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The Earth's Variable Rate of Rotation: A Discussion of Some Meteorological and Oceanic Causes and Consequences

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The Earth's variable rate of rotation: a discussion of some meteorological and oceanic causes and consequences

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Aspects of the Earth's variable speed of rotation, or variations in the length of day, and their geophysical consequences and causes are reviewed. Emphasis is placed on those areas which may benefit most from improved observations of the rotation rate. Seasonal changes in the length of day are primarily of meteorological origin. Zonal winds, in particular, play an important rôle, and year-to-year variations in the magnitude of the seasonal rotational characteristics provide information on the variability of the year-to-year atmospheric circulation. Changes observed since 1955 in the annual and semi-annual change in the length of day indicate a decreasing strength of the zonal circulation at these frequencies. Changes observed in the astronomical biennial term indicate that the biennial zonal winds propagate downwards to variable depths and that it is of variable period. Higher-frequency variations in length of day are also primarily of meteorological origin and will mask or interfere with other geophysical factors affecting the Earth's rotation, such as tides or earthquake caused changes in the inertia tensor. Thus improved observations of the variable rotation will have to be accompanied by improved global compilations of zonal winds so that the meteorological contribution can be evaluated with equal accuracy. Present compilations of wind data are inadequate for this. An area where satellite observations can make an important contribution to studies of the Earth's rotation concerns the separation of the secular tidal and non-tidal changes in length of day by studying the tidal perturbations in satellite orbits.

Introduction

The subject of the Earth's geophysical implications of the Earth's variable rotation was thoroughly reviewed in 1960 by Munk & MacDonald (1960) and since then a considerable amount of new information, both of an observational nature and of a geophysical nature, has become available. Some of this is collected in symposia proceedings, in particular those edited by Marsden & Cameron (1966) and by Mansinha, Smylie & Beck (1970). Short reviews of recent results have been given by Rochester (1970–3). Important developments over the last 15 years include the following:

(1) Precise length-of-day data have become available owing to recent improvements in both universal time and in atomic time. These data have led to high-frequency information in the length-of-day spectrum that was previously only suspected. They have also led to an improved understanding of year-to-year fluctuations in the seasonal terms and opened up the possibility of using the astronomical data as constraints on the atmospheric circulation.

(2) Precise pole positions have become available, including new results obtained from the analysis of satellite orbit perturbations. Many of the older data have been re-evaluated and more reliable Chandler wobble parameters can now be estimated.

(3) Geophysical knowledge of the Earth's interior has undergone a very considerable revision since 1960, leading to an improved understanding of the excitation functions and permitting more useful geophysical constraints to be drawn from the astronomical data. Considerably more information has become available on ocean and atmospheric excitations functions.

(4) An important recent literature exists on the interpretation of the ancient and mediaeval eclipse data, providing more reliable estimates of the secular tidal acceleration of the Earth's spin and of the Moon's orbital motion. The tidal dissipation question has also been recently re-analysed.

(5) New evidence on the Earth's deceleration over the geological past is available from various sources and this has further consequences on the past evolution of the Earth–Moon system.

Analysis of satellite orbits for variations in the direction of the rotation axis were first reported by Anderle & Beuglas (1970), who analysed perturbations in the motion of the Doppler navigation satellites of the Tranet network (see also Anderle 1973). Since 1972 these observations have been compared with more conventional astronomical observations and incorporated into the polar motion determination by the Bureau International de l'Heure (B.I.H. 1973). Laser range observations have also been used for determining polar motion by Smith *et al.* (1972) and Kolenkiewicz *et al.* (1974) (see also Lambeck 1971) but due to visibility problems and the relatively small number of tracking stations these determinations have not been as precise nor as uniformly distributed in time as the Doppler results of Anderle. Significant improvements in the use of laser tracking for polar motion determination will undoubtedly be made when the satellite Lageos is launched. This satellite was originally proposed and planned by the Smithsonian Astrophysical Observatory (Weiffenbach & Hoffman 1970) under the name of Cannonball.

Observations of the Earth's irregular rate of rotation are much more difficult to obtain from the analysis of satellite orbit perturbations and the attempt by Buonaguro (1972) using the Doppler observations of the Tranet network proved to be unsuccessful. Long-baseline radio interferometry appears to be a better method for this as first proposed by Gold (1967) and MacDonald (1967) but reliable results are not yet available.

In this paper we do not discuss the new methods of observing the Earth's rotation. Rather, we discuss some of the geophysical factors perturbing the Earth's rotation from what it would be if rigid-body rotation theory was valid. In particular we attempt to evaluate the contributions that improved observational data will make to our geophysical understanding of the irregular rotation.

The equations relating the astronomical quantities to the geophysical excitation function ϕ_i are given by Munk & MacDonald (1960) as

$$(\dot{m}_1/\sigma_r) + m_2 = \phi_2, \quad (\dot{m}_2/\sigma_r) - m_1 = -\phi_1, \quad \dot{m}_3 = \dot{\phi}_3,$$

where m_1 and m_2 represent the direction cosines of the rotation axis with respect to an Earth fixed coordinate system. That is, they represent the polar motion or the variation in astronomical latitude. The m_3 represents the difference between the instantaneous rate of rotation ω_3 about the rotation axis and a nominal rotation rate Ω. That is, $\omega_3 = \Omega(1+m_3)$. The observed quantity is not the m_3 but the integrated amount by which the Earth is slow or fast after a certain time interval, usually about 5 days, with respect to a uniform rotation rate. If the time kept by the Earth is denoted by Universal Time (here U.T. 1) and the uniform time by R, the measured quantity is, by convention $\tau = -(\text{U.T.} - R)$, τ being the amount by which the Earth is slow.

Variations in the length of day (l.o.d.), τ and m_3 are related by the following expressions:

$$m_3 = -\Delta(\text{l.o.d.})/\text{l.o.d.} = -\frac{\mathrm{d}\tau}{\mathrm{d}t} = \frac{\mathrm{d}(\text{U.T.}1-R)}{\mathrm{d}t},$$

$\sigma_3 = \Omega(C-A)/A$, where C and A are the polar and equatorial moments of inertia.

The excitation functions ϕ_i represent changes in angular momenta due to relative motion of matter with respect to Earth fixed axes, changes in the second order inertia tensor and torques acting on the Earth's mantle (it is the motion of the mantle, to which the observing stations are positioned, that is observed). The geophysical discussion concerns the evaluation of these functions so that the total effect equals the observed m_i. In this paper we limit the discussion to the component m_3, the variations in the speed of rotation.

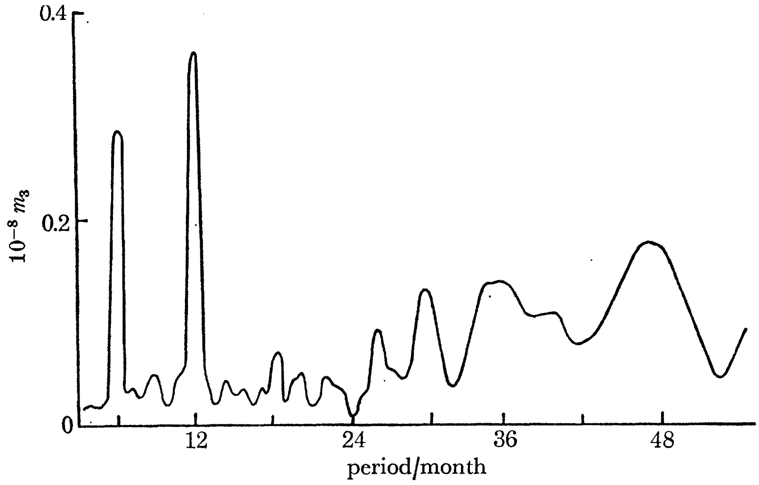

FIGURE 1. Harmonic analysis of the length of day variations near the seasonal periods.

LENGTH OF DAY

Seasonal variations

The seasonal variations in the length of day (l.o.d.) have been known to exist for some 30 years or more but it is only the astronomical data since about 1955 that is reliable. Figure 1 illustrates the results of an harmonic analysis of the l.o.d. data since this time. The principal terms are the annual and semi-annual periods, with a number of rays near 2–3 years. The last of these, which can be considered as a quasi-biennial oscillation, was first discussed by Iijima & Osaki (1966). These three seasonal terms are almost entirely due to the variations in the angular momentum associated with the zonal wind circulation as shown by Lambeck & Cazenave (1973). This is illustrated in figure 2, where the seasonal excitation functions are compared with the seasonal rotation changes over a 5-year period. The semi-annual tidal changes, responsible for about one half of the observed amplitude, has been included. The seasonal changes in the Earth's rotation therefore represent integrals of the zonal angular momentum variation in the atmosphere about the rotation axis, and as such one asks if such a measure may eventually be useful or not in studies of the atmospheric circulation on a time scale longer than a few months.

The annual wind oscillation, driven by the variable solar energy received in the atmosphere as the Sun follows its annual path back and fourth across the equator, clearly shows the opposition in phase of the circulation patterns in the two hemispheres; in the northern hemisphere the westerly winds reach their maximum value near 20° N in January while in the southern hemisphere the westerly winds reach a minimum value at this time. Due largely to the unequal ocean–continent distribution the circulation patterns are not completely anti-symmetric, with consequence that the changes in angular momentum of the two hemispheres do not cancel entirely, the difference being exchanged with the Earth. The annual term in the l.o.d. is therefore essentially a measure of the angular momentum imbalance between the circulation in the two hemispheres at the annual frequency.

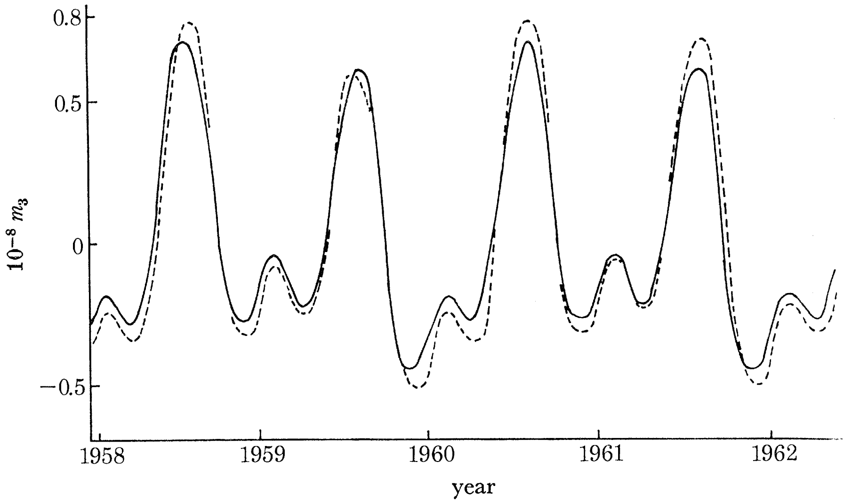

FIGURE 2. Comparison of mean seasonal changes in m_3 from 1958 to 1963 with the mean seasonal excitation function for the same period.

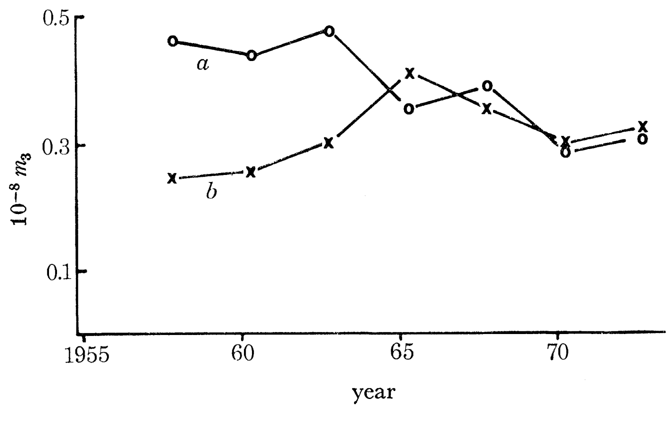

FIGURE 3. Variation in amplitude of the annual term in m_3 (a) and of the semi-annual term in m_3 (b) computed from 5-year periods.

Maximum annual fluctuations in the zonal winds occur near 60 km altitude with amplitudes of the order of 70 m s^{-1}, but because of the low density of the atmosphere at these altitudes the change in angular momentum is small. More important are the secondary maxima occurring in mid latitudes near the tropopause, although winds down to ground level contribute to the excitation function. If the amplitude of the annual term in the l.o.d. varies with time this would be a consequence of variations in this imbalance between the two hemispheres. In fact the astronomical data does indicate that there has been an important decrease in the amplitude of the annual term since 1955, as is illustrated in figure 3. The interpretation of this is ambiguous since the annual term represents the difference between the circulation in the two hemispheres, but a possible interpretation, in agreement with meteorological data, is that there has been a gradual, although non-uniform, decrease in the intensity of the annual zonal circulation in both hemispheres but with a more important decrease in the southern latitudes than in northern latitudes. A better understanding of this phenomena and better astronomical data may lead to a useful measure of the year-to-year variations of the atmospheric winds.

The semi-annual zonal wind pattern shows small maxima of about 5 m s^{-1} near the tropopause in equatorial latitudes. Greater amplitudes are observed near the stratopause but these do not contribute greatly to the angular momentum balance. Like the annual term, the semi-annual oscillation extends to all latitudes and down to low altitudes. Unlike the annual term, the main part of the oscillation is approximately symmetric about the equator; there is not the partial cancellation of the angular momenta of the two hemispheres. Thus fluctuations in the amplitude of the astronomically deduced semi-annual excitation is a reflection of variations in the total angular momentum of the atmosphere rather than of a difference in the two hemispheric momenta as it is for the annual term. The astronomical results show an increasing amplitude of the semi-annual term (figure 3), indicating a decreasing strength of the semi-annual wind oscillation.

The biennial wind oscillation reaches maximum values of about 20 m s^{-1} in the stratosphere near 25 km altitude although it propagates down to the tropopause. At lower altitudes its presence is not clearly established and surface pressure data shows only a small biennial component. The oscillation reaches its maximum intensity in equatorial latitudes and, like the semi-annual term, changes in the total angular momentum will reflect directly changes in the wind speeds. Over the equator, the winds near 30 km are out of phase with those near 12 km indicating that the biennial cycle commences at high altitudes and propagates down in altitude with time: when the lower altitudes are reached in this cycle, the next cycle has already begun higher in the stratosphere.

The quasi-biennial oscillation has a period that has been variously reported as between 20 and 30 months (Dartt & Belmont 1964). Furthermore, the data by Angell & Korshover (1970) indicate that there are rapid fluctuations with time in the altitudes at which the maximum wind intensities occur. The general picture is of a quasi-biennial wind oscillation that is a non-stationary phenomena and the excitation function will likewise be non-stationary. The astronomical data in figure 1 in fact suggests this; the peaks in the harmonic analysis between two and three years all being the consequence of this variable atmospheric circulation (Lambeck & Cazenave 1973). The time series of the astronomical data, after the removal of long period; annual and semi-annual terms gives considerable information on the biennial oscillation. This time series of m_3 represented schematically in figure 4 reveals the following characteristics for the biennial wind circulation (Lambeck & Cazenave 1973–4).

Before 1960 the biennial wind pattern was well established and propagated downwards to altitudes of as much as 12–14 km to contribute sufficiently to the excitation function. After 1960 the cycle is not evident in the m_3, presumable due to the fact that it did not propagate as far down in altitude as before in the previous years. This is in agreement with the equatorial wind profiles of Wallace (1966) that indicate that during 1960–1 the westerly winds in the lower stratosphere were of lesser intensity than during the preceding period. The cycle is again evident in the astronomical data by early 1962, suggesting that the easterly winds propagated down to their previously low level at this time. The cycle then continues until the end of 1964. According to

Wallace & Newell (1966) the zonal wind data exhibit a distinctly biennial component until mid-1963 only, but the astronomical data suggest that the oscillation continued for about another 12 months. The explanation of this discrepancy lies in the fact that the meteorological discussion centres around the circulation at stratospheric altitudes where this circulation is most pronounced whereas the excitation function responds more to circulation changes near and below the tropopause where the wind velocities are relatively small. As the biennial wind cycle propagates down in altitude with time a phase lag can be expected between the stratospheric observations and the Earth's rotational response. From mid-1964 to the end of 1966 the biennial cycle is absent from the rotation data, suggesting that either the cycle vanished as proposed by Wallace & Newell (1966) or that the cycle did not propagate as far down in altitude as usual.

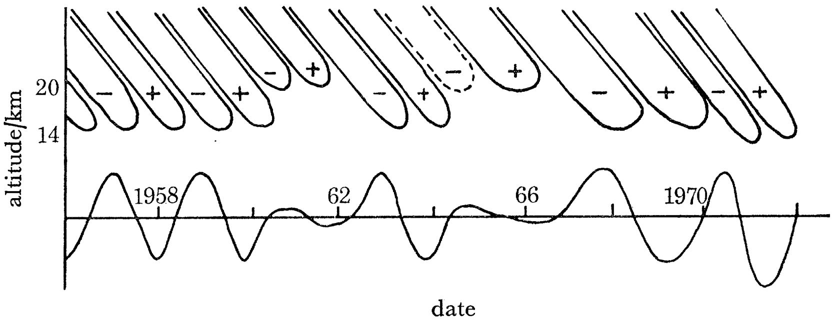

FIGURE 4. Schematic representation of the changes in m_3 that are of a biennial character, and the deduced schematic zonal biennial circulation near the equator. The positive cycle denotes eastward flow.

Stratospheric observations by Angell & Korshover (1970) indicate that the cycle, if it was absent for any time, must have re-established itself by about 1965. The cycle is again evident in the astronomical data from about the end of 1966 to early 1970, but now with a period of nearly 3 years rather than 2, and this lengthening of the period is also evident in the tropical profile of Wallace (1973). From 1970 onwards the biennial oscillation in m_3 has re-established itself with a period of 24 months and with the largest as yet observed amplitude, indicating that the maximum winds propagated down to altitudes of as low as 12 km. This is also suggested by the profiles of Wallace (1973).

This schematic wind profile represents only a global pattern but it does explain the astronomical data and is not in conflict with the meteorological conclusions based largely on the wind observations at high altitudes. It does indicate that the m_3 record may provide a useful index of the biennial oscillation in the troposphere, a region where this oscillation is not clearly established from the meteorological record.

The above discussion of the meteorological influences on the seasonal variations of the length of day suggests a number of ways in which the astronomical observations may contribute to a clearer understanding of the year-to-year variations in seasonal variations in the zonal circulation since they provide a boundary condition on permissible circulation models. Though the importance of these constraints is still to be tested the present evidence is encouraging. Particularly as the astronomical evidence is generally available long before the global wind compilations, the m_3 observation may serve as a preliminary measure of circulation trends. This was shown by Lambeck & Cazenave (1973), who made certain predictions about the zonal biennial oscillation that were subsequently verified by wind profiles published by Wallace (1973) (Lambeck & Cazenave 1974).

Some caution is, however, warranted in any interpretation of the annual terms in the rotation of the Earth since the astronomical observations are notoriously perturbed by seasonal atmospheric refraction variations and by catalogue errors that, since the same star pattern repeats itself annually, can also introduce annual errors. With the Bureau International de l'Heure results, which are based on observations from many stations in both hemispheres and referred to different catalogues, these errors are hopefully small.

Independent measurements of these changes in rotation are therefore of interest although the most promising method, long baseline radio interferometry, will also be very susceptible to error that follow a seasonal pattern. Satellite results in this respect may be of greater interest since there are no *a priori* reasons that these residual perturbations in the right ascension of the orbital plane follow seasonal patterns, and this can in fact be avoided by an appropriate choice of orbit.

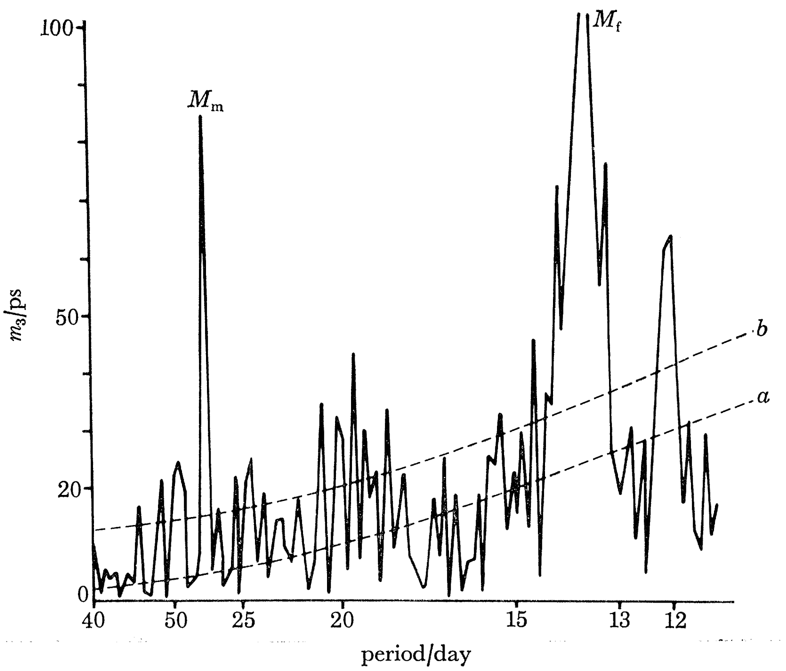

FIGURE 5. Power spectrum of variations in length of day at frequencies higher than 10 cycles/year. The curve *a* represents the estimated noise in the astronomical data while curve *b* represent the additional meteorological noise, or the continuum spectrum of the meteorological excitation.

High-frequency perturbations in the length of day

Apart from the seasonal variations the spectrum of the rotational variations shows very considerable power at higher frequencies. Munk & MacDonald (1960) conclude that severe meteorological anomalies persisting for a few months could cause detectable variations in the l.o.d. and that there is nothing mysterious in variations of a few parts in 10^9. In particular, they stress that the continuum may provide pertinent information concerning persistent anomalies in the weather. Markowitz (1970) also attributes the high-frequency components in the l.o.d. spectrum as being probably of wind origin. A quantitative evaluation was carried out recently by Lambeck & Cazenave (1974), who showed from their month-by-month calculation of the excitation function that indeed all irregular variations in rotation of frequencies between 0.3 and 6 cycles/year are of meteorological origin. Spectral analysis of zonal winds at higher frequencies reveals considerable power near 40–55 days (Madden & Julian 1971) between 15 and 25 days (Yanai & Murakami 1970) and between 10–15 days (Wallace & Chang 1969). At these higher frequencies the l.o.d. spectrum also shows considerable power that is above the estimated noise level of the astronomical data (figure 5) and an order of magnitude estimate by Lambeck & Cazenave (1974) indicates that this is due to these wind patterns. They have also estimated a meteorological noise spectrum over the frequency range of 6 to about 36 cycles/year (figure 5). Clear above the combined noise levels are the tidal frequencies M_m and M_f resulting from the zonal lunar tidal deformations of the Earth, and the amplitudes of these terms give the Love number k_2 at monthly and fortnightly periods (see, for example, Guinot 1974), but as there are also atmospheric oscillations and ocean tides at these frequencies the interpretation of these Love numbers is not evident.

An inspection of available wind profiles as a function of latitude, altitude and time reveals no single dominant wind pattern that is responsible for the more important short duration anomalies in the Earth's rotation. Some of the anomalies originate in the equatorial troposphere near the tropopause, others appear to be caused by wind régimes at higher latitudes. Some structure in this irregular spectrum has been suggested by Lambeck & Cazenave (1974) to be related to the mid-winter warming and the final collapse of the winter circulation in the two hemispheres, but the lack of a more general structure makes it difficult to envisage how the l.o.d. data can be used as boundary conditions on the circulation fluctuations without at least partial wind data being available.

The high-frequency meteorological noise has several important consequences upon the discussion of other geophysical factors acting on the Earth's rotation. First, it will mask most other irregular short-duration excitations that are not strictly periodic. For example, it will be unlikely that changes in m_3 due to earthquakes will rise above this noise level. Thus improvements in the accuracy of the l.o.d. determination will have little impact unless the meteorological excitation can be evaluated precisely. Lambeck & Cazenave (1974) conclude that the zonal wind data they analysed for the years 1958–63 gave a month-by-month excitation function for latitudes between $\pm 45°$ that is as precise as the astronomically observed month-by-month changes in l.o.d. The latter data have improved considerably since then but there does not appear to have been an equal improvement in global zonal wind compilations. In particular, high-latitude southern hemisphere data are still not available.

High-frequency periodic changes in l.o.d. will presumably rise above the meteorological noise if a sufficiently long period of observations is available. But excitation functions due to phenomena such as tides could be systematically biased by meteorological excitations at similar frequencies. As already indicated, this makes the interpretation of the rotational Love numbers uncertain and will probably prevent the determination of reasonable phase lags between the lunar zonal potential and the rotational response in m_3.

Another problem arising from the meteorological noise concerns the identification of the mechanism responsible for the 'decade' variations in l.o.d. Brouwer (1952) suggested that these changes in m_3 can be represented as a series of sudden changes in the acceleration or in $\mathrm{d}m_3/\mathrm{d}t$ (see also Markowitz 1970). The m_3 can then be represented by segments of straight lines. These changes could be caused by rapid changes in torques acting on the Earth, by rapid changes in $\mathrm{d}C/\mathrm{d}t$, where C is the moment of inertia about the rotation axis, or in $\mathrm{d}h/\mathrm{d}t$, where h is the relative angular momentum component along the rotation axis due to motion relative to the Earth fixed axes. Clearly a precise determination of the instants of these changes would contribute significantly to the understanding of the excitation mechanism. But not only improved astronomical data is required, the meteorological excitation must also be known in order to define the instants at which the acceleration changes rapidly.

Long period and secular changes in length of day

Figure 6 illustrates the long-period variations in l.o.d. observed since 1820. The data from 1820 to 1950 have been discussed by Brouwer (1952), Martin (1969) and Morrison (1973). Other analyses of the data since about 1900 have been carried out by Stoyko (1969) and Oesterwinter & Cohen (1972). The changes observed in m_3 since 1900 are of the order 5×10^{-7} from 1870 to 1900 compared with seasonal variations of amplitudes of about 0.4×10^{-8} and smaller.

FIGURE 6. Long-period variations observed in m_3 since 1820 as determined by Brouwer (——) and by Morrison (– –).

The excitation function for these variations is usually attributed to some form of core–mantle coupling and Rochester (1970–4) discusses various mechanisms. Of these the most plausible seems to be electromagnetic coupling, and most studies (for example, the recent papers by Roberts (1972) and Yukutake (1972)) show that this mechanism is almost capable of transferring the angular momentum between the core and mantle necessary to explain the decade variations in the length of day. In general, the longer the duration of the fluctuations the more readily they can be explained by an electromagnetic coupling of the core to the mantle. In particular, the non-tidal secular acceleration of the Earth has been attributed to this mechanism (Yukutake 1972), although this acceleration has also been attributed to the Earth's delayed response to the unloading of the Pleistocene polar ice and subsequent rise in sea level (O'Connell 1971).

Improved astronomical observations of the long-period variations may give a better understanding of the excitation function by enabling the turning points, the instants of the rapid changes in dm_3/dt, to be correlated with other geophysical observations. Brouwer's interpretation discussed above is in contrast to the earlier interpretation of Brown (1926) and de Sitter (1927), who approximate the τ by segments of straight lines. That is, the m_3 undergoes rapid changes every few years and this would imply that the changes are caused by a delta function change in the torque acting on the Earth, or by step function changes in h or C. Munk & MacDonald (1960) conclude that from the present data a distinction between the two interpretations of Brown–de Sitter & Brouwer is not possible. The improved astronomical data must, as emphasized above, be accompanied by improved meteorological data to ensure that the turning points can be determined with greater accuracy and also because there is apparently a long-period meteorological–oceanic component in the excitation function that may amount to as much as 20 % of the observed changes (Lambeck & Cazenave 1976). The curious thing about this excitation is that it appears to correlate significantly with the l.o.d. changes but lags it by about 10 or 15 years. This suggests that the two phenomena, long period changes in the l.o.d. and climatic changes on a 10–20 year time-span, may have a common origin (Anderson 1975).

An area where satellite observations make an important contribution to studies of the Earth's rotation concerns the secular acceleration. This is the question of the Earth's secular deceleration resulting from the dissipation of tidal energy. Dissipation of the tidal energy results in a deceleration of the Earth and in an increase in the Earth–Moon distance (Munk & MacDonald 1960; Jeffreys 1962). In addition to this deceleration due to either electromagnetic core–mantle coupling or to the post-glacial isostatic rebound, separation of the two parts is effected from observations of the secular accelerations in the longitudes of the Moon and Sun since these two observed quantities reflect differently the two accelerations. Another way of separating these two terms is to estimate the rate of dissipation in the Earth, mainly in the oceans, but this method has, until recently, met with only limited success through the absence of precise tide models. Jeffreys (1962) and Munk & MacDonald (1960) summarize the three methods by which the dissipation has been traditionally computed from tide models and both consider that the most precise method is to calculate the energy flux per unit time and per unit area across the entrances to shallow seas, assuming that the dissipation occurs only by friction along shallow sea floors. A second method is to calculate the rate of work per unit surface done by currents on the sea floor and the third method is to calculate the rate of work done per unit area by the Sun and Moon on the ocean surface. It turns out that this last method is a very precise way of evaluating the dissipation when it is recognized that only variations in the wavelength described by harmonics of degree 2 contribute (Lambeck 1975). These wavelengths appear to be relatively well known for the major ocean tides, but, perhaps more important, it is these same harmonics that give rise to periodic perturbations in the motion of close Earth satellites (Lambeck, Cazenave & Balmino 1974; Cazenave, Daillet & Lambeck 1976).

Analysing the available ocean tide models for the second degree terms, Lambeck (1975) estimates that the secular acceleration of the lunar longitude is $-35 \pm 4''$ (100 years)^2 compared with astronomical estimates of about $-40''$ (100 years)^2 from ancient eclipse observations (Newton 1970; Muller & Stephenson 1975), and from occultation and meridian observations of the Moon (Oesterwinter & Cohen 1972; Morrison 1973). Very recent analysis of the data seems, however, to reduce the value closer to the original value of Spencer Jones of about $-22''$ (100 years)^2 (Morrison & Ward 1975; Muller 1975) and the new discussion of the ocean tides *and* the new satellite results (Cazenave *et al.* 1976) also suggest that the value may be reduced somewhat. Results of this new evaluation will be discussed elsewhere; what does become evident is that reliable estimates of the tidal parameters from the satellite orbits, deduced from perturbations of a few tens of days duration, may provide better results about the tidal deceleration, and thus on the present rate of the secular evolution of the lunar orbit, than do several hundreds of years of astronomical observations.

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