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The Earth's rotation and atmospheric circulation: 1958–1980

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Summary. The excitation of the Earth's rotation by the zonal wind circulation has been evaluated for a 22 yr period and the astronomical observations of the length-of-day from 1958 to 1980 have been corrected for this contribution as well as for tidal effects. The spectrum of the excitation contains, in addition to the seasonal terms and other high-frequency fluctuations (~ 1 cycle per 9 month and ~ 1 cycle per 4 month), significant power at periods up to about 50 month. The spectrum of the length-of-day fluctuations corrected for winds and tides contains significant power only at periods above about 50 month. Other-than-atmospheric excitation mechanisms are required to explain this part of the length-of-day spectrum. Both the astronomical and wind data suggest that fluctuations occur in the amplitude of the annual term with maximum amplitude occurring at about 10 year intervals (1958–1960, 1968–1970, and 1977–1979).

Astronomical observations indicated that fluctuations in the length-of-day (lod) occur over a wide frequency range, fluctuations that are of considerable geophysical interest since they imply that changes occur in the mass distribution inside and on the Earth, or that torques are applied at the Earth's surface or at the core–mantle boundary (Lambeck 1980). An important source for the lod fluctuations is the variation in the zonal wind circulation covering a frequency range from about 0.2 cycle yr^{-1} to about one cycle per week and possibly higher (Lambeck 1980; Hide *et al.* 1980; Rosen & Salstein 1980; Lambeck & Hopgood 1981). The astronomical observations therefore provide a measure of the variability of the total zonal angular momentum of the atmosphere superimposed upon other geophysical factors that may perturb the rotation. For the solid-Earth geophysicist this interaction represents meteorological noise and prevents geophysical signals from being investigated in detail. Attempts have been made to evaluate quantitatively the meteorological contribution and to subtract it from the astronomically observed changes in lod (Lambeck & Hopgood 1981; Lambeck & Cazenave 1974) but these have been hampered by a lack of homogeneous global wind data for time intervals longer than a few years. Consequently, the emphasis on past studies has been on establishing the relationship between the atmospheric circulation and the Earth's rotation rather than on correcting the astronomical data (Lambeck 1980; Hide *et al.* 1980; Rosen & Salstein 1980; Lambeck & Hopgood 1981).

We are now able to report on such a comparison and correction for a 22 yr period and some of the implications of this corrected time series are briefly discussed.

The proportional change in length-of-day $\Delta(\text{lod})$, m, is defined as

$$m = \frac{-\Delta(\text{lod})}{\text{lod}} = \frac{\omega - \Omega}{\Omega} = \frac{d\tau}{dt}$$

where ω is the instantaneous velocity of the Earth about its rotation axis and Ω the mean velocity. The observed astronomical quantity is τ, the integrated amount by which the Earth is behind or ahead of time kept by a uniform standard. Fig. 1(a) illustrates the monthly mean m for the period 1955–1981. The values have been obtained by estimating daily values from a cubic spline interpolation of the International Bureau de L'Heure values given at 10 day (prior to 1962) and 5 day (after 1962) intervals and then averaging to obtain the monthly values. Fig. 2(a) illustrates the corresponding power and observational error spectrum. The latter spectrum is based on the older data and from about 1967 onwards its power is considerably less than adopted here (Lambeck & Hopgood 1981).

The observed meteorological quantity at time t is the zonal wind from which the total zonal angular momentum $h(t)$ is computed. The normalized angular momentum $-h(t)/\Omega I$, where I is the polar moment of inertia of the Earth, is referred to as the excitation function. The change in rotation due to a change in the zonal wind circulation is

$$\dot{m}(t) = \chi\,\Omega(t)$$

where χ is the Earth's response function. We have adopted $\chi = 1$ (Lambeck 1980). Zonal wind measurements have been analysed from 1958 to 1980 and monthly mean values of ψ have been estimated for this 22 yr period. Wind observations from 1958 to 1973 were provided by Environmental Research Technology (ERT) and additional data for this period and for the years 1973–1978 were provided by the National Centre for Atmospheric Research (NCAR). The most complete set in terms of global coverage is for the period 1967 July to 1973 April, when latitudinal coverage was complete in both hemispheres and the altitude coverage extended from 1000 to 10 mb (Lambeck & Hopgood 1981).

The data prior to about 1967 were less complete in their coverage of southern latitudes. From 1963 to 1967 the coverage was mostly complete down to latitudes of $-55°$ but occasionally extended down to only $-35°$. For 1958–1963 the coverage extended only occasionally below $-35°$. For those months where the coverage was insufficient, interpolated grid values have been supplemented with values based on an average monthly grid computed from the wind data for the years 1967–1973 of complete coverage. These corrections provide a time series in zonal angular momentum that is suitable for investigating low-frequency variations in rotation. The data set from 1973 to 1978 contained observations from only about 400 stations compared with about 600 for the years 1958–1967 and more than 1000 for the years 1968–1973 but nevertheless the latitudinal coverage is adequate. The altitude range extends only to 30 mb and this set has been supplemented for the 30–10 mb zone using the same process as before. Daily values of $h(t)$ for the period 1976 January–1980 April have also been computed independently as ERT (Rosen & Salstein 1980), from a data base that is considerably more complete than the above-mentioned NCAR data. The upper altitude range in the ERT calculations was only 100 mb ($\simeq$ 16 km) and their $h(t)$ has been supplemented from 100 to 10 mb using the average monthly winds. Included in this data set are aircraft and satellite observations and, since the station measurements may not adequately sample the intense mid-latitude streams over the oceans, the former observations may result in larger wind velocities for mid-latitudes than do the station data alone. A comparison of the angular momentum from ERT (h_{ERT}) with that computed from the NCAR (h_{NCAR}) data from an overlapping 3 yr period 1976–1978 confirms that

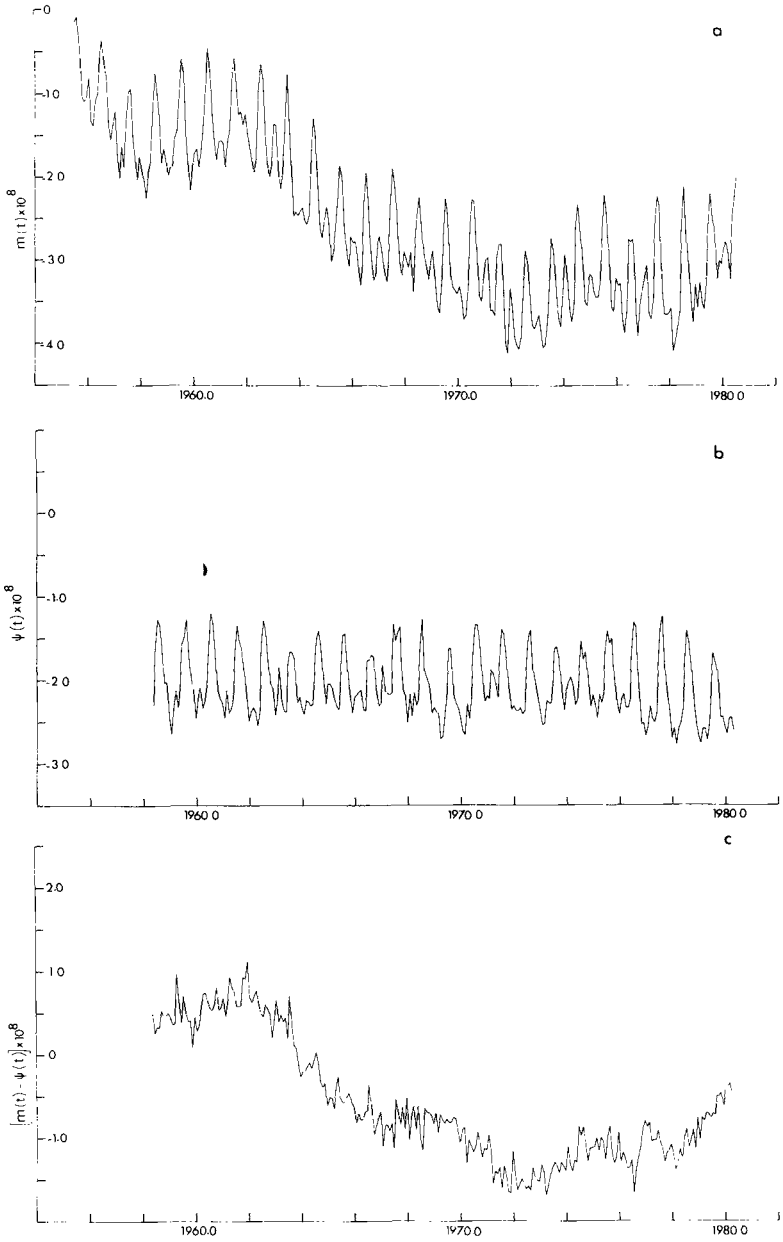

Figure 1. (a) Astronomical observations of the variations in the proportional change in the length-of-day $m(t)$ since the introduction of the atomic time in mid-1955. (b) Zonal wind excitation function $\psi(t)$ for a 22 yr period from 1958 May to 1980 April. (c) The length-of-day fluctuations corrected for zonal winds and tides.

the latter, based on fewer observations, is noisier and of smaller magnitude such that $|\langle h_{\mathrm{ERT}} - h_{\mathrm{NCAR}}\rangle / \langle h_{\mathrm{ERT}}\rangle| \simeq 8$ per cent. The seasonal variations in the two data sets are in good agreement. In view of the relative completeness of the ERT wind data for the years 1976–1980, and since the analysis technique used at ERT is very similar to ours, we have adopted this result after 'correcting' it by the above amount so as to preserve the overall homogeneity of the data set for 22 yr.

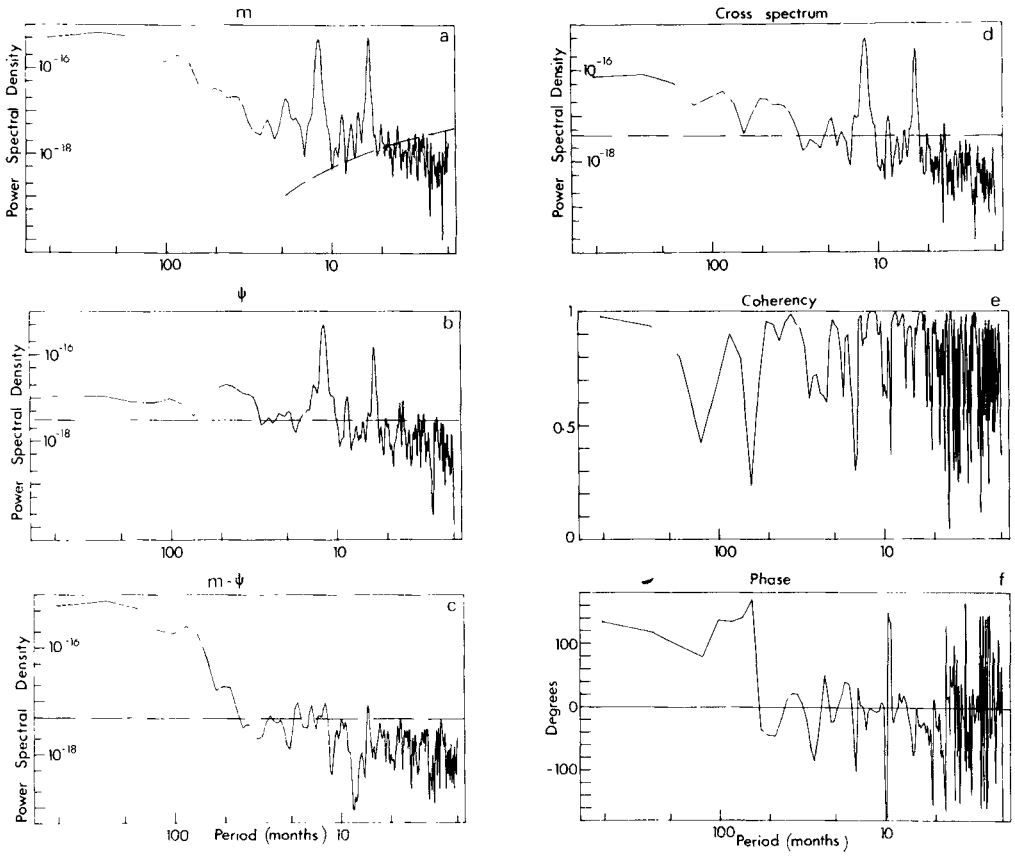

Figure 2. Power spectra of m (a), ψ (b), the difference $m-\psi$ (c), and the cross, coherency and phase spectra (d, e, f, respectively). All spectra are based on the 22 yr interval from 1958 May to 1980 April. The observational error spectra are indicated by the dashed lines. All time series have been detrended prior to computing the spectra.

The total time series of the excitation function is illustrated in Fig. 1(b) from 1958 May to 1980 April. The power spectrum of this series is shown in Fig. 2 together with the corresponding observational error spectrum (Lambeck & Hopgood 1981). Both the astronomical and excitation time series contain considerable high-frequency fluctuations that cannot be entirely attributed to noise in the two data sets. For the years of complete wind data, variations with frequencies up to about 4 cycle yr^{-1} rise above the noise (Lambeck & Hopgood 1981) but for the entire 22 yr period only frequencies up to 2 cycle yr^{-1} are considered to be significant. Power in the two spectra is very considerable over a broad frequency range and peaks, with corresponding maximum coherence and near-zero phase, occur at periods near 40, 20 and 9 month (Fig. 2). The comparison of the two time series, filtered such that only periods between 7 and 50 month are retained (Fig. 3a), provides further confirmation of the dominant role played by the atmospheric circulation on the variable lod in this period range. Clearly, taking into account the noise present in both series, the high-frequency fluctuations in $(\Delta m - \Delta\psi)$ – where Δm, $\Delta\psi$ are m, ψ less the seasonal terms discussed below – are attributable to measurement and meteorological noise (Fig. 1c) and there is no evidence to suggest that other geophysical excitation functions play an important role here and, by extension to earlier studies (Lambeck & Cazenave 1974; Hide *et al.* 1980; Rosen & Salstein 1980), at periods less than 1 month.

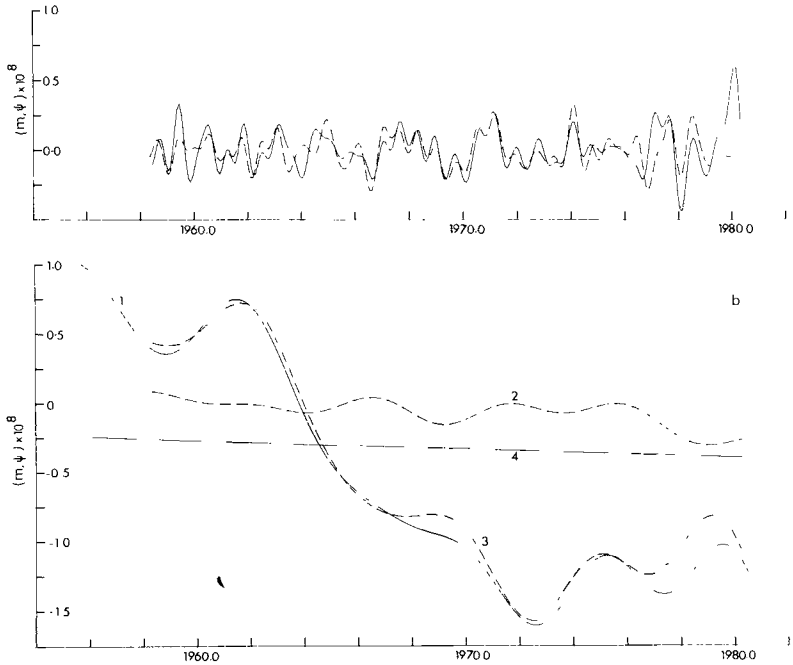

Figure 3. (a) Bandpass filtered m (full line) and ψ (broken line), to pass all periods in the range 7–50 month. (b) Lowpass filtered m (curve 1), ψ (curve 2) and $m - \psi$ (curve 3) to pass all periods greater than 50 month.

Seasonal variations are present in both time series. These have been discussed previously (Lambeck & Hopgood 1981), and the conclusions do not differ from these earlier results, namely that: (1) zonal wind and tidal contributions are the dominant cause of the annual and semi-annual periodicities in the Earth's rotation, and (2) the uncertainties in the excitation function (compare the observational error spectra of m and ψ, Fig. 2) are such that any disagreement between m and ψ cannot be used to draw conclusions about some of the more interesting geophysical problems such as the response function χ at seasonal frequencies or the frequency dependence of Love numbers defining the tidal contributions.

There is some evidence in both m and ψ to suggest that fluctuations occur in the amplitude of the annual term (Lambeck 1980; Okazaki 1977; Okazaki & Sakai 1981). Positional astronomical observations are subject to uncertainties at the seasonal frequencies but it is not evident that this can explain the variations (Okazaki 1975). The homogeneous and precise data set from 1967 onwards, for example, confirms this variable behaviour. The excitation function exhibits a similar trend, albeit less clear because of the incompleteness of latitudinal and height coverage for some months in the 22 yr data set. The annual term in lod is a measure of the angular momentum imbalance between the circulation in the two hemispheres and any variations in amplitude implies global changes in this imbalance. Without meteorological data it is not possible to deduce how these variations are achieved. However, the maximum seasonal amplitudes occur at about 10 yr intervals (1958–1960, 1968–1970 and 1977–1979) and this may be suggestive of a solar influence since these periods correspond roughly with times of high 10.7 cm solar flux and of high sunspot activity. A pronounced 11 yr cycle in the amplitude of seasonal tropospheric wind speeds has already been noted in the northern hemisphere (Nastrom & Belmont 1980) and from the above result it would appear that the seasonal momentum imbalance between the two hemispheres is also controlled in some way by the solar variability. That is, it can be anticipated that the

southern hemispheric seasonal zonal wind amplitudes will exhibit a similar 11 yr cycle as found in the northern hemisphere by Nastrom & Belmont.

The time series (Fig. 1), as well as the corresponding spectra (Fig. 2), indicate that only at periods longer than about 4 yr is there a distinct difference with lod exhibiting significant long-period variations that are absent in the excitation function. Fig. 3 illustrates the low-pass filtered time series such that only periods longer than 50 month remain. This filtered excitation function is devoid of signal and there is, for example, no evidence for a 10–11 yr solar cycle in the net zonal angular momentum of the atmosphere. Thus while the year by year variability in the seasonal zonal angular momentum may be linked to solar activity, there is no such connection at the low-frequency band of the spectrum. The absence of power in the excitation spectrum at long periods confirms that there is little variation in the yearly average zonal angular momentum. Currie (1981) suggested that the zonal winds generate an 11 yr term in lod but we find no evidence for this. The corresponding low-frequency lod fluctuations must be attributed to other-than-zonal-wind excitations.

The dominant non-meteorological change in lod in this 22 yr period is characterized by a change of $\Delta m \simeq 2 \times 10^{-8}$ from about 1962 to 1973. This is similar in amplitude and time interval to changes noted in the older, pre-atomic-clock data (Lambeck 1980; Morrison 1979), observations which are characterized by changes in m of the order 4×10^{-8} occurring on time-scales of 20–30 yr. Of this older data the power spectrum rises above the noise level only at frequencies below about 0.1 cycle yr^{-1} so that, on the basis of the present comparison, it is most unlikely that zonal winds contribute significantly to these 'decade' lod changes. Here also, other geophysical mechanisms must be evoked.

By a process of elimination, torques at the core–mantle interface appear to be the most likely case for the length-of-day fluctuations on the decade scale, a conclusion already reached in 1952 by Munk & Revelle (1952). Likely torques acting on the base of the mantle are of electromagnetic or topographic origin. The problem of investigating these excitation mechanisms is fraught with difficulties due to the non-uniqueness of many interpretations, limitations of the supporting geophysical observations and because of noise in astronomical data. The role of the atmosphere, unless corrected for, further complicates the interpretation by masking any high-frequency contributions and making it difficult to identify and correlate the longer period fluctuations with other geophysical observations. This will be particularly important in the period range of 3–5 yr.

A sequence of step function perturbations in the torque will result in variations in lod that can be described by a series of linear functions. The wind-corrected lod (Fig. 1c) would suggest that these perturbations occur at intervals from 3 to 5 yr and that these changes occur rather abruptly. This is consistent with the characteristics of the corrected spectrum (Fig. 2c). The filtered data are indicative of larger perturbations occurring less frequently but this may simply reflect an accumulative effect of these smaller and more frequent perturbations.

Disturbances in the velocity field of the outer core form a likely source for such torques. Variations in the non-dipole magnetic field of the Earth are usually taken as evidence that such disturbances occur, although on the Earth's surface only a part of the spectrum of fluctuations can be seen. These disturbances can result in torques exerted either by the pressures of the core fluid on an irregularly shaped core–mantle boundary (Hide 1969, 1977) or by electromagnetic forces associated with any change in intensity of the magnetic field in the core and by the relative motion at this boundary (Rochester 1960, 1970). Probably both mechanisms operate at the same time but an adequate theory still does not exist. One way to proceed would be to consider schematic expressions for the torques – of unknown magnitudes, time constants and occurrence times – and match the corresponding excitation functions to the wind-corrected lod data. Without further geophysical constraints

on the various coupling parameters this approach has not yet led to an improved insight into the problem.

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