EFFECT OF CLIMATE CHANGE ON SEASONAL LENGTH-OF-DAY VARIATIONS

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ABSTRACT. Global warming, by definition, changes the atmospheric temperature field. Since this temperature change is not expected to occur uniformly, either geographically, or with height in the atmosphere, changes can be expected in the pole-to-equator temperature gradient which, by the thermal wind equation, will cause changes in the atmospheric zonal wind field. Conservation of angular momentum dictates that as the wind-driven axial atmospheric angular momentum changes, so will the length-of-day (LOD). Here, observed changes in the strengths of the annual and semi-annual LOD signals during 1963–1991 are analyzed and shown to be both significantly correlated with the Southern Oscillation Index (S01), and to exhibit trends of comparable magnitude but opposite signs. The reported correlation between the S01 and the amplitude of the seasonal LOD signals demonstrates a linkage between seasonal LOD (and hence seasonal zonal wind) variability and the El Niño / Southern Oscillation phenomenon which can only arise through non-linear interactions. Furthermore, this study demonstrates that observed changes in the amplitudes of the seasonal LOD signals can be used to study the effects of climate change on the seasonal atmospheric zonal winds on interannual to decadal and longer time scales.

Over the past century, the global mean surface temperature has increased by a total of 0.45°C ± 0.15°C[1], and under the "business-as-usual" scenario of the Intergovernmental Panel on Climate Change (IPCC), the global mean temperature is expected to increase by about 0.2°C–0.5°C per decade[2,3] during the next century. Past temperature changes did not occur uniformly over the globe[1], and future changes also are not expected to occur uniformly. General Circulation Models (GCMs) of the atmosphere indicate that the surface temperature will increase more than average in the high northern latitudes in winter, and less than average in areas covered by sea-ice during the summer. The available meteorological data suggests that warming to date occurs at low latitudes as well[4–6]. However, both the data and the atmospheric general circulation models suffer from a number of problems and the actual geographical distribution of any global warming remains quite uncertain.

Because of the geographically non-uniform nature of the past and expected future atmospheric temperature changes, the pole-to-equator temperature gradient can be expected to vary during global warming, The global scale zonal winds which drive the seasonal fluctuations in the Earth's rotation rate are nearly geostrophic, and thus are related to meridional temperature gradients through the thermal wind relation[7]:

$$\frac{\partial u}{\partial z} \propto \frac{-1}{T \sin\phi} \frac{\partial T}{\partial \phi} \qquad (1)$$

where u is the zonal wind, z is the altitude, T is the temperature, and ϕ is the latitude. If it is assumed that: (1) the temperature (measured from absolute zero) is constant in the denominator of equation 1, (2) the winds at the surface are negligible, and (3) the meridional temperature gradient $\partial T/\partial \phi$ is independent of height, then changes $\delta\Lambda$ in the LOD can be directly related to changes δT_2^0 in the degree 2, order O coefficient of the spherical harmonic expansion of the vertically averaged atmospheric temperature distribution through[8]:

$$\delta\Lambda = -0.3458 \ \delta T_2^0 \qquad (2)$$

where δT_2^0 is measured in degrees Celsius and $\delta\Lambda$ is measured in milliseconds (msec). Comparison of actual T_2^0 and LOD data indicate that this relation, while not perfect, can explain most of the observed seasonal variation in the LOD (Eubanks *et* al,, 1994, manuscript in preparation).

In the absence of non-atmospheric excitation sources, the atmosphere and solid Earth can be viewed as a closed, dynamical system, the total angular momentum of which remains constant in time. As the atmospheric angular momentum changes (due, e.g., to global warming-induced variations in the strength of the zonal winds), then the angular momentum of the solid Earth must change by an equal, but opposite, amount in order for the total angular momentum of the atmosphere-solid Earth system to remain constant. In fact, numerous previous studies have shown that on time scales of a few days to a few years, the observed variations in the length-of-day (LOD) are caused dominantly by fluctuations in the atmospheric zonal winds[9–12]. In particular, it has been shown to within measurement uncertainty that seasonal LOD variations can be accounted for solely by seasonal variations in the atmospheric zonal winds[12-17]. Thus, any changes in the strengths of the seasonal zonal winds will be reflected in Earth rotation measurements and appear as changes in the strengths of the seasonal length-of-day signals. The excellent agreement (to within about 0.02 msec) found between the annual cycle of the geodetically-measured LOD and the meteorological excitation data[14] thus corresponds to a geodetic temperature sensitivity of better than 0.1 °C in the seasonal cycles.

In this study, observed changes in the strengths of the seasonal LOD signals are examined and interpreted as possibly being caused by the effects of climate change. In particular, it is shown that changes in the annual and semi-annual LOD amplitudes during 1963-1991 are significantly correlated with the Southern Oscillation Index (S01), and also exhibit trends of opposite sign. This demonstrates a linkage between seasonal LOD (and hence seasonal zonal wind) variability and the El Niño / Southern Oscillation phenomenon, and suggests that observations of the amplitudes of the seasonal LOD signals have the potential to be used as proxy measures of global warming-induced variations in the strength of the seasonal zonal winds on interannual to decadal and longer time scales.

The length-of-day data set used in this study, known as COMB92, is an extension of SPACE92[18] and is derived from a Kalman filter-based combination of independent Earth rotation measurements taken using the techniques of optical astrometry, very long baseline interferometry, and lunar laser ranging, A number of corrections—-including corrections to the bias, rate, and stated uncertainties—are made to each of the independent series in order to make them consistent with each other prior to their combination[18]. In addition, the annual term of the optical astrometric series is adjusted by applying a constant correction designed to make it agree, on average, with the average annual term exhibited in a combination of all the other, independent, geodetic-derived Earth rotation series used in forming COMB92. The effects of long period (fortnightly through lunar nodal) solid Earth tides on the Earth's rotation have been removed from the individual Earth rotation measurements by using the model of Yoder *et al.* [19], and the effects of ocean tides at the *Mf'* (13.63 day), *Mf* (13.66 day), *Mm (27.56* day), and *Ssa* (182.6 day) tidal periods have been removed by using the model of Dickman[20]. The resulting LOD series, COMB92, spans January 20,0, 1962 through January 17.0, 1993 at 5-day intervals and is shown in Figure 1a, with Figure 1 b showing the formal errors (one sigma) in its determination. The large, decadal-scale signal evident in Figure 1 a is thought to be caused primarily by core-mantle boundary processes[21–24], with atmospheric effects contributing a currently unknown amount to this observed decadal-scale LOD variation. Decadal LOD observations cannot be used directly to study decadal-scale atmospheric zonal wind variations because the dominating core-mantle boundary processes are difficult to model accurately, and hence cannot be reliably removed from the decadal LOD observations.

Superimposed on the decadal and interannual LOD signals in Figure 1a are the seasonal terms of annual and semi-annual period that are of interest in this study. They have been isolated from the total LOD signal by singular spectrum analysis (SSA), a data adaptive technique wherein a time series is decomposed into a set of orthonormal basis functions (called temporal empirical orthogonal functions) that are determined by the time series itself rather than being constrained to be, for example, functions of sines and cosines[25–28]. The. temporal empirical orthogonal functions (T-EOFs) are the eigenfunctions of the lag-covariance matrix of the time series. The associated eigenvalues indicate the fraction of the variance carried by the temporal principal components (T-PCS; the time-dependent coefficients of the eigenfunctions). Vautard and Ghil[27] have shown that pairs of eigenvalues can accurately capture oscillatory phenomena. Figure 2 shows the normalized spectrum of singular values of the COMB92 LOD time series obtained by applying SSA to it using a window width of 75 samples (375 days). The greatest percentage of the variance of the original time series (COMB92) is seen to be carried by the decadal fluctuations (first T-PC), with the annual term carrying the next greatest percentage of vari ante (second and third T-PCs), closely followed by the semi-annual term (fourth and fifth T-PCs). Figure 3a (solid line) shows the annual term recovered from the second and third T-PCs, and Figure 3b (solid line) shows the semi -annual term recovered from the fourth and fifth T-PCs. Also shown in Figure 3 are the amplitudes (dashed lines) of the annual and semi-annual terms that have been obtained by applying complex demodulation[29] to the annual and, separately, the semi-annual reconstructed time series. As can be seen, the amplitudes of the annual and semi-annual length-of-day terms have not been constant during 1963– 1991, but rather have exhibited variations on i nterannual to decadal time scales (shorter period variations have been removed by the SSA filtering procedure).

The amplitudes of the annual and semi-annual LOD terms (reproduced from Figures 3a and 3b) arc plotted as solid lines in Figures 4a and 4b, respectively. For comparison purposes, the running annual mean of the Southern Oscillation index (S01), computed for this study as the difference of the surface pressure between Tahiti and Darwin in millibars, is shown in Figures 4a and 4b by dashed lines. Note that in Figure 4a the negative of the SOI (termed here the Modified Southern Oscillation Index, or MSOI) is plotted at a lag of 4 months since this is found to give the maximum correlation (0.54) with changes in the amplitude of the annual LOD term. The greatest correlation between the SOI and changes in the amplitude of the semi-annual LOD term is found to be 0.60 at no lag. The sample autocorrelation functions (ACFs, not shown) of the series of annual and semi-annual LOD amplitudes indicate effective decorrelation lengths (given by the e-folding time of the central peak of the ACF) for these series of 2’77 and 256 days, respectively. Since each series spans 10400 days, these effective decorrelation lengths imply that these series have 38 and 41 effective degrees of freedom, respectively. (A similar examination of the ACF of the SOI indicates that this series has 40 effective degrees of freedom, a number comparable to those of the series of annual and semi-annual LOD amplitude changes.) Hence, the 99% significance levels are 0.42 and 0.40 for the correlations between the MSOI and annual LOD amplitude changes, and between the SOI and semi-annual LOD amplitude changes, respectively. Therefore, changes in the amplitudes of the annual and semi-annual components of the length-of-day are each found to be significantly correlated with the SOI during 1963–1991, with the semi-annual LOD amplitude changes being positively correlated with the SOI, and the annual LOD amplitude changes being negatively correlated.

As discussed above, the observed decadal variations in the length-of-day (Figure 1a) cannot be used directly to study decadal variations in the atmospheric winds since the decadal LOD variations are thought to be caused largely by core-mantle boundary processes. On interannual time scales, however, it has been shown that the observed LOD variations are largely caused by changes in the atmospheric winds, and, in particular, that the observed interannual LOD variations are negatively correlated with the SOI. Chao[30] reported finding such a correlation during 1957–1983 with a maximum value for the correlation coefficient of --0.56 obtained when the SOI leads the interannual LOD by 1 month; Eubanks elU1.31 reported a maximum correlation coefficient during 1962–1984 of about --0.5 when the SOI leads the interannual LOD by 3 months; Chao[32] reported a maximum value for the correlation coefficient during 1972–1 986 of--0.68 for a 2 month lead time; and Dickey *et aL*[33] have recently reported a maximum correlation coefficient during 1964--1989 of-0.67 for a 1 month lead time. Here it has been shown that comparable levels of correlation exist between the SOI and changes in the amplitudes of the annual and semi-annual LOD terms.

This reported correlation between the modulation of the seasonal LOD signals and the SOI indicates a linkage between seasonal LOD variability (and hence between seasonal zonal wind variability) and the El Niño / Southern Oscillation (ENSO) phenomenon, El Niño events usually peak in northern hemisphere winters[34], an observation that Tziperman *et al.*[35] have recently interpreted as arising from nonlinear resonances between the seasonal cycle and the equatorial Pacific ocean-atmosphere system. They modeled the ENSO cycle as a delayed-oscillator process driven by seasonal forcing and found that for small nonlinearity the solution maybe either quasi-periodic exhibiting no relation to the seasonal cycle, or may be mode-locked to a single nonlinear resonance in which case the solution is periodic. For larger values of the nonlinearity the solution becomes chaotic, exhibiting partial phase-locking to the seasonal cycle. Jin *et al.*[36], using a fuller dynamical model than that used by Tziperman *et al.*[35], have shown that the chaotic behavior of the partially phase-locked solution results from irregular transitions of the ENSO oscillator between overlapping nonlinear resonances with the seasonal cycle. In addition, Wang[37] has recently reported evidence of coupling between the annual cycle and ENSO variability in sea-surface temperature measurements of the tropical Pacific during 1950-1991. The fact that the seasonal LOD (and hence seasonal zonal wind) variability is correlated with the SOI is further evidence of a coupling between the seasonal cycle and the ENSO phenomenon.

From a linear least-squares fit for a mean and trend to the series of annual and semi-annual LOD amplitudes shown in Figure 4 it is found that the amplitude of the annual LOD signal has changed at an average rate of 2.8 ± 1.2 μsec/yr during 1963–1991, whereas the amplitude of the semi-annual LOD signal has changed at an average rate of –1.7 ± 0.8 μsec/yr during this same time period, The quoted uncertainties are the formal errors (one sigma) in the determination of the trends wherein the series of annual and semi-annual LOD amplitudes are assumed to have 38 and 41 effective degrees of freedom, respectively. These trends in the amplitudes of the annual and semi-annual LOD signals may reflect changes in the strength of the seasonal zonal winds associated with climate change. In any case, these small trends in the amplitudes of the seasonal LOD cycle indicate, through equation 2, that the corresponding trends in the amplitudes of the annual and semi-annual cycles of the atmospheric temperature coefficient T_2^0 during this time period is -0.0081 ± 0.0035 °C/yr and 0.0049 ± 0.0023 °C/yr, respectively.

Since seasonal LOD variations can be accounted for solely by seasonal changes in atmospheric zonal winds (at least to within measurement uncertainty), changes in the strengths of the seasonal LOD variations on all time scales can be attributed unambiguously to changes in the strengths of the seasonal atmospheric zonal winds on those time scales. Hence, the effects of changes in the strengths of the atmospheric winds on the LOD can be studied on time scales longer than interannual by analyzing changes in the amplitude of the seasonal LOD signals. Such studies cannot be done using decadal-scale LOD observations directly because of the dominant effects of core-mantle boundary processes at these time scales. Of course, a much longer time series of seasonal LOD observations should be analyzed in order to better define the decadal (and longer) time scale changes in the amplitudes of the seasonal LOD signals. Before the advent of atomic clocks in 1955, the most accurate LOD observations were obtained from lunar occultation measurements. By analyzing such measurements, Jordi *et al.*[38] have recent] y produced a series of Earth rotation determinations spanning 1830- 1955.5 at four-month intervals. They considered the interannual fluctuations evident in their series to be reliable back to 192S. However, the reliability of the seasonal terms, and hence of their utility as measures of changes in the seasonal zonal winds during 1830-1955.5, remains to be evaluated.

In summary, climate change can be expected to affect the pole-to-equator temperature gradient, thereby inducing changes in the atmospheric zonal winds, and, by conservation of angular momentum, causing changes in the length-of-day, Here it has been shown that changes in the amplitudes of the annual and semi-annual LOD signals during 1963--1991 are significantly correlated (at the 99% significance level) with the Southern Oscillation Index, thereby establishing a linkage between seasonal LOD (and hence seasonal zonal wind) variability and the El Niño / Southern Oscillation phenomenon, This study further demonstrates that changes in the strengths of the seasonal atmospheric zonal winds can be studied on interannual to decadal (and longer) time scales by analyzing changes in the amplitudes of the seasonal LOD signals. The results reported here warrant further investigation in order to gain greater insight into the nature of the global warming-induced LOD variations.

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FIGURE CAPTIONS

FIG. 1 Length-of-day determinations (a) and their formal errors (b) derived from a Kalman filter-based combination of independent Earth rotation measurements.

FIG. 2 Normalized eigenvalue spectrum of the lag-covariance matrix of the length-of-day time series shown in Figure 1a. Pairs of eigenvalues are associated with periodic signals.

FIG. 3 Annual (a) and semi-annual (b) components (solid lines) of the length-of-day series shown in Figure 1 a as recovered by singular spectrum analysis. The dashed lines show the amplitudes of the respective annual and semi-annual components as determined by complex demodulation.

FIG. 4 Comparison of the Southern Oscillation Index (dashed lines) with the amplitudes (solid lines) of the annual (a) and semi-annual (b) length-of-day components. Note that in (a) the negative of the SOI has been plotted at a lag of 4 months, Superimposed on the series of annual and semi-annual LOD amplitudes are the trends exhibited by these series as determined by a linear least-squares fit.

COMBINED EARTH ORIENTATION SERIES: COMB92

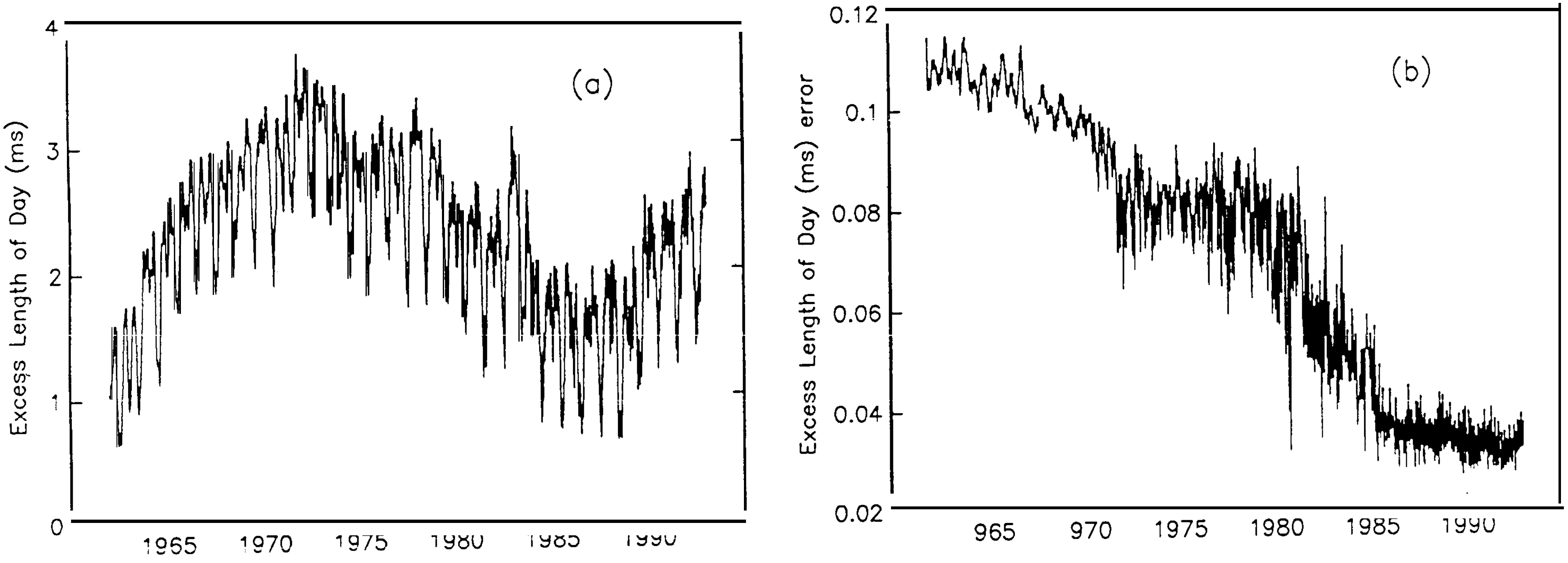


Fig. 1

Fraction of variance captured by each principal component

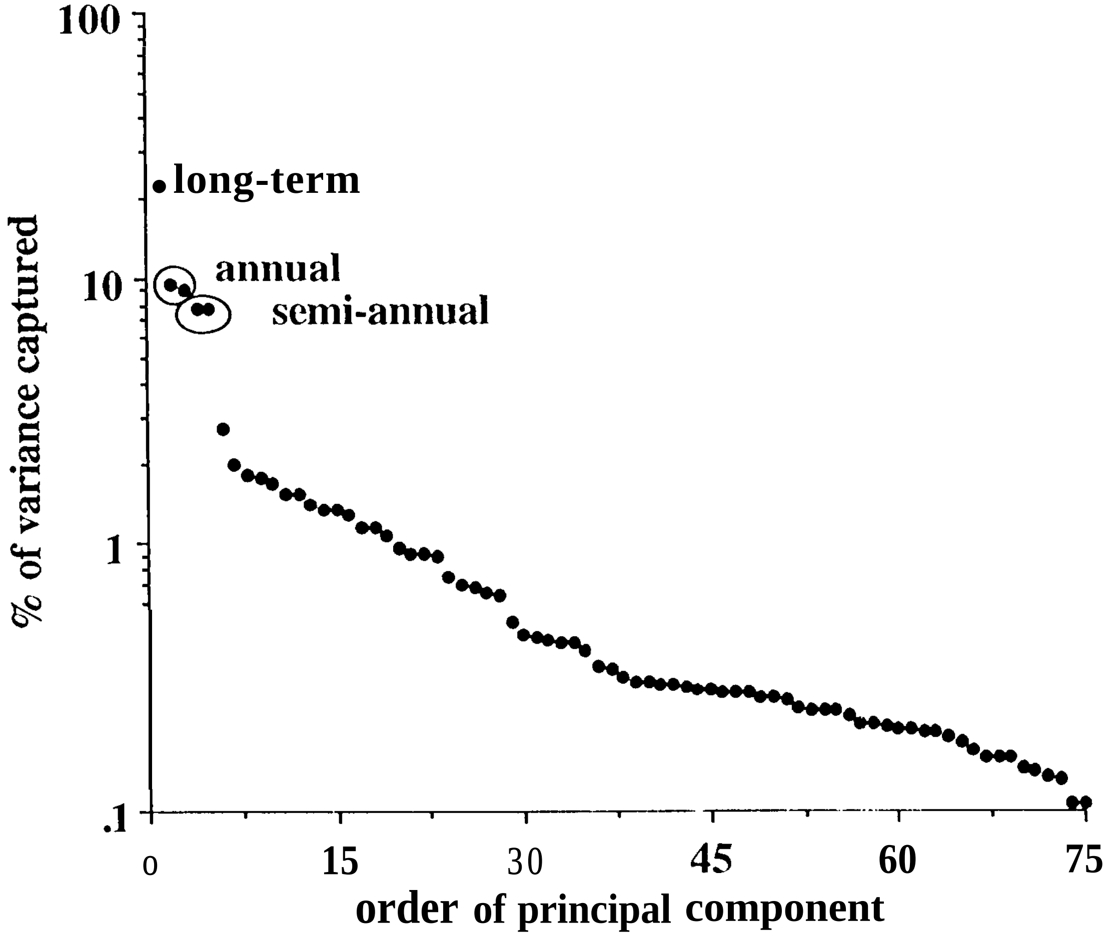


Fig. 2

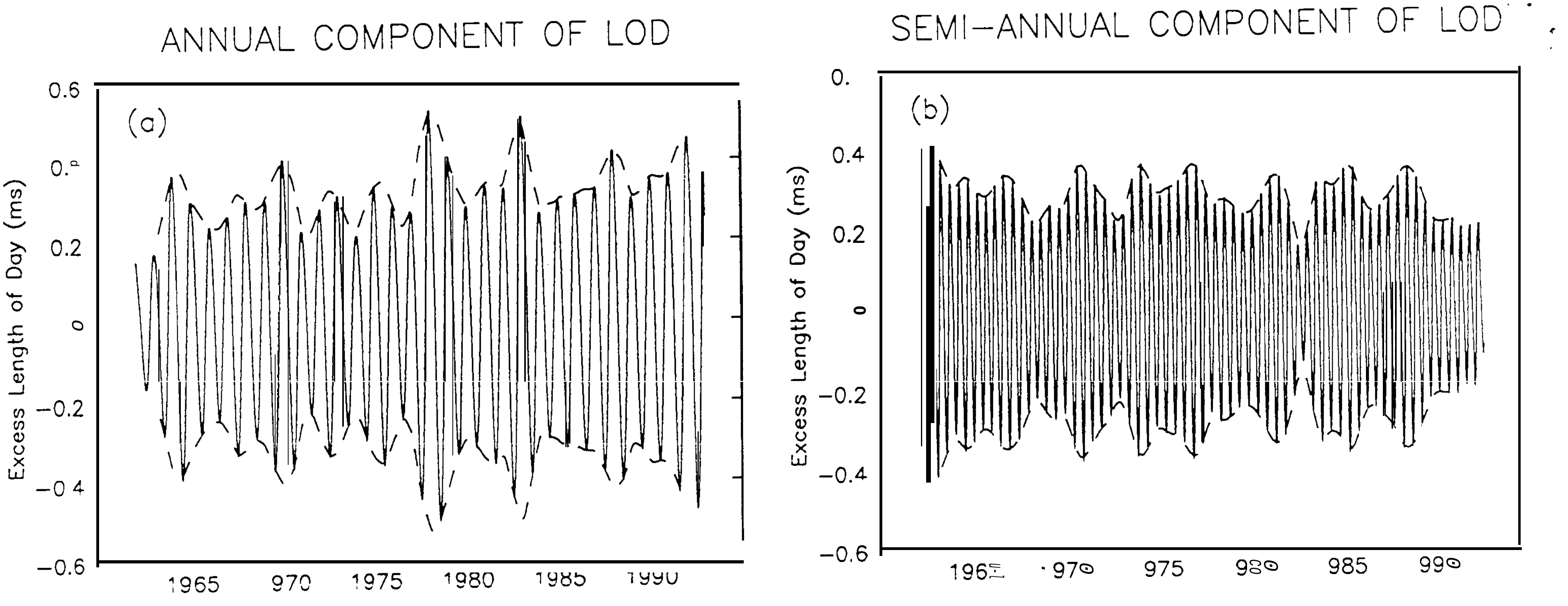
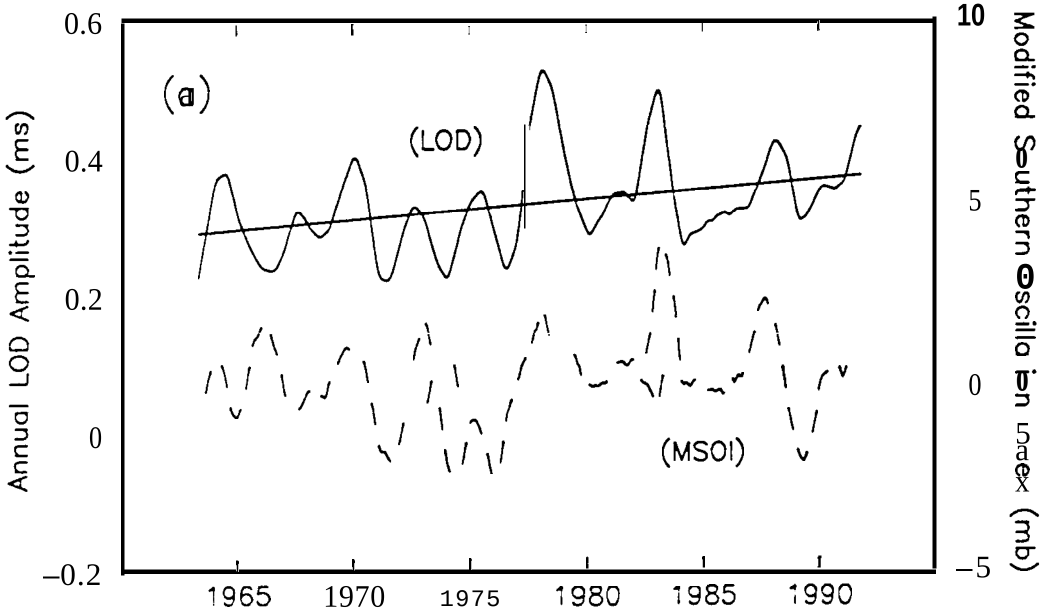

ANNUAL COMPONENT OF LOD
(a)
Excess Length of Day (ms)
0.6
0.
0.2
0
−0.2
−0.4
−0.6
1965
970
1975
1980
1985
1990
SEMI−ANNUAL COMPONENT OF LOD
(b)
Excess Length of Day (ms)
0.
0.4
0.2
0
−0.2
−0.4
−0.6
196
970
975
980
985
990

Fig 3

ANNUAL LOD AMPLITUDE & MSOI



SEMI–ANNUAL LOD AMPLITUDE & SOI

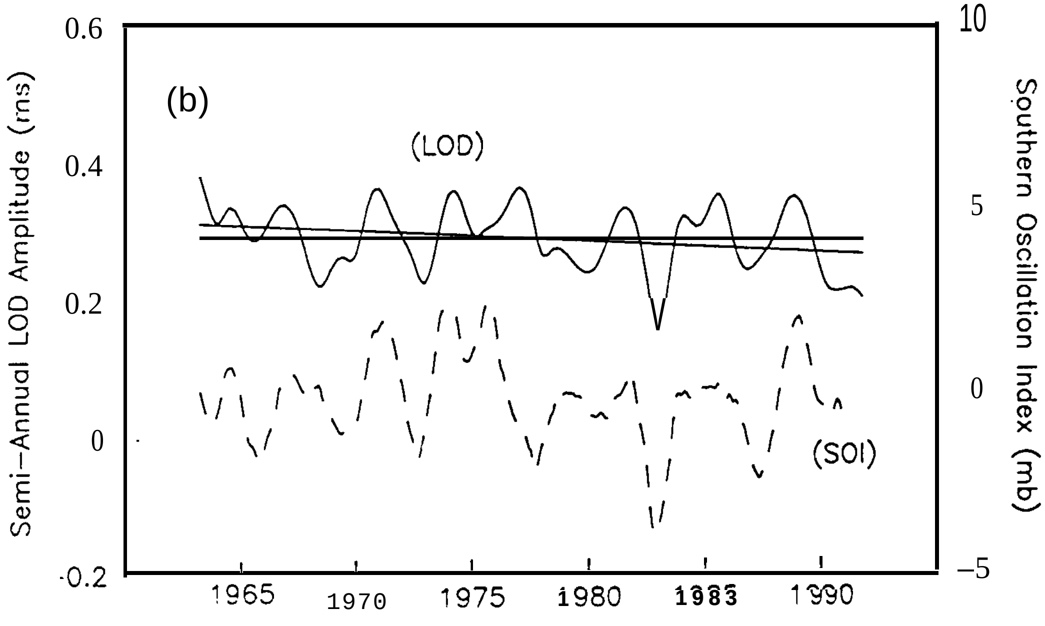


Fig. 4