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Fluctuations in the Earth's rotation since 1830 from high-resolution astronomical data

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SUMMARY

Fluctuations in the Earth's rotation since 1830, as evidenced by changes in the length of the day, are derived from astronomical data having subannual resolution. Before 1955.5, timings of linar occultations are used; after 1955.5, the data are taken from the time series TAI–UT1.

Although the data in the earliest period, 1830–90, display decade fluctuations in the length of the day, they are not accurate enough to reveal interannual variations. In this regard, also, the results from 1890–1925 are somewhat dubious. The quality of the data after 1925, though, is such that the temporal behaviour of the interannual fluctuations in the length of the day can be traced with confidence. We present plots of the interannual fluctuations in the period 1890–1987 and the longer-term decade fluctuations in the period 1830–1983.

The interannual fluctuations in the length of the day since 1925 are compared with an index of the El Niño/Southern Oscillation (ENSO) phenomenon in the ocean–atmosphere system and are subjected to spectral analysis. The results support the conclusions reached by other authors that these fluctuations are linked to circulation changes in the atmosphere associated with ENSO, and in part to the quasi-biennial oscillation in the equatorial stratosphere's zonal winds. A spectral analysis of our 62 yr series of length of day values since 1925 reveals two significant peaks in the interannual range 2–4 yr. One is roughly biennial and the other is about twice this period, broadly supporting results obtained previously from shorter records.

Our analysis of high-resolution data, therefore, contributes to ongoing efforts to establish a close relationship between the length of the day and aspects of the global climate system in the period before modern data became available in 1955.5.

Key words: atmospheric circulation, earth rotation, lunar occultations, time-scales.

1 INTRODUCTION

The observed fluctuations in the rate of rotation of the Earth provide important data for investigating some of the basic properties of the constitution of the Earth and the circulation of its oceans and atmosphere (Lambeck 1980). The external tidal torques exerted by the Moon and Sun, and the internal exchange of angular momenta between the core and the shell (consisting of the mantle and crust) and between the shell and atmosphere, produce measurable variations in the rotation of the planet. These variations are conventionally expressed as changes in the length of the day (l.o.d.) and are measured in milliseconds (ms).

With the introduction of atomic clocks and the construction of the international atomic time-scale (TAI) beginning in July 1955, astronomical observations have clearly revealed fluctuations in l.o.d. in the range 0.1–1 ms on time-scales of days to a few years. These are due to the interchange of angular momentum between the shell and atmosphere. The data since 1955.5 also reveal a slow change of about 2 ms over several decades, which is attributed to torques operating between the core and the shell.

We are interested in tracing fluctuations in l.o.d. back before the atomic time-scale. The most accurate set of data prior to 1955.5 for this purpose is the long series of timings of occultations of stars by the Moon that extends back to the early part of the 17th century, when the telescope was introduced for astronomical observation. Morrison (1979) analysed the observations in the period 1860–1955.5 and extended this forward to 1978 using the atomic time-scale data. He concluded from the decade fluctuations in the l.o.d. that the torques operating between the core and shell reached a maximum of 10^{18} Nm around 1900.

In his analysis, Morrison worked with annual mean values of the astronomical data. This was satisfactory for exploring the decade fluctuations, but the binning at intervals of a year may have smoothed out, or at least greatly reduced, possible changes occurring over two or three years, which are commonly referred to as interannual changes. McCarthy & Babcock (1986) also produced a time-series of l.o.d. values at six-monthly intervals for the period 1860–1984.5, but this affords no better resolution for the period 1860–1943 than Morrison's data because their series is derived from Morrison's annual values by smoothing and interpolation. (For the period 1943–55.5 they used monthly values supplied separately by Morrison, thus giving improved time resolution during this period.)

Much interest now attaches to these interannual changes in the l.o.d. because they appear to be associated with major changes in the circulation of the ocean and atmosphere (Chao 1984, 1988, 1989; Salstein & Rosen 1986; Dickey *et al.* 1992, 1993). We, therefore, undertook to re-reduce the occultation data in the period 1860–1955.5 analysed by Morrison and to extend the investigation back to 1830 and forward to 1992. Our main aim is to investigate the spectral characteristics of the interannual changes by binning the data at finer intervals than Morrison did. Besides finer binning, two major improvements have occurred which should, potentially, enable greater resolution of the fluctuations in the Earth's rotation to be extracted from these data.

The first improvement is the availability of the ephemeris DE200/LE200 developed at the Jet Propulsion Laboratory (JPL). This numerically integrated ephemeris, which incorporates high-precision data from Lunar Laser Ranging, replaces the analytical ephemeris that was based on Brown's *Tables of the Motion of the Moon* (1919). Remarkable though Brown's tables are, they are deficient in some respects, particularly in the planetary perturbations, and this is rectified by using LE200.

The second improvement is in the accuracy of the reference frame defined by the catalogue of star positions. The reference frame defined by the FK5 used here is the successor to the FK4, which was used by Morrison in his analysis of the occultations. Zonal systematic errors in the FK4 could distort the results for changes in l.o.d.

2 TIME-SCALES AND CHANGES IN L.O.D.

Fluctuations in the rate of rotation of the Earth introduce irregularities in the universal time-scale (UT1) which is derived from the diurnal rotation of the Earth. Orbital motions in the Solar System, on the other hand, are free from such fluctuations, apart from known gravitational perturbations. Thus, by inverse interpolation to the observed positions in their geocentric ephemerides, it is possible to measure the intervals of time between observations on the dynamical time-scale implicit in the ephemerides and to construct the uniform time-scale, Terrestial Time (TT). The position of a planet or an event, such as an eclipse or occultation—noted at some instant on the UT1 scale—is compared with the calculated time on TT. The difference, TT–UT1, usually denoted by ΔT, is a measure of the cumulative discrepancy in time due to the departure of the Earth from uniform rotation.

The unit and origin of the TT scale are fixed relative to the TAI scale, as defined by Recommendation IV of the IAU Working Group on Reference Systems (Hughes 1991). The unit of the TT scale is the SI second and its origin is specified by the relation TT = TAI + 32.184 s at the epoch 1977 January 1.0. The first derivative in time of $\Delta T(t)$ is a measure of the change in l.o.d. relative to the standard length which is 86 400 SI seconds exactly.

The times of occultations in the catalogues of Morrison (1978) and Morrison, Lukac & Stephenson (1981) are given in the system UT0 rather than UT1 before 1947. UT0 is the universal time-scale derived directly from observation and is uncorrected for the effect of oscillatory changes in the longitude of the observers due to polar motion. Beginning in 1947, some observatories started to correct UT0 for polar motion and thus they transmitted UT1. This practice, however, was introduced by only a few observatories; the majority continued to use UT0. The maximum contribution in time in the period 1900–55 due to polar motion is $0^{\mathrm{s}}.01 \tan \phi$, where ϕ is the observer's latitude. The predominant part of this signal is the Chandler wobble with a period of 14 months. We have not corrected the occultation times for this relatively small effect. It is an order of magnitude smaller than the cumulative changes in time due to interannual fluctuations in l.o.d.

3 OBSERVATIONS

About 53 000 observations of lunar occultations in the period 1830–1955.5 were taken from the catalogues of Morrison (1978) and Morrison *et al.* (1981). The timings are given to a precision of 0.1 s.

In a parallel analysis, about 111 000 observations made during the period July 1955 until the end of 1980 were used to investigate systematic errors in timing occultations ('personal equation') and the datum of Watts' (1963) limb corrections. The observations in the period 1955.5–72 were taken from Morrison (1978) and for 1972–80 from Appleby, Morrison & White (1984). It is possible to separate these correlated effects after 1955.5 because the time-scale TT is known *a priori* from the relation TT = TAI + 32.184.

3.1 Distribution of observations

Occultation observations are not evenly distributed with time because of a few basic factors that govern their observability. Fig. 1 shows the distribution of the observations binned at four-monthly intervals in the period 1830–1955.5. The synodic month (lunation) of 29.5306 mean solar days is used throughout this analysis. The two World Wars of 1914–18 and 1939–45 made a noticeable impact on

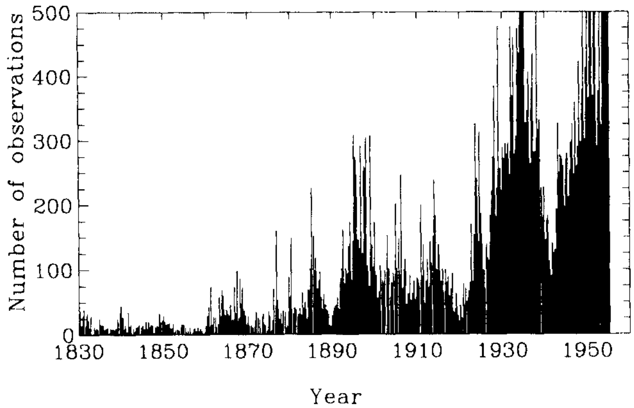

Figure 1. Histogram of occultation observations in four-lunation bins in the period 1830–1955.5.

the numbers of observations. The distribution of the number of observations falls approximately into three periods: 1830–90, 1890–1925, and 1925–55.5. Between each period there is about a fourfold increase in the number of observations.

There is an annual cycle in the number of observations, which arises from the fact that most of the observations were made in the winter nights in the Northern Hemisphere. This is most pronounced in the years 1950–55, as can be seen in Fig. 2, which shows the period 1925–55 of Fig. 1 in greater detail. Before 1950 the annual pattern is not regular, with the maxima often dispaced from the beginning of the year. This is not an artefact of the four-lunation binning, but a real effect caused by the preponderance of occultations of a few first-magnitude stars which attracted many observations regardless of the season. The annual values in Morrison (1979) and subsequently McCarthy & Babcock (1986) are thus not based on equally spaced mean epochs, and this would distort a sprectral analysis of these series.

Figure 3 shows the distribution of the observations within the synodic month. The mode of the distribution is just after the first quarter. This is due to the fact that most occultations were observed during the first half of the month when the unilluminated edge of the Moon advances into the star field. However, there are significant variations from this pattern in some months, as for example, when the bright

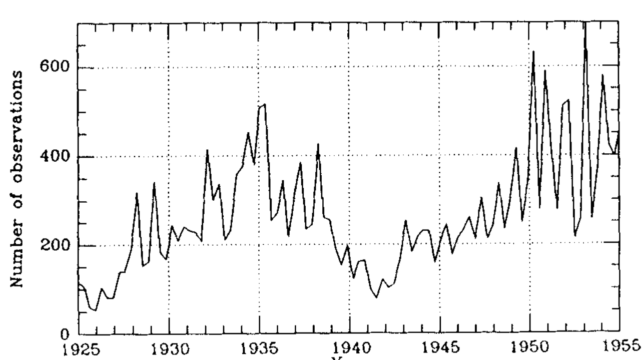

Figure 2. Number of occultation observations in four-lunation bins in the period 1925–1955.5 showing the modulation in numbers during the year.

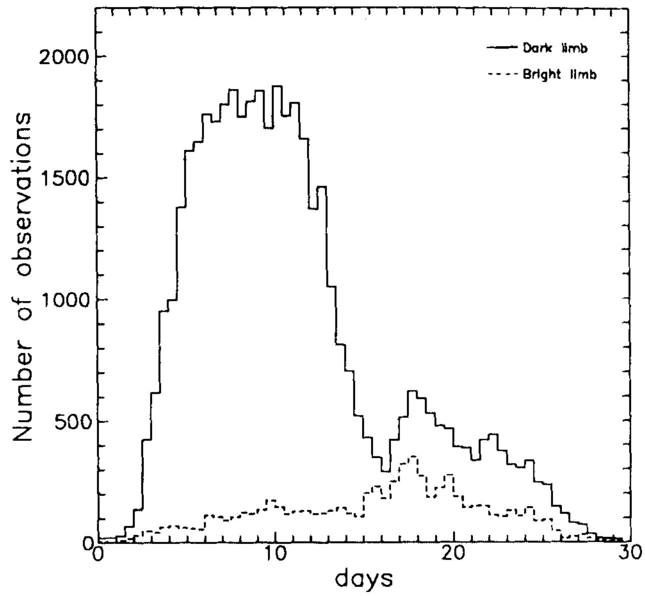

Figure 3. Distribution of occultation observations within the lunation. New moon, first quarter, full moon and last quarter occur at 0, 7.4, 14.8 and 22.1 days, respectively. Most of the occultations were observed between new and full moon with the stars occulted at the dark, leading edge of the Moon.

star cluster, the Pleiades, was occulted. About 70 per cent of the occultations were observed around the first quarter, disappearing at the dark limb of the Moon. About 20 per cent were observed as they reappeared at the dark limb around the third quarter. The remaining 10 per cent were observed at the illuminated limb, either as reappearances around the first quarter or disappearances around the last quarter.

3.2 Accuracy

The accuracy in timing an occultation depends on the method of observation used by the observer, and whether or not the occultation was observed at the illuminated limb. There are two components in the accuracy of timing that are due to the observer. The first is a systematic delay between the event and the time noted by the observer, which is commonly known as the personal equation. The second is a random error that remains after the subtraction from the observed time of the average personal equation.

The observations at the illuminated limb have much greater errors than those at the dark limb, and they are also much less numerous, as remarked above. For these reasons, they were deleted from the data set.

The standard deviation of a single observation due to errors in timing, the star positions, and Watts' limb-profile corrections (see Section 6) is approximately ± 0.9 s. The technique of timing and hence the accuracy of an observation did not change significantly in the period 1830–1955.5. Indeed, the standard deviation of the observations binned at four-lunation invervals bears this out, with values close to 0.9 s throughout the whole period. With the fourfold increase in numbers around 1890 and again in 1925, we therefore expect to find an improvement by a factor of two in the accuracy at these epochs. This is

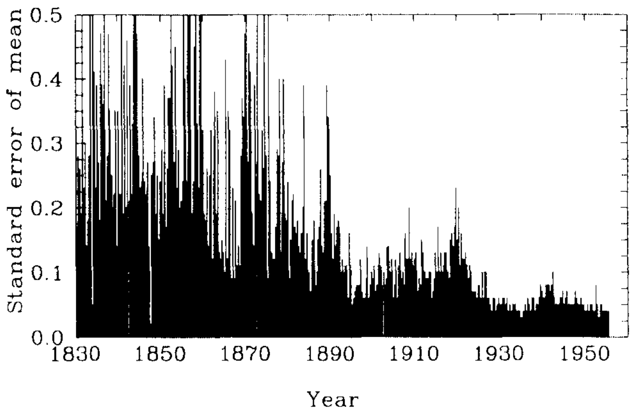

Figure 4. Standard errors of the four-lunation mean values of ΔT.

borne out by Fig. 4 which shows the standard errors of the four-lunation means. The general trend is reversed around 1920 when the number of observations temporarily drops to the pre-1890 level.

Now, from a study of the atomic time-series data since 1955.5, Dickey *et al.* (1993) find interannual fluctuations in the l.o.d. with a characteristic amplitude of about 0.2 ms. Cumulatively, this amounts to a difference in time of about 0.07 s from one year to the next. From Fig. 4 it is seen that the standard error of the four-lunation means drops to about 0.08 s at 1895, increases to about 0.16 s at 1920, and decreases again to about 0.04 s at 1925. There should, therefore, be good prospects of delineating the interannual fluctuations after 1925, but with less prospect before then. This was also the conclusion reached by Dickey *et al.* (1993) from the coarser-resolution time series they used.

4 STAR POSITIONS AND REFERENCE FRAME

The positions and proper motions of occulted stars have been taken from various catalogues, depending on their accuracy at the epoch of the occultation observations. The reference frame defined by the FK5 catalogue is the most accurate available at present; so we have attempted to refer the positions of non-FK5 stars to this frame. Of course, the positions of stars in the FK5 were taken unaltered from that catalogue.

Because the observations under analysis span the interval 1830–1955.5, we decided to use the Zodiacal Catalogue (Robertson 1940), which has a mean epoch around 1905. The positions and proper motions in the Zodiacal Catalogue were adjusted to the reference frame embodied in the FK5 catalogue through the analysis of 431 stars that are common to both catalogues. The mean differences in hourly bands of right ascension were removed from the ZC positions and proper motions.

Stars not included in the FK5 nor ZC catalogues were taken, in order of preference, from PPM-North (Röser & Bastian 1991), Carlsberg Meridian Catalogue Number 4 (CMC4, 1989), and the SAO catalogue. PPM-North and CMC4 are already referred to the FK5/J2000 frame. The SAO Catalogue is referred to the FK4 frame, so their positions were transformed to the FK5 system/J2000 using the procedure of Aoki *et al.* (1983) and the systematic corrections (FK5–FK4) tabulated in the FK5 catalogue (Fricke, Schwan & Lederle 1988).

Table 1. Number of observations of stars in each catalogue.

FK5	15 972
ZC	27 674
PPM-North	6 309
CMC4	831
SAO	2 454
Total	53 240

The number of observations of stars in each catalogue is given in Table 1.

5 LUNAR EPHEMERIS AND TIDAL ACCELERATION

The ephemeris DE200/LE200 was generated at JPL by numerical integration of the equations of motion of bodies in the Solar System. The coordinates were rotated on to the mean equator and the dynamical equinox of the standard equinox J2000.0 (Standish 1982). The system of constants used in the construction of this ephemeris is slightly different from that adopted by the IAU (1977). We have used the system of constants of the ephemeris DE200/LE200 in order to be consistent with it.

For long-term studies, the principal defect of the ephemeris LE200 is in its value of the tidal acceleration. The value $-23''.9/\mathrm{cy}^2$ (cy being century) is implicit in LE200, whereas the most recent result from lunar laser ranging is $-26''.0 \pm 1''.0/\mathrm{cy}^2$ (Williams, Newhall & Dickey 1993). The difference of $-2''.1/\mathrm{cy}^2$ leads to a secular change of $+0.1\ \mathrm{ms\ cy}^{-1}$ in l.o.d. deduced in this analysis. This has very little effect on the interannual variations under investigation in this paper, so we have ignored this small secular change.

6 LIMB PROFILE CORRECTIONS

The height of the outline of the Moon at the point of occulation was taken from the digitized version by Morrison & Martin (1971) of Watts' (1963) charts of the 'marginal zone of the moon'. A correction of 0.25° was applied to the position angle of Watts' charts (Morrison 1970; Van Flandern 1970; Salazar 1979). The Moon's radius adopted in this work is 1738.0 km at a mean Earth–Moon distance of 384 747.966 km. An analysis of the parallel data set for 1955.5–80, similar to that of Rosselló, Jordi & Salazar (1991), was undertaken to derive systematic corrections to the radius, location of the centre, and ellipticity of the datum of Watts' charts. The effects of these corrections were subtracted from the occultation timings.

About 3000 observations were rejected because they had poor or no limb corrections in Watts' charts.

7 REDUCTION

The reduction of the observations was performed as described in Jordi & Rosselló (1987). After the removal of the effects of all the corrections derived in the parallel analysis, the remaining difference between the computed time of the occultation on the TT scale and the observed time on the UT scale was interpreted as ΔT. Weighted annual mean values of ΔT were formed for the purpose of rejecting outliers.

8 ANALYSIS AND DISCUSSION

8.1 ΔT time series 1830–1992

The natural grouping of occultation observations around the first quarter of each month (see Section 3.1) lends itself to the formation of a time series of ΔT at lunation intervals. However, many lunations before 1890 do not have any observations. Desirous of forming as long a time series as possible, yet with an interval not too great to preclude the investigation of interannual variations, we decided on a compromise of four lunations for forming mean values of ΔT. This enabled a continuous time series of almost equally spaced values of ΔT to be constructed in the period 1830–1955.5. Two intervals of four lunations had no observations: means of adjacent intervals were taken in these cases. Before 1830 there were several periods of four lunations with no observations. This investigation was curtailed at that epoch for that reason.

The four-lunation mean values of ΔT for the period 1830–1955.5 are plotted in Fig. 5. These data have been extended forward to 1992 by taking values of TAI–UT1 + 32.184 s at four-lunation intervals from the data published in the Annual Reports of the Bureau International de l'Heure (BIH) and the International Earth Rotation Service (IERS), Observatoire de Paris. Only values of TAI–UT2 are available in the period 1955.5–62. Here we added the standard seasonal variation, UT2–UT1, in order to obtain TAI–UT1. The decrease in the scatter of the points in the period 1830–1955.5 follows the behaviour of the standard errors of the four-lunation means plotted in Fig. 4. The accuracy of the data after 1955.5 is better than 1 ms.

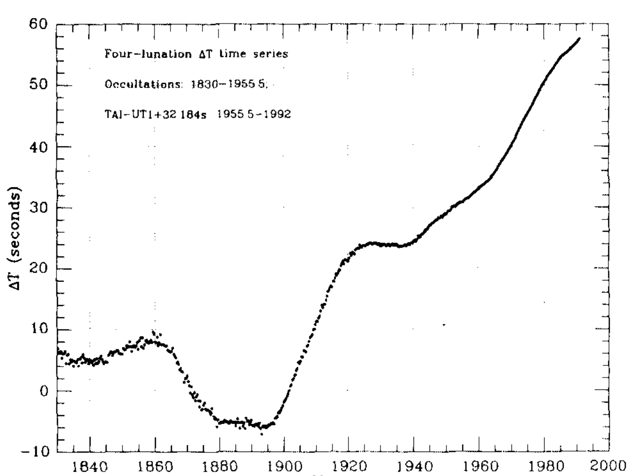

Figure 5. Four-lunation ΔT time series. The values in the period 1830–1955.5 were obtained from lunar occultations (see text), and the values after 1955.5 were taken from TAI–UT1 published by the BIH and IERS.

8.2 l.o.d. time series 1830–1987

The change in l.o.d., with its direct correspondence to the change in angular momentum, is a more useful geophysical parameter than the cumulative error in time, ΔT. We formed a l.o.d. time series by finite differencing of the four-lunation ΔT series as follows. First, the 1955.5–92 data were smoothed using a Gaussian convolute with a FWHM of 12 lunations to remove periods of a year or less. The l.o.d. values computed from the first differences of this series are plotted in Fig. 6 for the period 1955.5–87. The error bars are smaller than 0.02 ms. Secondly, using these very reliable results for 1955.5–87 as a control on the size of the fluctuations before 1955.5, the four-lunation solutions for ΔT in the period 1830–1955.5 were smoothed using a Gaussian convolute with a FWHM of 18 lunations ($\sim$1.5 yr). It was tacitly assumed that the interannual variations before 1955.5 would have a similar character to those after 1955.5. The l.o.d. values computed from the first differences are also plotted in Fig. 6. The different degrees of smoothing before and after 1955.5 produce a discontinuity at that epoch. Several points have been omitted from Fig. 6 around 1955.5 for that reason.

The solid curve in Fig. 6 for the period 1838–1983 was obtained by strongly smoothing the ΔT series with a Gaussian convolute of 60 lunations (4.8 yr) and differencing the results. This strongly smoothed l.o.d. series is dominated by the decade fluctuations and is very similar to the series derived by Morrison (1979). The changes in angular momentum corresponding to the changes in l.o.d. around 1900 imply torques of up to 10^{18} Nm operating on the shell of the Earth.

8.3 Interannual variations in l.o.d. 1890–1987

The l.o.d. series plotted in Fig. 6 shows evidence of interannual variations superimposed on the decade trends. Considering that the error bars after 1955.5 are smaller than 0.02 ms, the fluctuations are undoubtedly real. As a result of the degree of smoothing applied, the character of the fluctuations for several decades before 1955.5 is similar to those after 1955.5. Before about 1925 the scatter increases, in keeping with the behaviour of the errors displayed in Fig. 4, and we have less confidence in discerning interannual

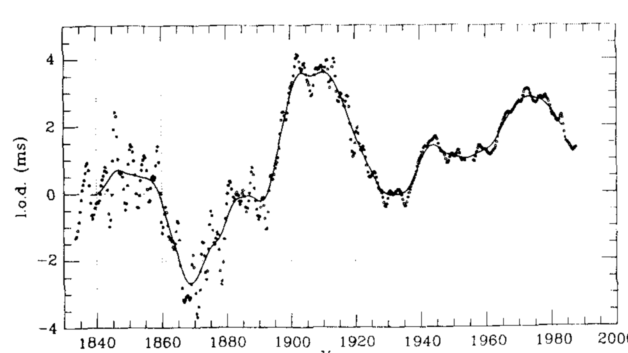

Figure 6. Four-lunation l.o.d. time series with weak smoothing (open circles) and strong smoothing (continuous curve), displaying interannual and decade fluctuations. The rationale for the degrees of smoothing is given in the text.

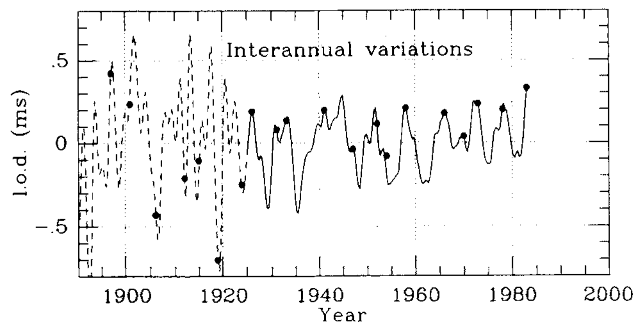

Figure 7. Interannual variations in l.o.d. in the period 1890–1983 derived by subtracting the two series plotted in Fig. 6. Dots mark northern winters that fall at the end of years during which the Southern Oscillation index was anomalously low (see text).

variations in that period. Certainly, before 1890, it appears to be impossible. For this reason, we restricted further investigation to the period after 1890.

A new time series of l.o.d. in the period 1890–1983 was formed by subtracting the underlying decade trend from the weakly smoothed four-lunation l.o.d. series described in Section 8.2. The points of this time are joined by a continuous line after 1925 in Fig. 7. As already noted from Fig. 4 and the discussion of accuracy in Section 3.2, the interannual variations before 1925 are likely to be masked by noise. For this reason the points of the time series in the period 1890–1925 are joined by dashed lines.

After 1961 our results are very close to those of Dickey *et al.* (1993) because we have used effectively the same l.o.d. series derived from TAI–UT1. Between 1955.5 and 1961, Dickey *et al.* used USNO PZT data whereas we used BIH data, but our results for the interannual variations are similar. Before 1955.5 our results are similar in nature, but different in detail, to those obtained by Dickey *et al.* who used the series of McCarthy & Babcock (1986) described in Section 1. These dissimilarities in detail arise partly from the differences in smoothing applied by McCarthy & Babcock and ourselves. Unfortunately, the high-frequency noise in the data before 1955.5 forced us to use a Gaussian smoothing convolute of FWHM 1.5 yr rather than a narrower convolute near to 1 yr, and thus, in this respect, we have damped interannual variations more strongly than is otherwise desirable. Nevertheless, our series still has the benefit of being derived from a new reduction of the basic occultation material using an improved lunar ephemeris and system of star positions. We, therefore, regard our results for the temporal behaviour of the interannual variations before 1955 depicted in Fig. 7 as being more reliable than those derived previously.

Interannual variations in l.o.d. are associated with fluctuations in the atmosphere's angular momentum, which are related to large-scale circulation changes on interannual time-scales. The most notable of these changes occur in conjunction with the coupled ocean–atmosphere phenomenon known as the El Niño/Southern Oscillation (ENSO). A strong connection has been established between interannual fluctuations in l.o.d. and ENSO, such that years with ENSO warm events are marked by westerly wind anomalies in the tropics and subtropics and, hence, an excess of atmospheric angular momentum and an accompanying decrease in the solid Earth's rotation rate (Rosen *et al.* 1984; Chao 1984, 1988, 1989).

Following the approach of Salstein & Rosen (1986), we noted from the list compiled by Halpert & Ropelewski (1992) those northern winters that fall at the end of years in which the Southern Oscillation index was anomalously low (corresponding to ENSO warm events). These are marked by dots in Fig. 7. For the period since 1925, a Student's t-test of the difference between the mean l.o.d. anomaly of the 13 winters marked by ENSO warm events (0.110 ms, s.d. = 0.12 ms) and that of the 46 non-ENSO winters (−0.031 ms, s.d. = 0.13 ms) yields a value of $t = 3.44$ which is statistically significant at the 95 per cent level of confidence.

Recent studies of ENSO (e.g. Rasmusson, Wang & Ropelewski 1990; Barnett 1991; Ropelewski, Halpert & Wang 1992) have focused on the components that appear to describe its temporal behaviour, including a biennial pulse and a lower frequency signal. The former may result from ocean–atmosphere feedbacks over the tropical Indian and Pacific oceans (Meehl 1993). Dickey *et al.* (1992) identify a 2.4 yr periodicity in an index of the Southern Oscillation during 1976–91, which they associate with a pattern of propagation of anomalies in zonal mean fields of atmospheric angular momentum across the globe. Complicating the interpretation of quasi-biennial fluctuations in l.o.d. is the possibility that they may be related not only to the tropospheric ENSO phenomenon but also in part to the equatorial stratosphere's well-known quasi-biennial oscillation in zonal winds (Lambeck 1980, Section 7.5; Chao 1989). Current evidence indicates that these tropospheric and stratospheric signals are largely independent of each other (Xu 1992).

We carried out a power-spectrum analysis of the weakly smoothed four-lunation l.o.d. series plotted as open circles in Fig. 6 in order to investigate the spectral characteristics of the interannual variations. The analysis was restricted to the period 1925–87 which contains the most reliable data. The resultant power spectrum, shown in Fig. 8, clearly reveals

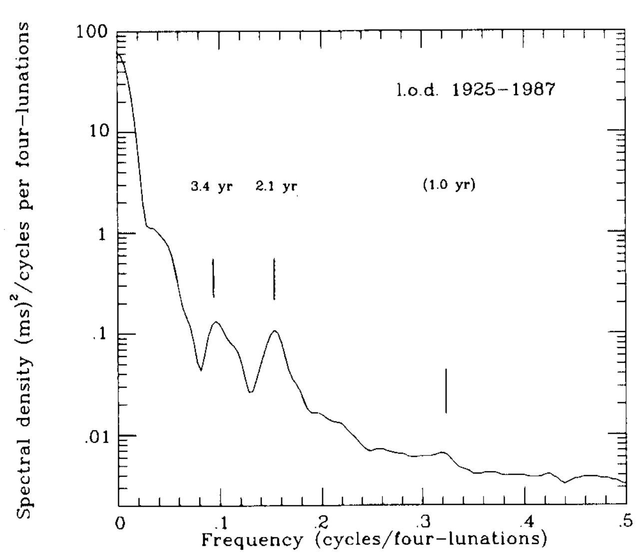

Figure 8. Spectrum of the weakly smoothed four-lunation l.o.d. series for the period 1925–87. Spectral density estimates smoothed with a Tukey window of bandwidth 0.02 cycles/four-lunations.

two broad peaks around periods of 2.1 yr and 3.4 yr, and power rising steeply towards decadal periods. The power at 1 yr and less has been attenuated by the smoothing applied to the time series, as described in Section 8.2.

A near-biennial signal has been known for some time. Iijima & Okazaki (1972) confirmed the existence of a 2.1 yr period from UT1 data for the years 1955.5–69. The two broad peaks at interannual periods in Fig. 8 can also be compared with the findings by Dickey *et al.* (1992) of power at about 2.3 yr and 4.0 yr in the l.o.d. and 2.4 yr and 4.3 yr in the Southern Oscillation series in the period 1976–91, and by Penland, Ghil & Weickmann (1991) of similar signals in an 11 yr subset of the atmospheric angular momentum series using adaptive filtering and maximum entropy techniques.

Some discrepancies between the position of the peaks derived here and those in the papers mentioned above are to be expected from the non-stationarity of the interannual signals in the l.o.d., as pointed out by Gambis (1992). Perhaps all that can safely be concluded from our analysis is that there is significant power in the interannual range 2–4 yr and it is concentrated in two periods, one roughly biennial and the other at about twice this period. It is noteworthy that the presence of enhanced power around a period of 2 yr suggests that the nearly biennial component of the ENSO cycle has been a persistent feature of the Earth's momentum budget.

9 CONCLUSIONS

The changes in l.o.d. in the period 1830–1990 displayed in Fig. 6 are characterized by decade and interannual fluctuations. The decade fluctuations derived here are in agreement with those found by Morrison (1979) and we thus confirm his estimate of 10^{18} Nm for the upper bound of the torque operating on the shell of the Earth around 1900.

The interannual fluctuations in l.o.d. after 1955.5 shown in Fig. 7 are similar to those deduced by other investigators (e.g. Salstein & Rosen 1986; Dickey *et al.* 1993). Before 1955.5, however, there are significant differences between our l.o.d. series and those used by others. We regard the present series as more reliable because we have re-reduced the basic occultation data by employing an improved lunar ephemeris and system of star positions.

A spectral analysis of the present 62 yr l.o.d. data set spanning 1925–87 supports conclusions reached by previous authors from a shorter data set that there is a nearly biennial and a lower frequency mode in the interannual band (Fig. 8). These spectral characteristics, combined with our temporal analysis of ENSO signals and the l.o.d. shown in Fig. 7, strongly support the conclusion of Dickey *et al.* (1993) that these astronomical data can serve as a proxy for atmospheric signals back to around 1925.

Copies of the four-lunation ΔT time series for the period 1830–1955.5 and a one-lunation ΔT time series for 1890–1955.5 (not discussed in this paper) can be obtained on request from the first two authors.

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