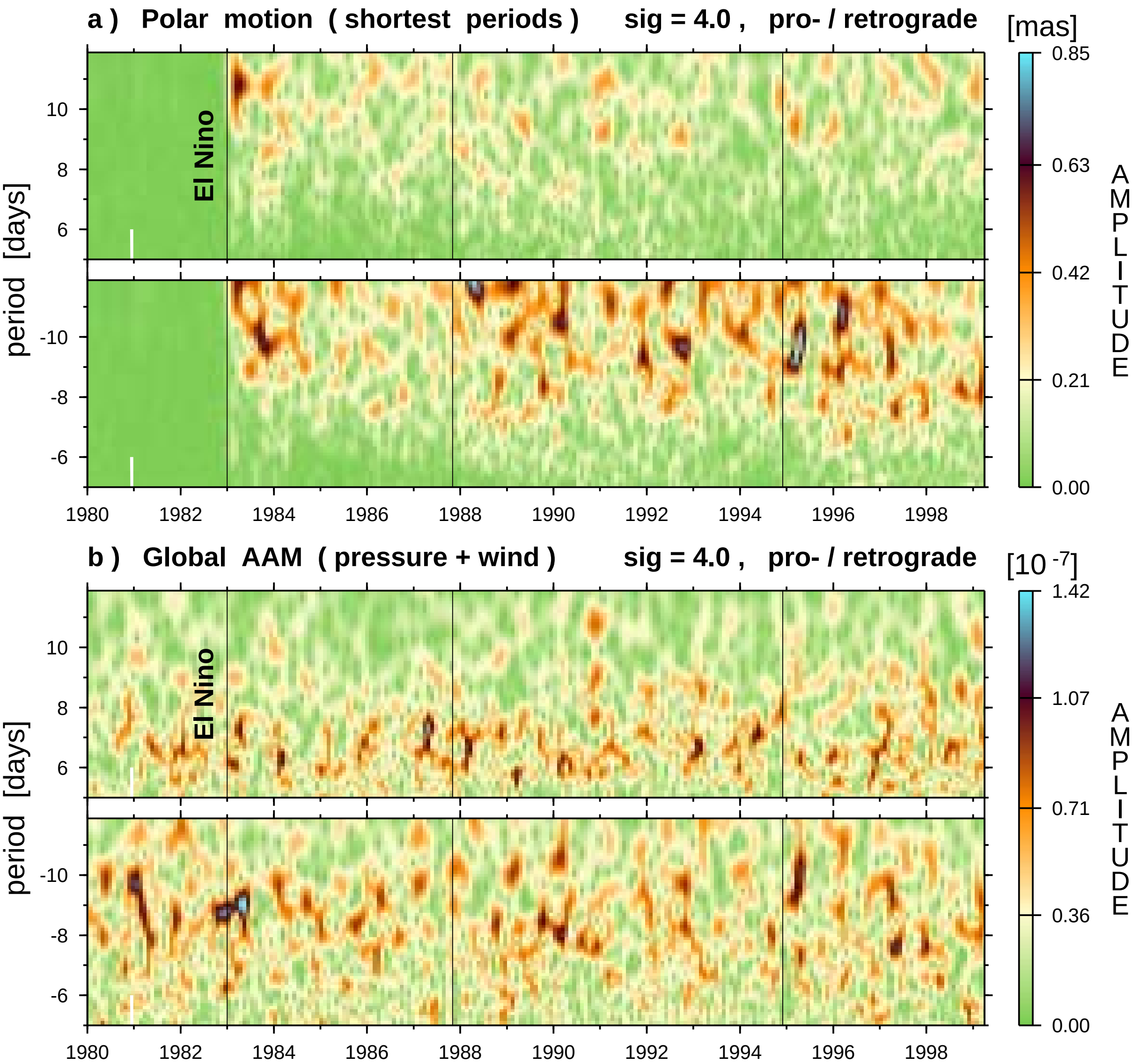

Fig. 7: Wavelet spectra of polar motion (a) and of AAM (b) for periods between 5 and 12 days