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Contribution of Tropical Winds to Subseasonal Fluctuations in Atmospheric Angular Momentum and Length of Day

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Changes in the globally integrated angular momentum of the atmosphere from 1983 to 1987 were computed from Fleet Numerical Oceanography Center wind analyses and compared to astronomically measured changes in length of day obtained from the U.S. Naval Observatory. In agreement with previous studies, the two time series are highly coherent and in phase at periods ranging from 40 days up to the longest periods that are resolved by the data. By examining the contribution to the global atmospheric angular momentum from the tropical and extratropical regions separately, it is found that fluctuations in the Earth's angular momentum and length of day at subseasonal periods of 50–100 days are dominated by wind changes in the tropics.

1. INTRODUCTION

The past decade has brought a significant increase in our understanding of the relationship between changes in the angular momentum of the atmosphere and changes in the rotation rate of the Earth (that is, the length of day). Recent evidence has shown that variations in the length of day on time scales of a year or less are almost entirely due to meteorological influences. This is not only true for variations at the annual period, which represents the clearest and largest signal, but also for semiannual and other subseasonal periods as well [*Lambeck and Cazenave*, 1977; *Rosen and Salstein*, 1983, 1985; *Barnes et al.*, 1983; *Eubanks et al.*, 1985; *Morgan et al.*, 1985]. Of special meteorological interest is the discovery of coherent fluctuations at time scales of 40–60 days [*Feissel and Gambis*, 1980; *Langley et al.*, 1981; *Barnes et al.*, 1983; *Rosen and Salstein*, 1983; *Anderson and Rosen*, 1983; *Madden*, 1987, 1988] because of their possible connection to the well-known 40- to 50-day oscillations in the tropical wind field [*Madden and Julian*, 1971, 1972; *Lau and Chan*, 1985; *Madden*, 1986].

The purpose of this note is to show that the coherent relationship between fluctuations in atmospheric angular momentum and length of day on subseasonal time scales is primarily due to variations in the tropical atmosphere. Some of the studies mentioned earlier have already addressed the question of regional contributions to fluctuations in atmospheric angular momentum and length of day. For example, *Barnes et al.* [1983] analyzed 16 months of data and found that fluctuations in atmospheric angular momentum, integrated over the northern and southern hemisphere, respectively, and having a period of about 7 weeks, were in phase and were highly coherent with fluctuations in the length of day. The fact that the respective contributions from the northern and southern hemispheres to this 7-week fluctuation were comparable in magnitude and similar in phase strongly suggested that the fluctuations were of tropical origin. *Anderson and Rosen* [1983] applied a band-pass filter to 5 years of zonal wind data to examine the latitude-height structure of fluctuations in atmospheric angular momentum at periods of 40–60 days. They found that the variations were associated with wavelike motions in the tropical upper troposphere that propagated poleward and downward. The largest part of the variance (36%) was explained by a single (propagating) mode of variability in the upper and middle troposphere that extended from about 20°S to 60°N. Additional contributions to the band-pass filtered angular momentum fluctuations came from the high latitudes of the southern hemisphere. Most recently, *Madden* [1987, 1988] has shown that tropical oscillations in the wind stress are of sufficient amplitude and phase to account for the observed 40- to 50-day fluctuations in the length of day. Thus existing evidence already indicates that the tropics are important for affecting changes in the length of day at subseasonal time scales. The present note, based on data from different sources and covering different time periods than those in other studies, complements the previously mentioned studies and provides further evidence that subseasonal changes in the length of day are due to meteorological fluctuations in the tropics.

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2. DATA AND ANALYSIS

The relationship between changes in atmospheric angular momentum and changes in the length of day is based on the assumption that the Earth and atmosphere constitute a closed dynamical system. Thus changes in the total angular momentum of the entire atmosphere should be accompanied by equal and opposite changes in the angular momentum of the solid earth (neglecting oceans and the Earth's liquid core). The relationship is [*Rosen and Salstein*, 1983]

$$\delta \mathrm{LOD}_{\mathrm{atm}} = \left(\frac{\mathrm{LOD}_0}{\omega_0 I}\right) \delta M \qquad (1)$$

where $\delta\mathrm{LOD}_{\mathrm{atm}}$ is the difference between the length of day and the standard value (LOD_0 = 86,400 s), δM is the difference between the angular momentum of the atmosphere and a standard value (taken equal to zero as by *Rosen and Salstein* [1983]), $\omega_0 = 7.2921 \times 10^{-5}$ s^{-1} is the mean sidereal rotation rate of the Earth, and I is the moment of inertia of the Earth's mantle and crust. If δM is in kg m^2 s^{-1}, and δLOD is in seconds, the constant of proportionality in (1) is $\mathrm{LOD}_0/\omega_0 I = 1.68 \times 10^{-29}$. In (1) the subscript "atm" is used to indicate the length of day, as determined by the atmospheric angular momentum. The atmospheric angular momentum is computed from

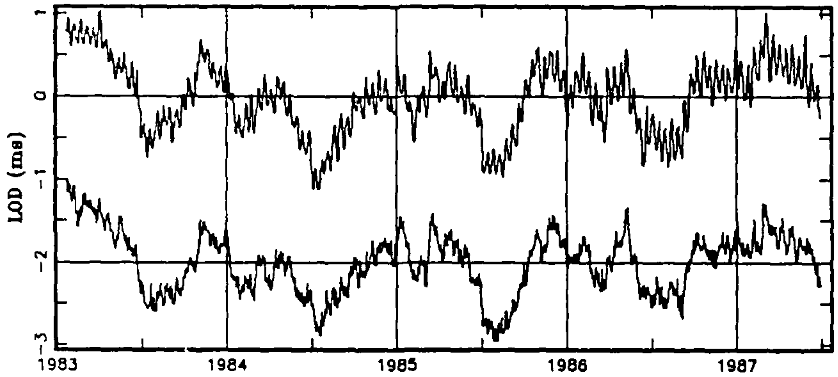

Fig. 1. Detrended time series of (top) δLOD_{USNO} and (bottom) δLOD_{atm} (offset by −2 ms).

$$\delta M = \frac{2\pi a^3}{g} \int_{100\,\mathrm{mbar}}^{1000\,\mathrm{mbar}} \int_{-\pi/2}^{\pi/2} [u] \cos^2 \phi \, d\phi \, dp \quad (2)$$

where a is the mean radius of the Earth (6.37×10^6 m), g is the acceleration of gravity (9.81 m s^{-2}), $[u]$ is the zonally averaged value of the zonal wind component, ϕ is latitude, and p is pressure. Combining (1) and (2),

$$\delta LOD_{atm} = \frac{2\pi a^3}{g} \left(\frac{LOD_0}{\omega_0 I} \right) \cdot \int_{100\,\mathrm{mbar}}^{1000\,\mathrm{mbar}} \int_{-\pi/2}^{\pi/2} [u] \cos^2 \phi \, d\phi \, dp \quad (3)$$

Twice daily global analyses of the zonal winds from January 1983 through June 1987 were used to compute δLOD_{atm} from (3). The wind analyses were obtained from the Fleet Numerical Oceanography Center (FNOC) and are based on the Navy Operational Global Atmospheric Prediction System [*Rosmond*, 1981]. The analyses are prepared on nine standard pressure levels (1000, 850, 700, 500, 400, 300, 200, 150, and 100 mbar, and at 2.5° latitude-longitude grid intervals. The archived data had few (less than 4%) missing analyses. All of the missing wind analyses were spaced such that linear extrapolation of the mising winds could be made. The resulting time series of δLOD_{atm} was smoothed with a three-point running average filter and decimated to 1622 elements (that is, one value per day).

Measured values of the length of day (denoted δLOD_{USNO}) for the period January 1983 through June 1987 were obtained from the U.S. Naval Observatory, Washington, D.C. Earth rotation measurements have significantly improved since the adoption of Monitor Earth Rotation and Intercomparison of Techniques of Operation and Analysis (MERIT) standards by both the U.S. Naval Observatory and the Bureau of International de l'Heure (BIH) in 1983. These standards include recently developed and internationally accepted values for solid-body tidal terms, rotational constants, and measurement techniques [*Melbourne et al.*, 1983]. In addition to the classical methods for determining the length of day (optical astronometry), the new methods of lunar laser ranging, very long baseline interferometry, and satellite laser ranging were added to produce extremely accurate values of length of day as well as other Earth rotation parameters. The U.S. Naval Observatory length-of-day data compare well with the BIH data from 1983 to the present.

Time series of δLOD_{atm} and δLOD_{USNO} during the 4.5-year period of this study are shown in Figure 1. Both time series have been detrended [*Bendat and Piersol*, 1971], and their respective means have been removed before plotting. The δLOD_{USNO} data had a small downward trend associated with decadal fluctuations in the length of day caused by coreshell coupling [*Munk and McDonald*, 1960; *Lambeck*, 1980], while the atmospheric wind data had no trend. The two time series are very highly correlated, with the most pronounced signals at the annual and semiannual periods [*Munk and McDonald*, 1960]. Interannual variability is also apparent in the form of abnormally longer days during the early months of 1983 and of 1987. The anomalously high values in early 1983 also appear in other data sets [e.g., *Morgan et al.*, 1985], and they have been linked to the 1982–1983 El Niño [*Rosen et al.*, 1984; *Wolf and Smith*, 1987]. It is therefore quite possible that the abnormally high values during the early part of 1987 are likewise associated with the 1986-1987 equatorial warm event [*Kousky*, 1987]. The high-frequency variation in the δLOD_{USNO} time series is due to a tidal oscillation at 13-day period that was not filtered out of the original data.

A spectral analysis was used to study the relationship between δLOD_{atm} and δLOD_{USNO} as a function of frequency. The data were processed and the spectral analysis was carried out using the fast Fourier transform (FFT) methods described by *Eubanks et al.* [1985, section 4]. To use FFT methods, each time series was extended from 1622 to 2048 data points, following the procedures given by *Eubanks et al.* [1985]. The resulting spectral estimates, f_n, $n = 1, \cdots 1024$, were smoothed with a seven-point unweighted moving average to give 14 degrees of freedom for calculating confidence and significance levels. Although this spectral smoothing in the presence of a pronounced annual and semiannual signal certainly distorts the spectrum of low frequencies, it increases the statistical reliability of the spectrum at subseasonal periods, which is the main focus of the study.

The results of the spectral analysis of δLOD_{USNO} and the global quantity δLOD_{atm} (Figure 2) are in very good agreement with the comprehensive spectral analysis of similar global data from 1977 to 1982 by *Eubanks et al.* [1985]. In particular, the power spectral density estimates of both time series are proportional to the inverse frequency squared for periods between about 3 days and 1 year. The power spectra have broad peaks at the annual and semiannual periods as well as at subseasonal periods, centered near 75 and 50 days.

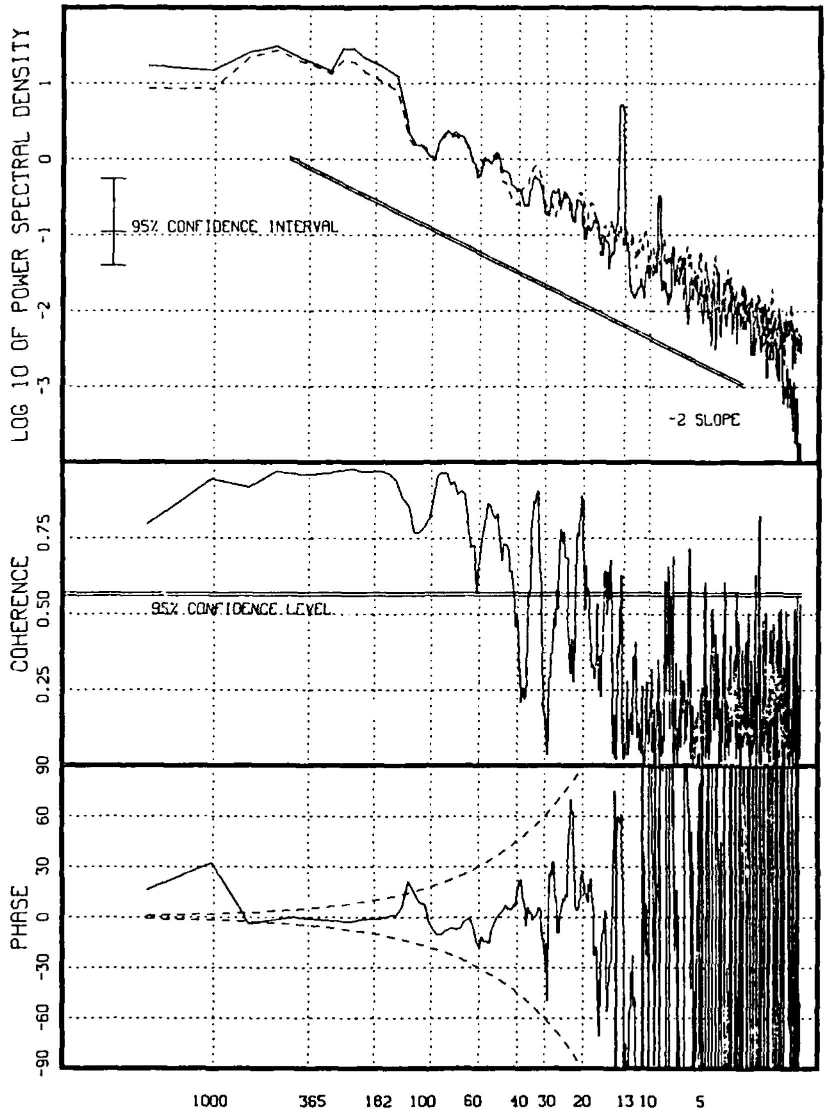

Fig. 2. (Top) Power spectral density of δLOD_{USNO} (solid curve) and δLOD_{atm} (dashed curve) and (middle) the coherence and (bottom) the phase between δLOD_{USNO} and δLOD_{atm}. Dashed curves in the phase plot are 5-day lead (upper curve) and 5-day lag (lower curve) of δLOD_{USNO} with respect to δLOD_{atm}. The 95% confidence intervals and levels are shown.

The slight difference in power between δLOD_{atm} and δLOD_{USNO} at the lower frequencies is probably due to the neglect of stratospheric winds in computing δLOD_{atm}. Thus the tropical stratosphere quasi-biennial oscillation, which is no doubt reflected in the δLOD_{USNO} data, is not present in the δLOD_{atm} data. As given by *Eubanks et al.* [1985], the coherence is significantly high, and the phase is essentially zero, from the lowest periods resolved by the data to periods as short as 40 days. There is also a significant dip in both the power and the coherence at a period of 100 days.

In order to investigate the contributions to δLOD_{atm} from the tropics and extratropics separately, the pole-to-pole integration over latitude in (3) was split into two parts, one over the tropics (20°S to 20°N) and one over the extratropics (90°–20°S plus 20°–90°N). Thus

$$\delta LOD_{atm} = \delta LOD_{atm1} + \delta LOD_{atm2} \qquad (4)$$

where δLOD_{atm1} represents the contribution from the tropics and δLOD_{atm2} represents the contribution from the extratropics. The spectral analysis of the tropical and extratropical contributions to δLOD_{atm} is shown in Figures 3 and 4, respectively. Looking first at the low-frequency part of both spectra, it can be seen that the power spectral density of δLOD_{atm1} and δLOD_{atm2} are both less than that of δLOD_{USNO}, and therefore also less than that of δLOD_{atm}, at all periods equal to or greater than semiannual. This implies that low-frequency (that is, annual) fluctuations in the angular momentum of the atmosphere as a whole, and in the length of day, are affected by wind changes in both the tropics and extratropics. This result is consistent with the study by *Rosen and Salstein* [1983], which shows (their Figure 9) more generally the contribution of various latitude bands to annual fluctuations in the Earth's angular momentum.

By contrast, the major contribution to changes in δLOD_{atm} at subseasonal periods originates almost entirely in the tropics. This is seen in Figures 3 and 4, where the power spectral density of the tropical contribution, δLOD_{atm1}, at

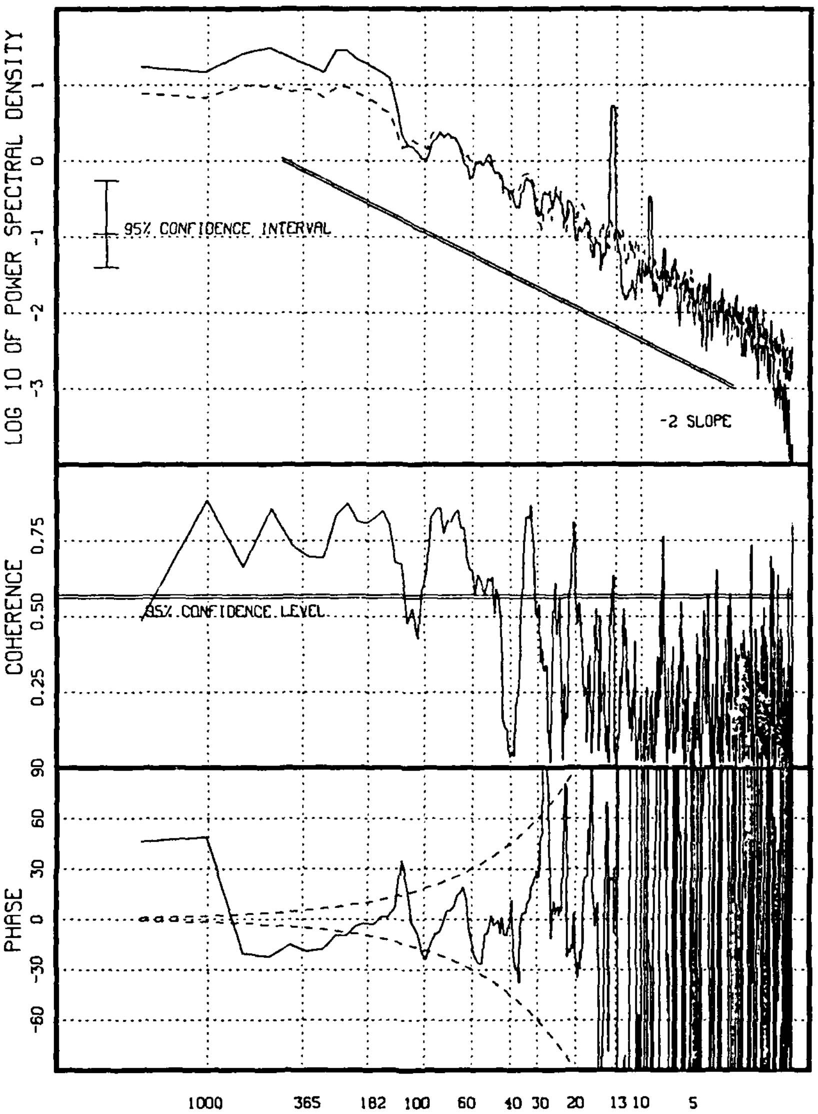

Fig. 3. As in Figure 2, except for δLOD_{USNO} and δLOD_{atm1}.

periods of 40–100 days is essentially the same as that of δLOD_{atm}, while the spectral power of the extratropical contribution, δLOD_{atm2}, is significantly less. At a period of about 75 days, for example, the spectral power of δLOD_{atm1} is almost an order of magnitude greater than that of δLOD_{atm2}. In addition, the coherence between δLOD_{atm1} and δLOD_{USNO} at these periods is significantly high (almost as high as the coherence between δLOD_{atm} and δLOD_{USNO}), while the coherence between δLOD_{atm2} and δLOD_{USNO} is insignificant. Finally, the phase between δLOD_{atm1} and δLOD_{USNO} is consistently near zero, while the phase between δLOD_{atm2} and δLOD_{USNO} varies wildly across the spectrum. The strong and significant relationship between δLOD_{atm1} and δLOD_{USNO} at subseasonal periods, together with the absence of a similar relationship between δLOD_{atm2} and δLOD_{USNO}, clearly shows that nearly all of the contribution to subseasonal changes in the global angular momentum of the atmosphere comes from fluctuations in the tropics. The direct association between the angular momentum of the global atmosphere and length of day at these periods, shown by previous studies as well as here, therefore implies that subseasonal fluctuations in the length of day are almost entirely forced by meteorological events in the tropics.

3. Discussion

Recent studies, made possible by precise timekeeping and astronomical measurements of the rotation rate of the Earth, have shown that changes in the length of day on time scales of a year or less are almost entirely due to meteorological causes. The present note simply serves to emphasize the important role of meteorological events in the tropics in producing length-of-day changes at subseasonal time scales. The importance of the tropics for subseasonal fluctuations in the length of day had previously been suggested by the work of *Barnes et al.* [1983] and *Anderson and Rosen* [1983].

An obvious weakness of the present note is the fact that we have not investigated the physical nature of the meteorological events in the tropics that are responsible for producing the observed changes in length of day. Nor have we investigated the possible mechanisms by which the angular momentum of the atmosphere is actually transferred to the solid Earth. Such an extensive investigation is beyond the scope of this short report. However, as noted by *Barnes*

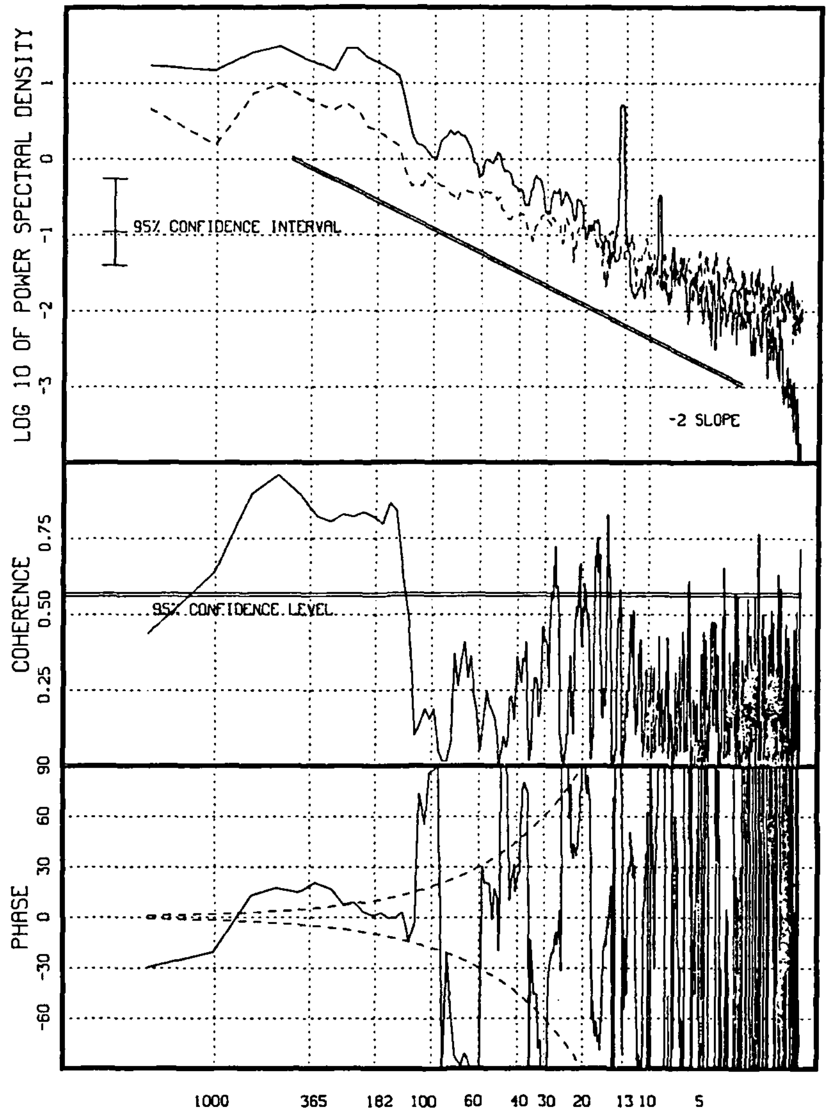

Fig. 4. As in Figure 2, except for δLOD_{USNO} and δLOD_{atm2}.

et al. [1983] and *Anderson and Rosen* [1983], the most relevant meteorological phenomenon that could be influencing the atmospheric global angular momentum at these subseasonal periods is the well-known atmospheric 40- to 50-day oscillation in the tropics [*Madden and Julian*, 1971, 1972]. This hypothesis is strongly supported by the recent studies of *Madden* [1987, 1988] which specifically link 40- to 50-day variations in angular momentum and length of day to frictional torques at the surface of the Earth driven by convection associated with these waves. Whether the same tropical phenomenon is active at somewhat longer periods (75–100 days) is not clear. Finally, we have not explored the vertical structure of the contributions to δLOD_{atm}, but it seems safe to assume from the work of *Rosen and Salstein* [1983] that the major contribution comes from the upper troposphere. It therefore appears that further advances in our understanding of the specific meteorological processes associated with changes in the length of day will depend on the availability of accurate wind analyses in the tropical upper troposphere and lower stratosphere.

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