



IERS TECHNICAL NOTE 26

The impact of El Niño and other low-frequency signals on Earth rotation and global Earth system parameters

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Contents

	page
IERS Technical Notes	iv
Introduction	1
IERS Gazette N 21: Call For El Niño papers	2
THE IMPACT OF EL NIÑO AND OTHER LOW-FREQUENCY SIGNALS ON EARTH ROTATION AND GLOBAL EARTH SYSTEM PARAMETERS American Geophysical Union 1998 Spring Meeting, Boston, MA, USA (Sessions Program)	3
IDENTIFICATION OF EL NIÑO SIGNALS WITH SATELLITE ALTIMETRY D.P. Chambers, J.L. Chen and B.D. Tapley	5
ATMOSPHERIC ANGULAR MOMENTUM DURING THE 1997-98 EL NIÑO EVENT D.A. Salstein	13
SIGNATURE OF EL NIÑO IN LENGTH OF DAY AS MEASURED BY VLBI J.M. Gipson and C. Ma	17
EL NIÑO IMPACT ON ATMOSPHERIC AND GEODETIC EXCITATION FUNCTIONS OF POLAR MOTION B. Kolaczek, M. Nuzhdina, J. Nastula, and W. Kosek	23
THE 1997-1998 EL NIÑO EVENT: INSIGHT VIA SPACE GEODESY J.O. Dickey, P. Gegout, and S.L. Marcus	29
ANGULAR MOMENTUM AND TORQUES DURING THE 1982-83 EL NIÑO R.M. Ponte and R.D. Rosen	33
FLUCTUATIONS OF THE EARTH ROTATION AND EL NIÑO EVENTS V. Frède and P. Mazzega	37
TROPICAL PACIFIC OCEAN LONG WAVES CONTRIBUTION TO LENGTH OF DAY DURING ENSO IN 1980-1997 R.J. Abarca del Rio, B. Dewitte, Y. duPenhoat, and D. Gambis	45
EL NIÑO SIGNAL IN LOCAL AND GLOBAL ATMOSPHERIC TORQUES O. de Viron, V. Dehant, P. Pâquet, and D.A. Salstein	51
ATMOSPHERIC-OCEANIC INFLUENCE ON INTERANNUAL LENGTH-OF-DAY VARIABILITY LINKED TO EL NIÑO/SOUTHERN OSCILLATION L.I. Fernández and E.F. Arias	57
CORRELATION OF INTRASEASONAL LENGTH OF DAY AMPLITUDE MODULATION WITH ENSO Zhong Min, Zhu Yao-zhong, and Gao Bu-xi	67

IERS Technical Notes

This series of publications gives technical information related to the IERS activities, e.g., reference frames, excitation of the Earth rotation, computational or analysis aspects, models, etc. It also contains the description and results of the analyses performed by the IERS Analysis Centres for the Annual Report global analysis.

Back issues still available

- No 14: P. Charlot (ed.). Earth orientation, reference frames and atmospheric excitation functions submitted for the 1992 IERS Annual Report.*[Superseded by T.N. 17]*
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- No 17: P. Charlot (ed.). Earth orientation, reference frames and atmospheric excitation functions submitted for the 1993 IERS Annual Report.*[Superseded by T.N. 19]*
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- No 24: C. Boucher, Z. Altamimi, P. Sillard (eds.). Results and Analysis of the ITRF96.
- No 25: J. Ray (ed.). Analysis Campaign to Investigate Motions of the Geocenter.
- No 26: D. Salstein, B. Kolaczek, D. Gambis (eds.). The impact of El Niño and other low-frequency signals on Earth rotation and global Earth system parameters.

INTRODUCTION

During most of 1997 and into 1998, a strong El Niño event occurred which was in many ways similar to earlier such phenomena, especially the last strong El Niño, of 1983. The El Niño/Southern Oscillation (ENSO) is a large-scale phenomenon in the ocean-atmosphere system, centered in the tropical Pacific, but with influences in areas well beyond. During ENSO, the normal tropical atmospheric and oceanic states are disturbed. Each El Niño event includes increases of sea surface temperature (SST) along the Pacific west coast of South America and further into the eastern tropical Pacific. This oceanic warming is part of one phase of the so-called Southern Oscillation, a shifting of atmospheric mass across the breadth of the Pacific Ocean. In the El Niño phase, the oscillation typically produces anomalously high pressures over the West Pacific-Australian-Indonesian region and low pressures further to the east, over the central Pacific. Modification of zonal winds during an El Niño episode are observed over much of the Pacific. Low latitude easterly winds tend to collapse and the middle latitude westerlies usually increase. In this way influence of ENSO phenomena on atmospheric processes goes beyond the tropics to connect to middle latitude regions.

The changes in wind patterns and redistribution of masses in the atmosphere and ocean are accompanied by noted variations in Earth rotation, due to changes of angular momentum and its exchanges between the solid Earth and its fluid envelope. Typically, positive anomalies of length-of-day (LOD) and noticeable disturbances of polar motion occur during ENSO events. Following an El Niño event, often the negative phase of the ENSO cycle occurs, now known as a La Niña, with the opposite response in LOD as in the El Niño case.

The strong El Niño of 1997/98 was the first to occur during the era in which Earth rotation parameters are determined by high accuracy space geodetic techniques, reaching tenths of a millisecond of arc on the Earth surface. Additionally, the TOPEX/Poseidon's precise altimetric measurements of sea level variations were available during that time as well. At the same time, series of Atmospheric Angular Momentum, from atmospheric operational analyses and reanalyses, as well as Ocean Angular Momentum from ocean models have been available. Thus, comprehensive studies of the most recent El Niño, including its influence on Earth rotation parameters, namely length of day and polar motion, have become possible in the present era.

Noting in September 1997 that we were in the midst of a strong El Niño, we issued a call from the IERS to study the present El Niño event's impact on Earth orientation parameters in Gazette #21 (attached), and we followed this call by the organization at the American Geophysical Union (AGU) '98 Spring Meeting, held in Boston May 26-29, 1998, of the special Geodesy Session, "Impact of El Niño on other Low-Frequency Signals on Earth Rotation and Global Earth System Parameters" (D. Salstein and B. Kolaczek, conveners; program session attached).

This volume consists of papers dealing with this subject, many of which were presented at the AGU meeting. Some of the themes that are represented in this collection include

- strong impact of El Niño on LOD variations;
- new facts dealing with El Niño impact on polar motion, and
- importance of altimetry measurements in studies of El Niño;
- similarities and differences of El Niño phenomena in 1983/1984 and 1997/1998;
- characterization of the statistical nature of El Niño.

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 No 21, 30 September 1997

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 WWW: <http://hpiers.obspm.fr>

Title: El Niño/Southern Oscillation and Earth rotation variations
 Author: D. Salstein

**Call for
 Investigations of interactions between El Niño/Southern Oscillation
 and Earth rotation variations**

The El Niño/Southern Oscillation (ENSO) phenomena is a large-scale process in the ocean-atmosphere system, primarily in the tropical Pacific. During ENSO, the normal tropical atmospheric and oceanic states are disturbed. Each El Niño event includes increases of sea surface temperature (SST) long the west coast of South America and elsewhere. This oceanic warming is part of one phase of the so-called Southern Oscillation (SO), a shifting of atmospheric mass across the breadth of the Pacific Ocean. In the El Niño phase, the oscillation typically produces anomalously high pressures over the West Pacific-Australian-Indonesian region and low pressures further to the east, over the central Pacific. Modifications of zonal winds during an El Niño episode are observed over the entire equatorial Pacific. Easterly winds collapse and westerlies usually increase. The influence of ENSO phenomena on atmospheric processes go beyond the tropics to connect to middle latitude regions.

Motion and redistribution of masses in the atmosphere and ocean may be accompanied by noted variations of Earth rotation. Strong positive anomalies of length of day occur during ENSO events; such signals have been investigated by many past studies. The impact on polar motion can be important as well. The global ENSO signal in Earth rotation may be related to other climate phenomena. Additionally, the correlation between geodetic and atmospheric excitation Earth rotation functions may be particularly high during times of active El Niño activity.

It is clear that a new strong El Niño is presently unfolding with important climatic consequences. Given past results, detailed investigation of ENSO influences on Earth rotation variations is a timely pursuit. Because each El Niño event has separate characteristics, different analyses might be done for individual cases. Study of recent cases, as well as the current 1997 event, are particularly important because their occurrence during a period of high accuracy of Earth rotation parameters (EOP). An understanding of the relationships between lengthy records of ENSO and EOP is also important.

Weekly updates for relevant climate parameters, including SST, 850-hPa wind, and outgoing longwave radiation (OLR), a measure related to SO phase, are available on the Climate Prediction Center homepage:

<http://nic.fb4.noaa.gov> (ENSO Update)

We ask that observers of geophysical fluids (atmosphere and ocean) and of the various techniques for Earth rotation/polar motion consider the details of their products keeping in mind the analysis and possible forecast of the geodetic impacts of El Niño, especially for the recent and current El Niño events. We will coordinate the results of such investigations on this topic. Discussions of this topic will be included at the 1998 IERS Workshop at other relevant science conferences.

THE IMPACT OF EL NIÑO AND OTHER LOW-FREQUENCY SIGNALS ON EARTH ROTATION AND GLOBAL EARTH SYSTEM PARAMETERS

American Geophysical Union 1998 Spring Meeting, Boston, MA, USA

Session G21: Tuesday, May 26, 1998, 8.30 - 12.00 h.

The Evolution of the 1997/1998 El Niño/Southern Oscillation (ENSO): C.F. Ropelewski - invited

Identification of El Niño Signals with Satellite Altimetry: B.D. Tapley, D.P. Chambers, J. Chen - invited

Earth System Science via Gravity: Insight on Seasonal and Interannual Time Scales: J.O. Dickey, G.S. Lagerloef, J. Wahr - invited

The 1997-1998 El Niño and Atmospheric Angular Momentum: D.A. Salstein

Accuracy and Consistency of Earth Rotation Measurements Over Long Time Scales: D. Gambis - invited

Signature of the ENSO in LOD: J.M. Gipson, C. Ma

Impact of El Niño on Polar Motion: B. Kolaczek, M. Nuzhdina, J. Nastula - invited

The 1997 El Niño: Insight via Space Geodesy: J.O. Dickey, P. Gegout, S.L. Marcus

Torques Responsible for Evolution of Atmospheric Angular Momentum During the 1982-83 El Niño Event: R.M. Ponte, R.D. Rosen

The Atmospheric Excitation of Rapid Polar Motions: T.M. Eubanks, J.R. Ray, B.J. Luzum

Inherent Accuracy of 24-hr VLBI EOP Measurements Derived from Two Simultaneously Observing networks: C. Ma, J.W. Ryan

Session G22A: Tuesday, May 26, 1998; POSTERS

Atmospheric Torques on the Surface of the Oceans and Solid Earth: B.V. Sanchez, A.Y. Au

Geophysical Contributors to Interannual Variations of the Gravity Field: D. Dong, J. O. Dickey, R. Gross, M.K. Cheng

Progress in GPS Determination of Universal Time: P. Kammeyer

In Situ Measurement of Earth Rotation Using a Ring Laser: U. Schreiber, M. Schneider, G. Stedman, C. Rowe, S. Cooper, W. Schluter, H. Seeger

Prediction of Post-Glacial Sea-Level Change in Australia and New Zealand: Application of a New Sea-Level Theory: G.A. Milne, J.X. Mitrovica

Session G22B: Tuesday, May 26, 1998, 13.30 - 14.30 h

Rapid Fluctuations in Earth Rotation Are Chaotic: V. Frede, P. Mazzega

**Stability Variations in Rapid Fluctuations of Earth Rotation Caused by El Niño Events:
V. Frede, P. Mazzega**

**Monthly and Fortnightly Ocean Tide Models Empirically Estimated Exclusively From TOPEX/
POSEIDON Altimetry with Implications for Mantle Anelasticity: S.D. Desai, J.M. Wahr**

**Dynamic Effect of Long-Period Ocean Tides on Length of Day as Determined by a
Topex/Poseidon
Tide Model: R.S. Gross, S.D. Desai**

IDENTIFICATION OF EL NIÑO SIGNALS WITH SATELLITE ALTIMETRY

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ABSTRACT

El Niño warming in the equatorial Pacific causes a distinctive change in both local and global sea level, which can be measured quite accurately with space-borne satellite altimeters such as TOPEX/POSEIDON. The sea level changes are reflective of changes in the internal density structure of the ocean due to variations in the ocean heat storage and mass. Because the anomalous warming tends to begin significantly below the ocean's surface, altimetry can detect El Niño signals weeks to months before surface temperature measurements detect them. An example of this is tracking strong Kelvin waves across the Pacific several months before the peak of El Niño warming. Although the altimeter data alone cannot differentiate between changes in ocean heat storage and mass, by combining altimetry with other data and output from numerical models, one can begin to study how changes in the ocean mass influence the Earth's rotation. These signals are examined during the El Niño event of 1997.

INTRODUCTION

Until the last several decades, the El Niño phenomenon was considered a localized interannual variation in the waters of the eastern Pacific, with a frequency of 3 to 7 years. Villagers along the Pacific coast in Peru and Ecuador had known about the intermittent warming of the ocean for centuries. Recent studies, however, have shown that the phenomenon extends across the equatorial Pacific and is coupled with the atmosphere, and that El Niño in the Pacific can effect weather patterns in many portions of the Earth [Philander, 1990].

Although the precise mechanism of El Niño is still not completely understood, the most recent models present several steps in the evolution of a typical El Niño event. During normal years, the trade winds blow strongly from the east to the west across the equatorial Pacific. Water warmed by the sun flows westward in surface currents to pool in the western Pacific and also flows poleward due to Ekman drift. Several months before El Niño warming peaks in the eastern Pacific, the trade winds relax and the westward surface currents slow, as does the Ekman drift. During extreme El Niños, the winds may even reverse, causing the westward currents to disappear and eastward currents to appear along the equator.

These wind changes can force downwelling equatorial Kelvin waves. Kelvin waves have wavelengths of several thousand km and move eastward along the equator at speeds of 2-3 m/sec. Kelvin waves can cause currents which advect some of the water from the warm pool in the west eastward [Harrison and Schopf, 1984], but they mainly cause a deepening of the thermocline in the eastern Pacific, which leads to a rise in sea level. The heating of the eastern Pacific intensifies as surface currents continue to bring warm water from the west and

also because the solar insolation has not changed significantly but the advection of warm water out of the eastern Pacific has slowed. Thus, El Niño is essentially an interannual change in where heat is stored in the equatorial Pacific. The increase in heating in the eastern Pacific causes ocean temperatures to increase and, since water expands when it warms, the sea level rises as well.

Remote sensing from satellites has helped to improve our knowledge of El Niño, from sea surface temperature measurements made by meteorological satellites to measurements of sea level elevation made by satellite altimeters. This paper will discuss the role of satellite altimeters in detecting El Niño signatures in sea level elevation as well as the use of altimetry to study the ocean's role in variations in Earth rotation during El Niño events.

SATELLITE ALTIMETRY AND EL NIÑO

The satellite altimeter measures the distance from the satellite to the ocean surface by transmitting a radar pulse and measuring the time it takes for the reflected pulse to return. The range must be corrected for atmospheric effects which slow down the pulse, and many thousand pulses are averaged together to obtain a single 1-sec measurement [Stewart, 1985]. If the altitude of the satellite above a reference ellipsoid is known precisely, then the sea surface height (SSH) can be determined quite accurately by computing the difference

$$\text{SSH} = \text{satellite altitude} - \text{range}. \quad (1)$$

For the TOPEX/POSEIDON (T/P) satellite, the accuracy of the SSH is estimated to be about 5-6 cm for a 1-sec measurement [Fu *et al.*, 1994]. However, much of the error is due to random noise, and if appropriate smoothing is used, the accuracy can increase to about 2-3 cm [Cheney *et al.*, 1994; Mitchum, 1994], which is comparable to tide gauge measurements made at the ocean's surface. T/P flies along a repeat track of about 10-days, with coincident ground tracks separated by about 2.8° at the equator. This means that T/P repeats measurements at nearly the same geographical location every 10 days.

The SSH is of the order of several hundred meters, but most of this is due to the Earth's gravity field and steady ocean circulation features, and is unchanging. Since variations in SSH caused by El Niño are several order of magnitudes smaller than the SSH, the mean sea surface at each geographic location is removed and sea level anomalies (SLAs), variations in the sea level from the mean, are computed [Chambers *et al.*, 1998a]. A map of SLAs in the tropical Pacific from T/P for the 10-day cycle from December 9 to 19, 1997 is shown in Figure 1. This time period is during the peak of the 1997 El Niño. Sea level throughout the central and eastern Pacific is 15 to 30 cm higher than normal, while sea level in the eastern Pacific is lower than normal. This is due to the changes in oceanic heat storage in the tropical Pacific during El Niño [Chambers *et al.*, 1998b]. It is important to note that the heating changes do not take place in only the top few meters of the ocean, but in fact take place to a depth of 100-150 m (Figure 2). The subsurface temperature changes are often significantly larger than temperature changes at the surface. It is because such a large layer of water is warmed that the sea level rise is large enough to detect.

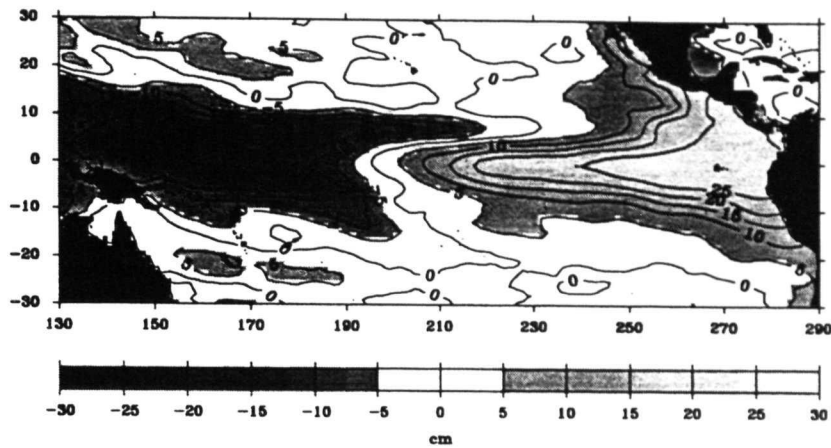


Figure 1. Sea level anomalies observed by T/P from December 9-19 1997. The mean annual signal has been removed. Data have been processed and filtered as described in *Chambers et al.* [1997a].

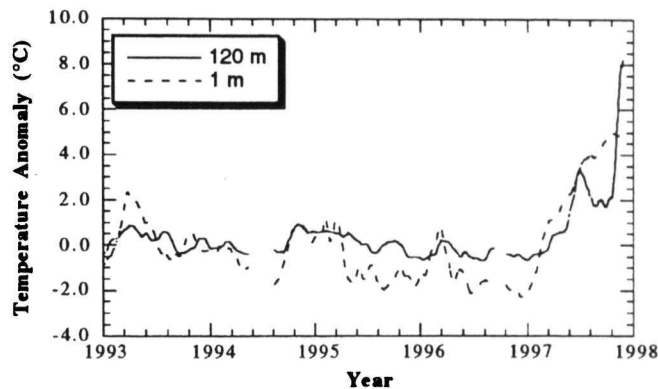


Figure 3. Temperature anomalies recorded by a moored buoy at 2°S, 265°E at depths of 1 m and 120 m. Data have been smoothed with a running-mean boxcar filter with a window of 30 days.

Not only can altimetry detect and measure El Niño signals after it has formed, altimetry can also detect important precursors to El Niño weeks to months before sea level begins to rise significantly in the eastern Pacific. The role of Kelvin waves at the beginning of an El Niño has already been discussed. For many years, it was theorized that strong Kelvin waves should precede an El Niño because of the wind changes in the western Pacific. However, it was difficult to observe Kelvin waves unequivocally with the scattered in situ measurements available before altimetry [*Knox and Halpern*, 1982; *Eriksen et al.*, 1983]. *Miller et al.* [1988] provided the first complete observations of the sea level variations caused by a large Kelvin wave before El Niño warming developed in the eastern Pacific by using data from the Geosat altimeter satellite. However, the Kelvin wave was discovered significantly after the El Niño had developed during 1987.

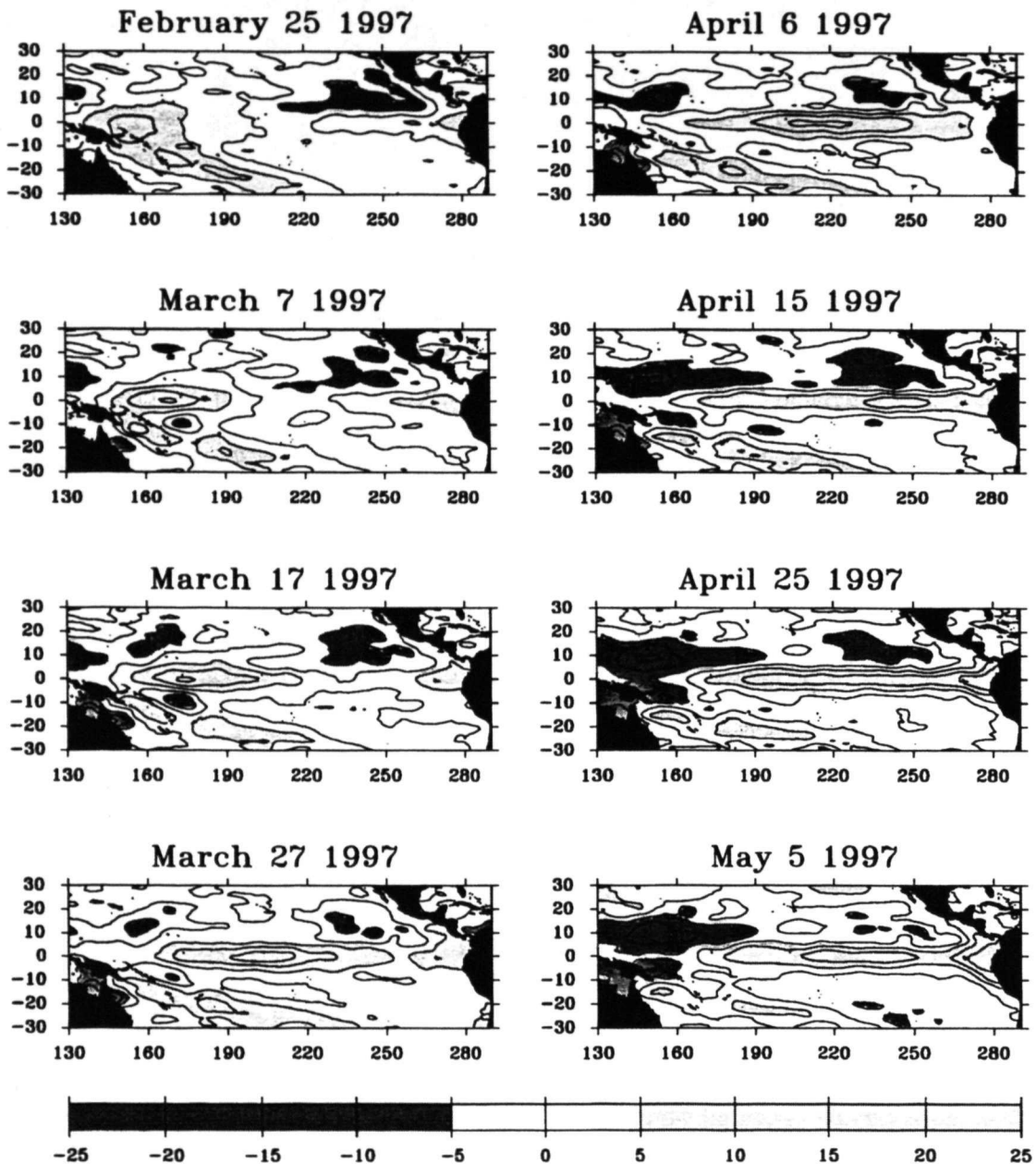


Figure 4. Sea level anomalies in cm observed by T/P from February to May 1997 showing progression of a Kelvin wave from the western Pacific to the east along the equator. The date above each picture is the start of a 10-day repeat cycle. Data have been processed and filtered as described in *Chambers et al.* [1997]. SLAs smaller than - 5 cm have been shaded dark gray and SLAs greater than 5 cm have been shaded light gray.

Large Kelvin waves have continued to be observed in satellite altimeter data since the study by *Miller et al.* [1988]. However, most of the results have come months to years after the waves and the onset of El Niño, such as observations by T/P of a Kelvin wave before the small El Niño of 1993 [*Tapley et al.*, 1994]. Recently, though, observations of sea level anomalies from T/P are available over the internet within a few days to a month after the measurement is made, which allows near realtime tracking of Kelvin waves.

An example of T/P observing Kelvin waves during the 1997 El Niño is shown in Figure 4. In late February, sea level was already beginning to rise in the eastern Pacific after an earlier Kelvin wave had reached the coast of South America. Between February 25 and March 7, sea level increased dramatically along the equator in the western Pacific between 150°E and 190°E. Ten days later, the front of this region of large, positive SLAs had moved eastward, indicative of a downwelling Kelvin wave. Over the next month, the Kelvin wave crossed the Pacific and by the beginning of May sea level was more than 15 cm higher than normal off the coast of South America. Sea level was also significantly higher than normal throughout the central and eastern equatorial Pacific, indicating that El Niño warming was beginning.

EFFECT OF EL NIÑO ON EARTH ROTATION

Studies have shown that time series of the Earth's length of day (LOD) have interannual variations similar to El Niño [e.g., *Rosen et al.*, 1984]. However, the dominant portion of the nontidal signal at most frequencies can be attributed to mass variations within the atmosphere [e.g., *Eubanks et al.*, 1985]. Generally the day is slightly longer than normal during an El Niño. Although the LOD and the effect of the atmosphere on LOD have been studied to some degree, the effect of mass variations in the ocean is more poorly understood.

The sea level measured by altimetry changes because of variations in the density of the ocean. As already noted, water expands (the density decreases) as it warms with no change in mass. However, precipitation, evaporation, and transport of water with differing salinity also effect the density by changing the mass in a particular location. The first effect should cause no fundamental change in the LOD since mass remains constant, but the second effect may contribute to a variation in LOD.

The global mean sea level variation measured by T/P shows a very strong increase in mean sea level correlated with the 1997 El Niño (Figure 5). However, several recent studies have shown that much of the sea level variation is caused by thermal expansion [*White and Tai*, 1995; *Chambers et al.*, 1997, 1998b; *Wang and Koblinsky*, 1997; *Stammer*, 1997].

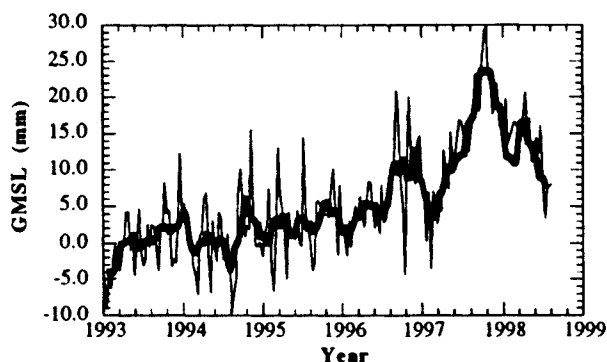


Figure 5. Global mean sea level variations from T/P. The thick solid line shows the time series after applying a 60-day running mean boxcar filter. The time series has been computed as suggested by *Nerem* [1995].

This is demonstrated in Figure 6, where sea level variations from T/P are compared to sea level variations computed from thermal data on moored buoys that are part of the NOAA Tropical Atmosphere-Ocean (TAO) program in the Pacific [McPhaden, 1993]. Only in the west Pacific is there a significant difference in sea level at interannual frequencies, caused by mass variations due to changes in precipitation/evaporation during El Niño events [Chambers *et al.*, 1998b]. However, even in the western Pacific, the sea level change due to mass variations is much smaller than the sea level change due to thermal expansion.

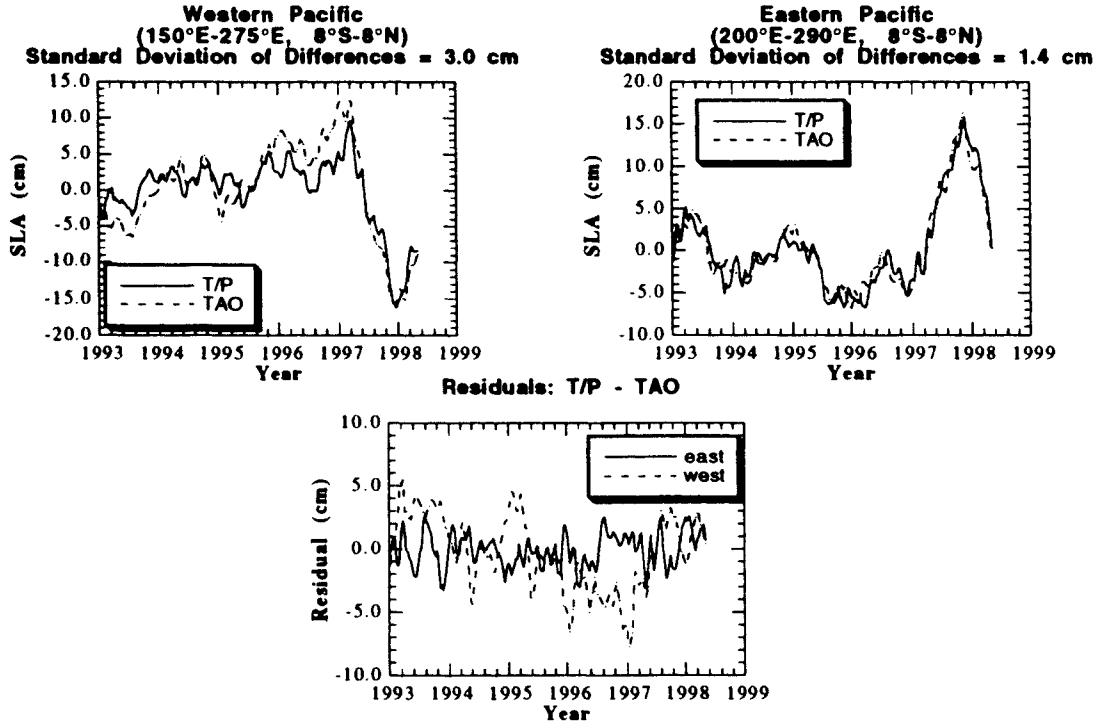


Figure 6. Sea level anomalies in western and eastern Pacific from T/P and TAO thermal data (top) and the residual after subtracting thermal sea level variations from T/P (bottom). Data are compared only around TAO buoys and have been smoothed with a running-mean boxcar filter with a window 30 days. The mean annual signal has been removed.

Although altimetry alone cannot separate between thermal and mass effects, by combining altimetry with other measurements of the thermal sea level variation, an approximation of the mass variations can be determined [Chen *et al.*, 1998a,b]. To do this, thermal sea level variations have been computed from an annual climatology [Levitus and Boyer, 1994] away from the equatorial Pacific and from TAO buoys near the equatorial Pacific, interpolated to a uniform 1° grid. The thermal sea level variations are then subtracted from gridded T/P SLAs to form a residual of mass variations. The residuals are then integrated globally to compute LOD variations [Chen *et al.*, 1998b]. The results are plotted in Figure 7, along with the LOD computed by the International Earth Rotation Service (IERS) [IERS, 1998], and LOD from an atmospheric model [Salstein and Rosen, 1997].

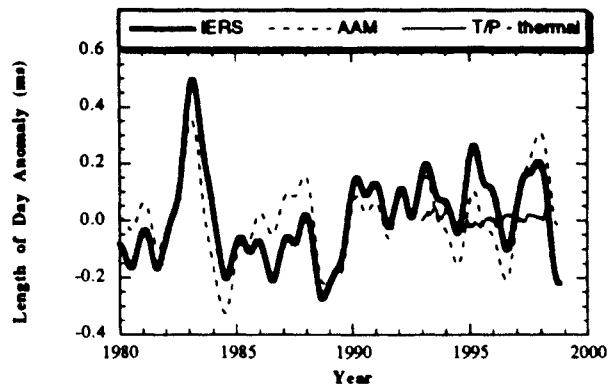


Figure 7. Interannual variations in total length of day from observations (IERS), atmospheric angular momentum (AAM) from a model, and the oceanic contribution from T/P minus thermal sea level variations. Tidal signals have been removed. A decadal signal has been removed from the IERS time series.

While the change in LOD near the end of 1997 appears to be smaller than the changes during the 1982 and 1994 El Niño events, much of this is due to uncertainty in the estimation of the decadal trend near the end of the time series. Different estimates can increase or decrease the amplitude during the 1997 event. However, the important message in Figure 7 is the relative contribution to interannual changes in LOD from oceanic mass variations. Based on the T/P altimetry results, after estimating and removing thermal expansion effects, the oceanic contribution to LOD is quite small during an El Niño. This is because El Niño largely causes changes in oceanic heat storage and not mass.

CONCLUSIONS

TOPEX/POSEIDON has proven very valuable for tracking and monitoring the strength of the 1997 El Niño, since accurate data are available within a month of the initial observation. T/P was able to track Kelvin waves before El Niño signals began to appear in the eastern Pacific, and the altimeter data was useful for monitoring the size and extent of El Niño warming throughout 1997. However, since most of the sea level variations are caused by thermal expansion, the oceanic portion of the LOD signal was very much smaller than the signal from the atmosphere.

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ATMOSPHERIC ANGULAR MOMENTUM DURING THE 1997-98 EL NIÑO EVENT

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The El Niño event of 1997-98 caused a dramatic change in the atmospheric circulation over the Pacific Ocean and strongly influenced weather patterns over much of the globe. A measure of the overall strength of the zonal circulation is the global atmospheric angular momentum (AAM) about the rotation axis relative to Earth's surface. AAM may be defined as

$$AAM = \frac{a^3}{g} \iiint u \cos^2 \phi d\phi d\lambda dp$$

where a is the radius of Earth, g acceleration due to gravity, and u zonal wind, with the integral performed over all latitudes, ϕ , longitudes, λ , and pressures, p . Because of its global scope, the AAM time series forms a climate-sensitive index of the atmosphere's circulation. To understand its long-term characteristics, we have calculated this index from over 40 years of the NCEP/NCAR Reanalysis; in Fig. 1 the various signals in this curve are clearly seen, especially the strong seasonal fluctuations which peak in Northern Hemisphere winter; noticeable interannual variability is evident too. The two highest peaks occurred in January 1983 and February 1998 during major El Niño/Southern Oscillation events.

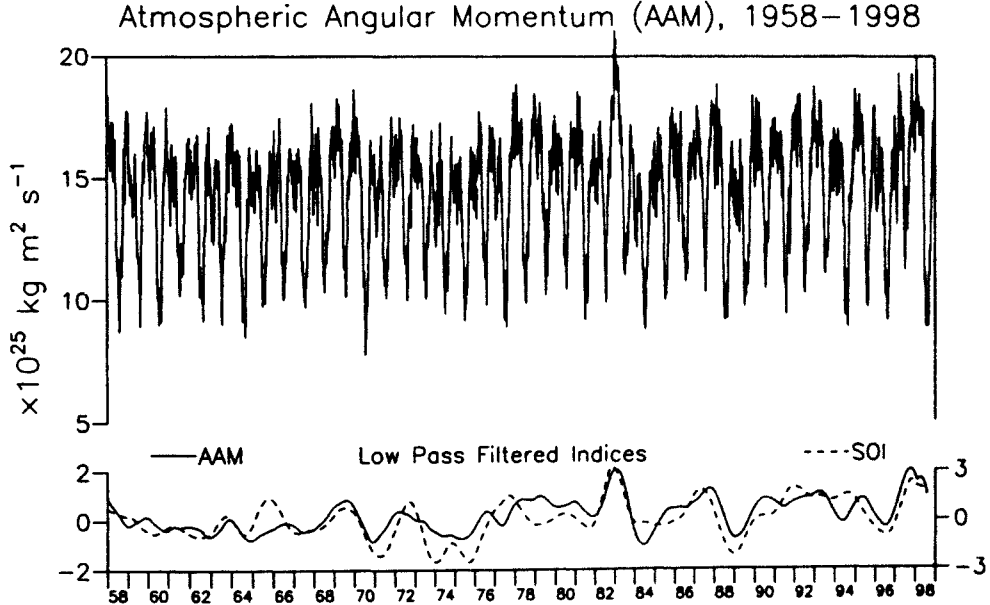


Figure 1. (Top) Daily values of atmospheric angular momentum from the NCEP/NCAR Reanalysis. The angular momentum is integrated globally between 10 and 1000 hPa. (Bottom) Interannual variations of AAM (solid, scale on left) and the Southern Oscillation Index (dashed, scale on right), both low-pass filtered.

The close connection between the AAM index and ENSO can be seen by comparing the curves at the bottom of Fig. 1. Here, interannual variations of AAM and the modulating Southern Oscillation Index, are isolated with a low-pass filter. The correlation between the two filtered series is 0.72.

The close connection between the AAM index and ENSO can be seen by comparing the curves at the bottom of Fig. 1. Here, interannual variations of AAM and the modulating Southern Oscillation Index, are isolated with a low-pass filter. The correlation between the two filtered series is 0.72.

Prior to May 1998, values of AAM were very high during most of the period since March 1997 (Fig. 2), when the El Niño began, undergoing some intraseasonal pulses in the early part of this period. In particular, values were consistently greater than their climatological means for a period of 11 months, between June 1997 and May 1998. After that time, the shift to La Niña conditions has resulted in negative anomalies.

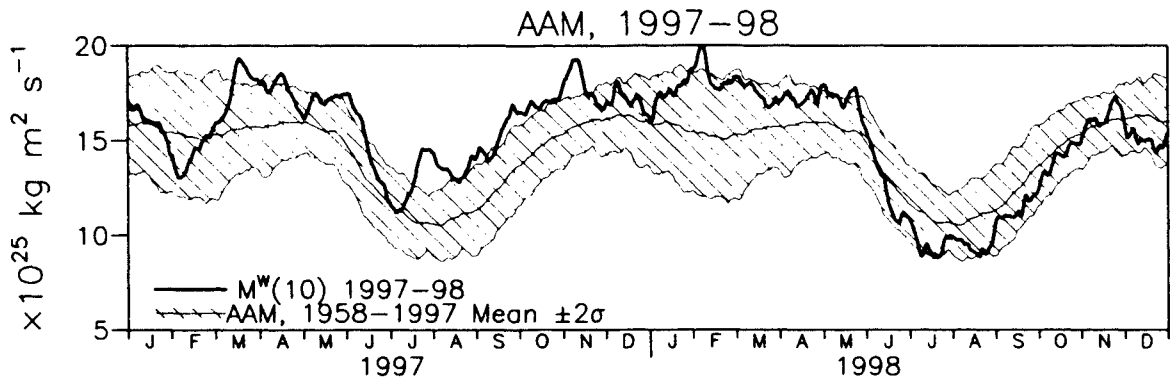


Figure 2. Values of AAM since January 1997 (heavy). The central curve shows the daily climatological mean of AAM values based on 40 years, and the gray shaded region indicates values within two standard deviations of that mean.

Because of angular momentum conservation in the Earth-atmosphere system, changes in global AAM are matched by those in the solid Earth, as indicated by variations in the length of day (Salstein et al. 1993). The strong agreement between the two series (Fig. 3) confirms this relationship and, here, the influence of the El Niño on the rotation rate of Earth. In particular, l.o.d. also achieved a peak at the time of the February 1998 AAM maximum.

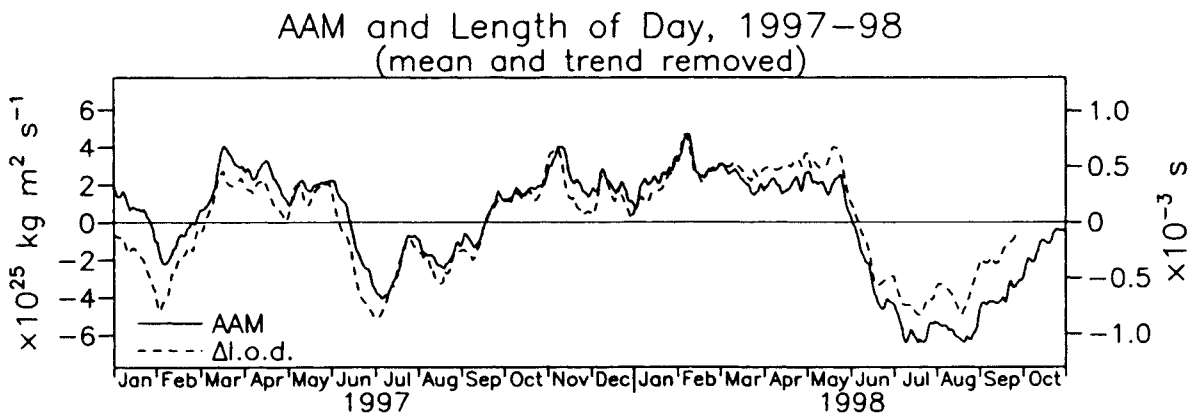


Figure 3. Daily values of AAM (scale on left) and departures of the length of day (l.o.d., scale on right) derived from space-based geodetic measurements, since January 1997.

A normalized AAM anomaly may be defined as the difference between its value and climatology, divided by the standard deviation of the AAM series, for the calendar date (Fig. 4). Anomalies of nearly two standard deviations or more were present for the four-month period between mid-July and mid-November 1997, an extent not observed elsewhere in the series. Record values of this normalized index, exceeding 4 standard deviations, occurred in July and November 1997. The index then became strongly negative in the recent La Niña period.

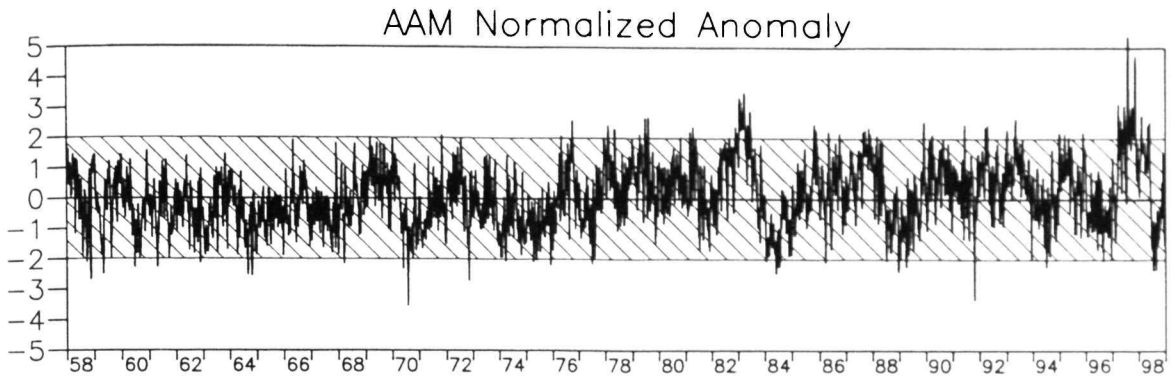


Figure 4. Normalized AAM anomaly is defined as the difference between its value and climatology, divided by the standard deviation of the AAM series for a calendar date (all from Fig. 2).

To determine the meridional zones in which angular momentum was most anomalous, we have subdivided the atmosphere into 46 equal-area latitude belts (Rosen and Salstein 1983) for every day since January 1997 and calculated momentum anomalies in each belt. In Fig. 5, note how positive momentum anomalies first appear in the tropics (in late February 1997), experience several intraseasonal pulses, and appear to expand by November 1997 into middle and higher latitude of both hemispheres. By June 1998, positive anomalies are confined to the highest southern latitudes, while negative momentum anomalies appear in the tropics related to the start of La Niña. The transition from El Niño to La Niña appears to have been very abrupt.

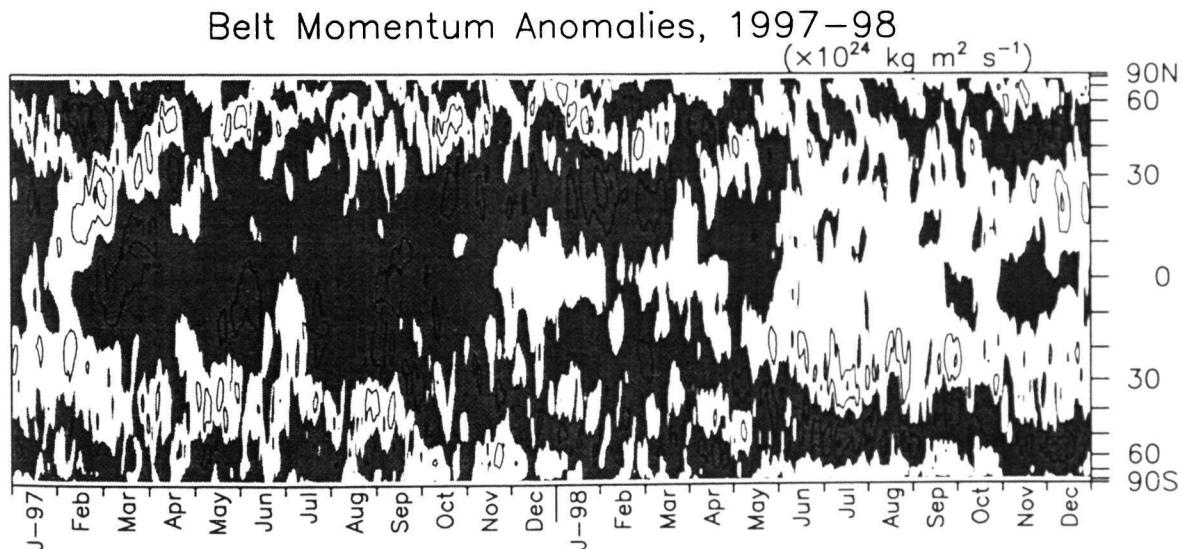


Figure 5. Anomalous values of angular momentum in 46 equal-area latitude belts for every day since January 1997. Positive values are shaded.

The regional pattern of AAM signals in February 1998, the month with the highest global value, is shown in Fig. 6a. Middle latitude centers over the Pacific in both hemispheres are very strong. These features and many others, like the striking pattern over North America, duplicate the February 1983 El Niño pattern, seen in Fig. 6b.

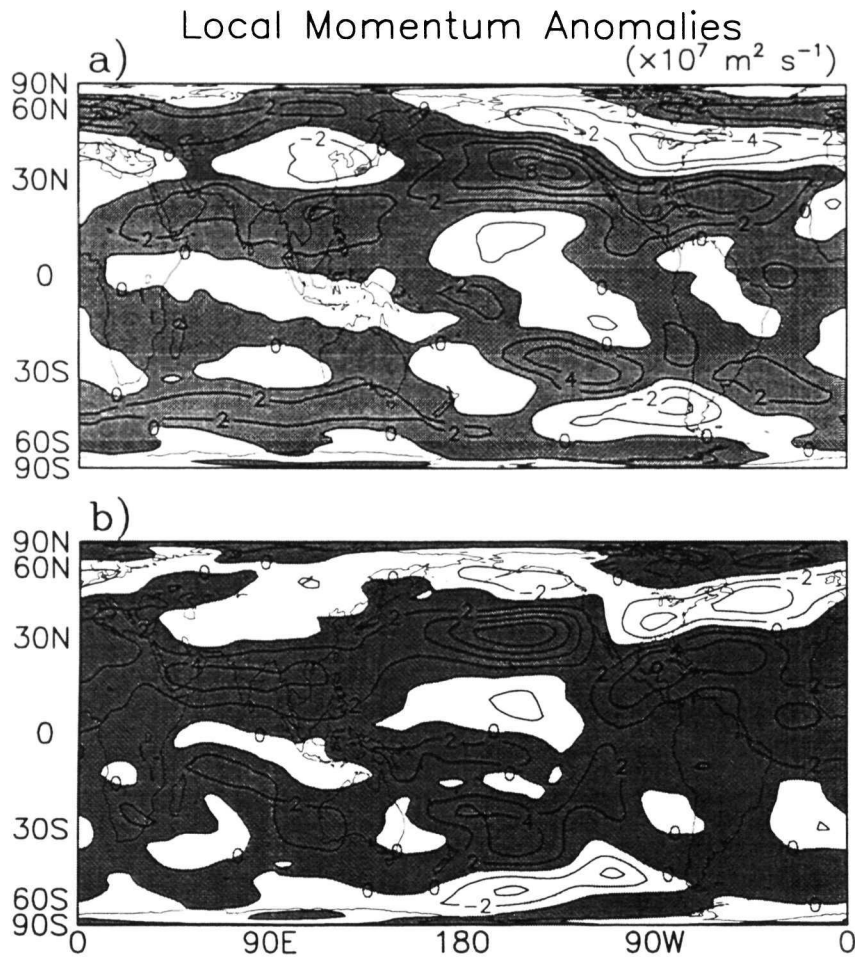


Figure 6. (a) Anomalous values of atmospheric angular momentum per unit mass during February 1998 and (b) February 1983. Positive values are shaded.

Work is underway to evaluate the torque mechanisms responsible for the distinctive positive anomalies in 1997 and the rapid transition to negative anomalies in mid-1998.

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Acknowledgments

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SIGNATURE OF EL NINO IN LENGTH OF DAY AS MEASURED BY VLBI

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INTRODUCTION

Very Long Baseline Interferometry (VLBI) is one of the most accurate techniques for measuring Earth orientation parameters (EOP), and is unique in its ability to make high accuracy measurements of UT1, and its time derivative, which is related to changes in the length of day, conventionally called LOD. The accuracy of the best VLBI measurements using 24 hours of data is 2 μ s for UT1, 4 μ s/day for LOD. Changes in EOP are due to either external torques from gravitational forces, or to the redistribution of angular momentum between the solid-Earth, atmosphere, oceans and inner core. Discrepancies between predicted and measured EOP values point to areas where either the measurements or the models need improving.

The theoretical models that predict the response of the Earth to external forces are conceptually simple. To a good first approximation, the planets can be represented as point masses. Highly accurate predictions for nutation have been around for some time, and continue to be refined. Furthermore, EOP changes due to external forces are for the most part strictly harmonic in nature, and the analysis of the nutation measurements is amenable to the techniques of harmonic analysis. Measurements taken at different times can be combined to estimate the harmonic amplitudes of the nutation series. Since both the theoretical predications and VLBI measurements are very precise and of comparable precision, the status of comparisons between observation and theory is fairly mature. For example, a comparison of the predicted nutation series with the VLBI measured series led to the conclusion that the nutation model was incorrect. The VLBI measurements led to a change in the ellipticity of the inner-core. VLBI measurements continue to be used to check and improve the nutation models.

In contrast, the changes in the orientation of the Earth due to exchange of angular momentum between the Earth, core, oceans and atmosphere are by their very nature much more complicated. Instead of dealing with simple gravitational forces, you are dealing with a complicated distributed system specified by many more parameters. After compensating for external torques, the total angular momentum of the Earth-atmosphere-oceans-core is constant:

$$J_{Earth} + J_{Atm} + J_{Ocean} + J_{Core} = J_{Total}$$

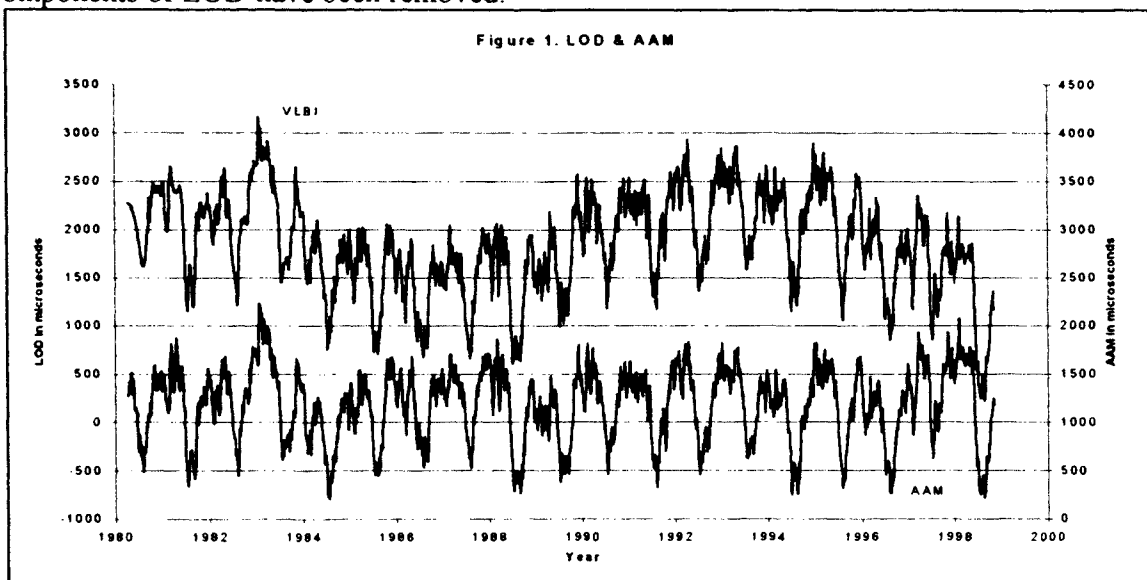
The only quantity that is directly measurable is the first. The remaining contributions must be indirectly inferred. For the atmosphere and the oceans this is done by calculating the angular momentum predicted by some global circulation model [Salstein, 1997]. Comparisons of the

predictions of these models with measured LOD indicate generally good agreement, although currently the discrepancies between different models is much larger than the uncertainties in the VLBI measurements.

In this note we study the influence of the El Nino – La Nina on LOD, as measured by VLBI. We find that these have obvious signatures in LOD. During an El Nino, the atmospheric angular momentum increases, and hence the angular momentum of the Earth decreases. The Earth slows down, and the length of day increases. In a La Nina exactly the opposite happens.

LOD AND AAM

Beginning in 1979 and continuing to the present time the international VLBI community has conducted over 2700 VLBI experiments. The spacing of the VLBI data is far from uniform. However, from 1984 onwards there was at least one VLBI experiment per week specifically designed to measure EOP. The VLBI measurements of LOD are displayed in Figure 1. The VLBI data has been Kalman filtered to obtain daily estimates of EOP. The tidal components of LOD have been removed.

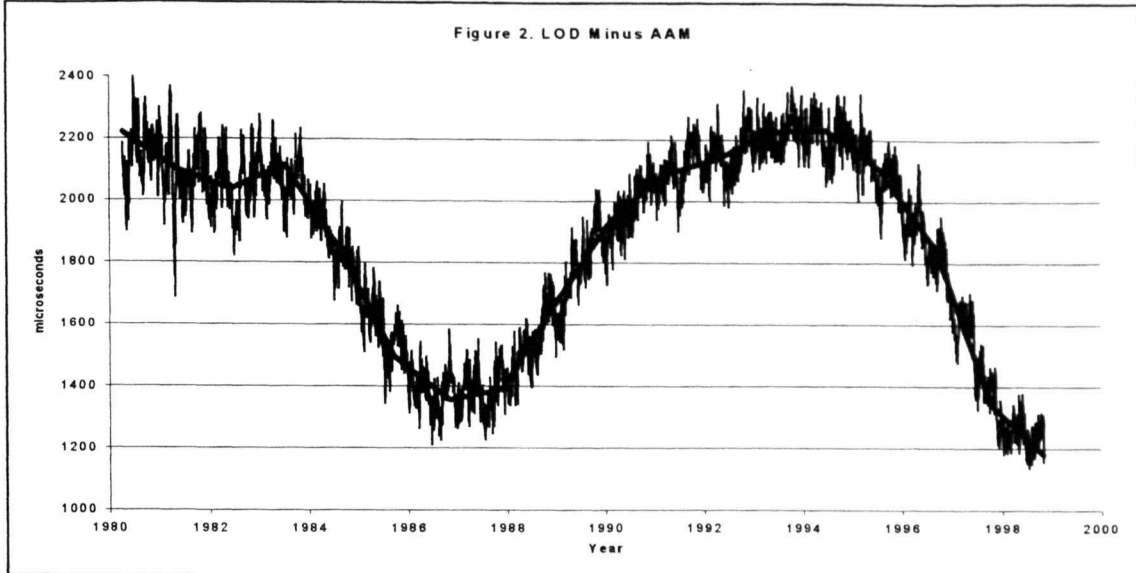


Also plotted on Figure 1 is the total atmosphere angular momentum (AAM). This data is derived from the NCEP global circulation model, and was provided by AER [Salstein and Rosen, 1998]. It includes wind and pressure terms to the top of the model (10 mbar) and uses the inverted barometer approximation for the oceans. The AAM data has been converted to LOD to make comparison between the VLBI measurements and AAM easier. The AAM vertical axis, which is on the left of the plot, has been displaced from the LOD to make comparison easier.

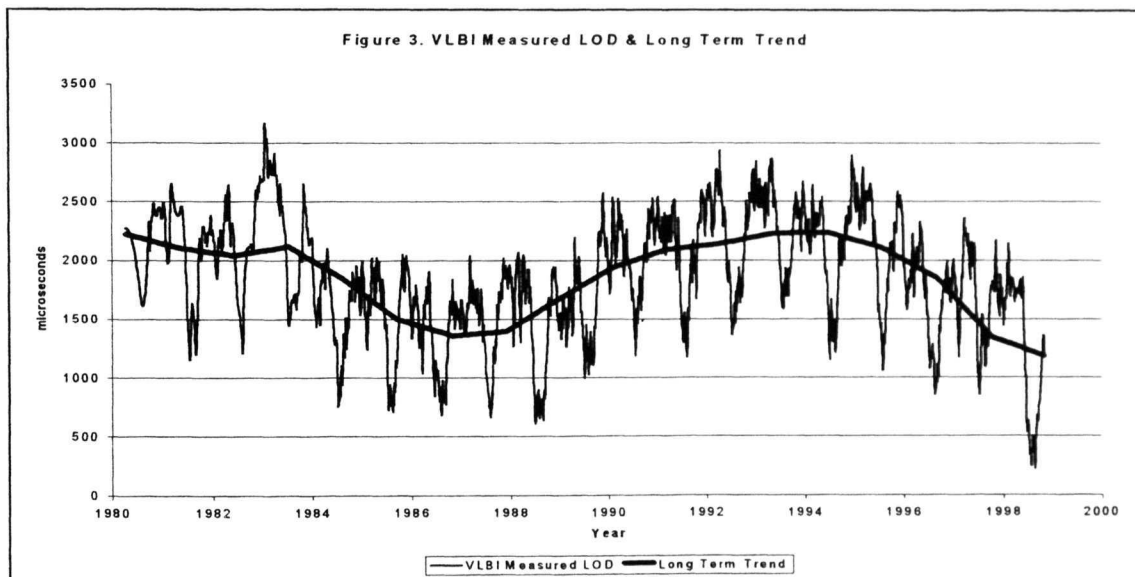
It is also apparent that there is excellent short-term agreement between LOD and AAM. Both LOD and AAM have seasonal variations of order 1000 $\mu\text{s}/\text{year}$. The AAM values oscillate about some mean. In contrast, the LOD measurements have a long term drift, which is thought to be due to exchange of angular momentum between the mantle and the core. This introduces a time varying offset between LOD and AAM.

This drift is emphasized in Figure 2, which plots the difference between LOD and AAM. Note that the vertical scale is different from Figure 1. The sub-annual variation is reduced by almost

an order of magnitude, indicating that most of the short-term variation in LOD is due to AAM. The variation in the residual curve is due either to other EOP contributions, e.g., the oceans or the core, or to errors in either the LOD measurements or AAM predictions. In any case, after removal of the residual sub-annual variation, this difference curve should be a good proxy for the “long term” behavior of LOD.



We tried various means of fitting the long-term variation in LOD while leaving the short-term variation alone. This included Fourier filtering, singular spectrum analysis, temporal empirical



functions, and fitting the difference curve to a piecewise linear function. All of these techniques gave similar results except at the end of the data. We finally settled on using the piecewise linear function. This approximation is displayed in Figures 3 and 4 as a solid curve, with rate breaks every 400 days. We tried using intervals between 100 and 700 days, and settled on 400 as a compromise between capturing yearly and longer variations without being unduly influenced by the short variation.

To study the short-term behavior of LOD we need to remove the long-term drift. The result is shown in Figure 4. This figure emphasizes the seasonal dependence of LOD. It is worth noting that the day is longer by about 1 ms in the Northern Hemisphere winter than in the summer.

The physical reason for this is that the atmosphere carries more angular momentum in the winter. The asymmetry between summer and winter is because the landmass of the Earth is not symmetrically distributed between Northern and Southern hemispheres.

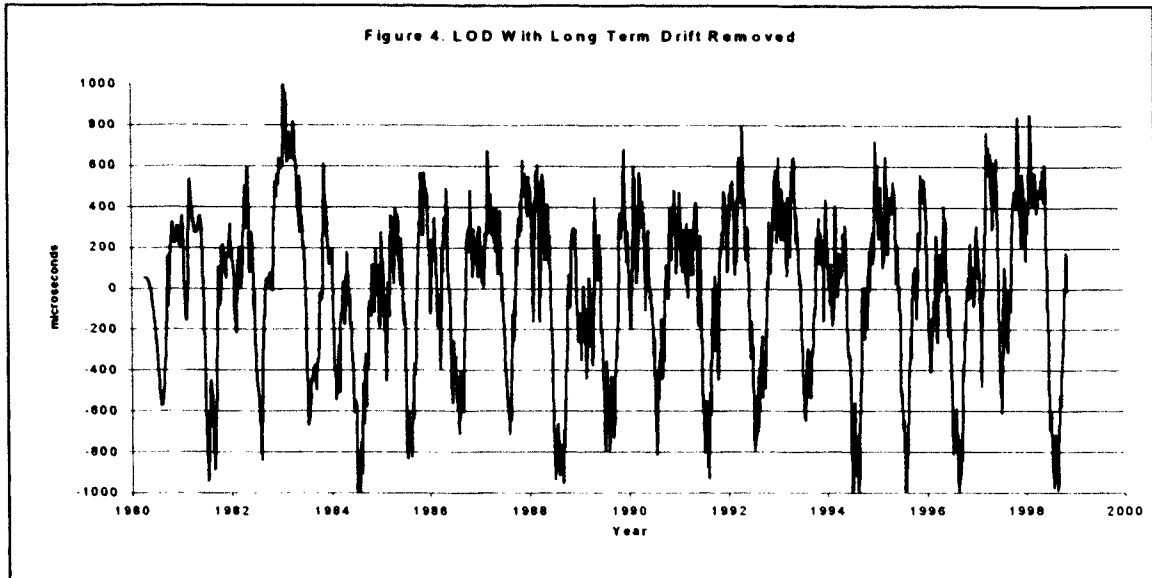
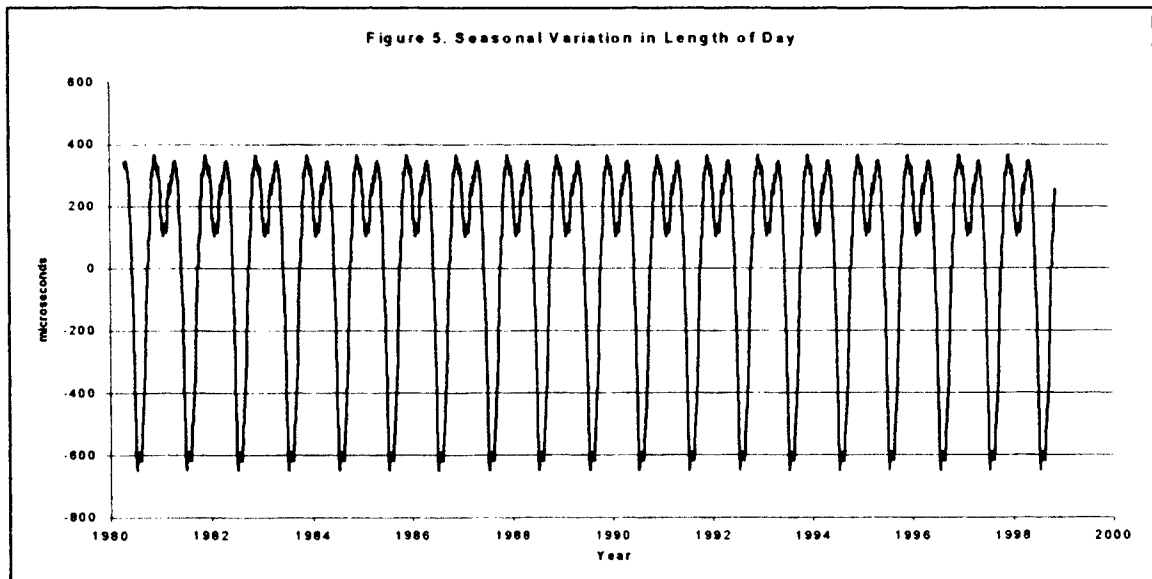
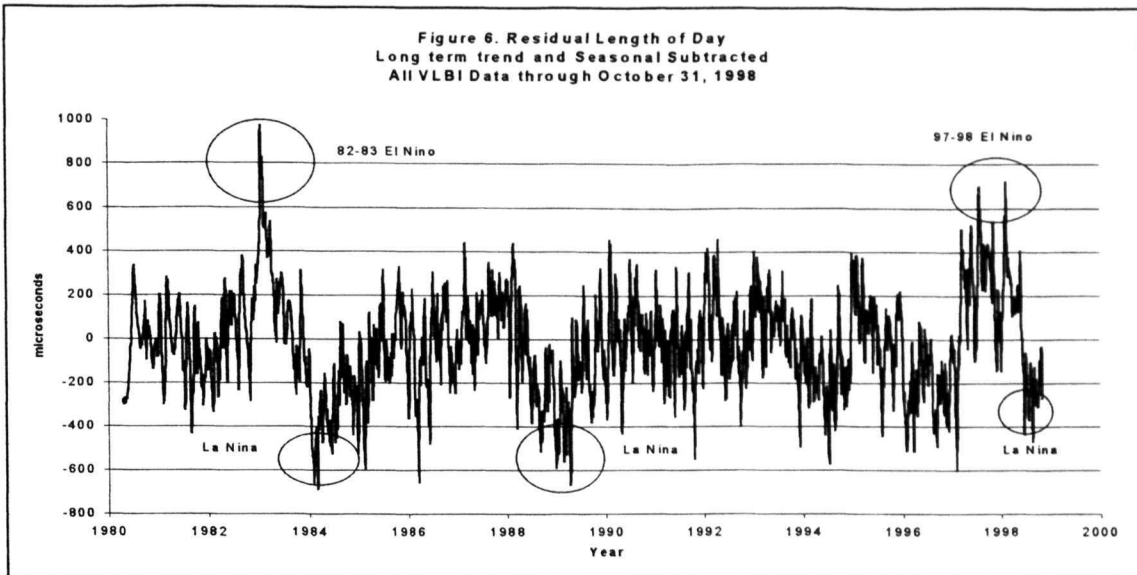


Figure 5 plots the purely seasonal variation in LOD. We generated this figure by calculating the average LOD as a function of the day of the year, and plotting the results.

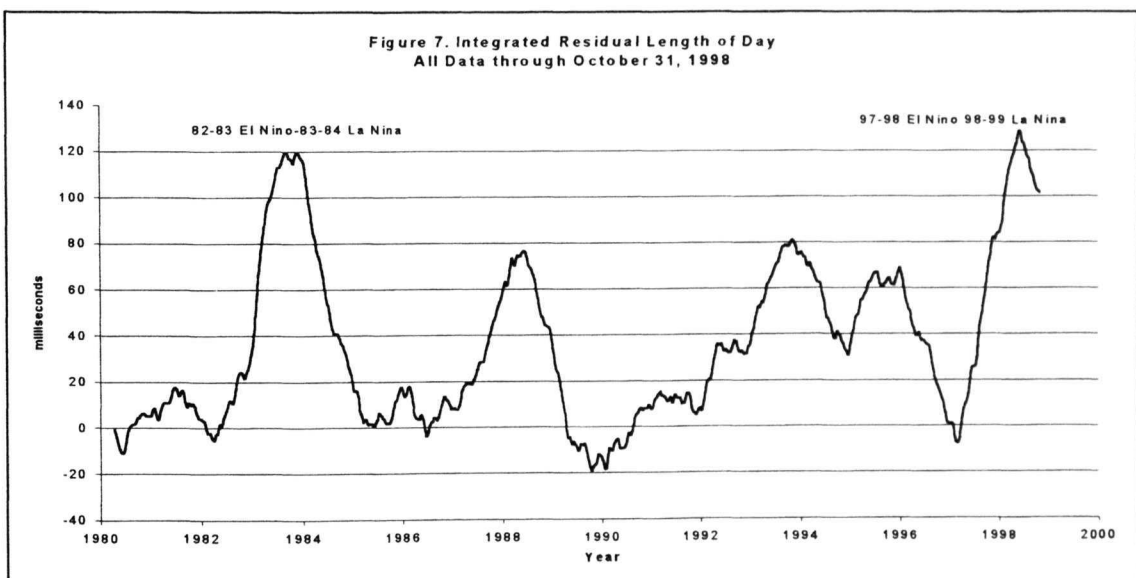


To isolate the anomalous behavior in LOD we need to remove both the long-term drift and the expected seasonal variation. The residual LOD is shown in Figure 6. All of the excursions are associated with El Nino – La Nina events. The most prominent of these is the 1982-83 El Nino, which was followed by a La-Nina. As the angular momentum of the atmosphere increased, the Earth slowed down. As the Earth slowed down, the length of day increased. The maximum change in LOD was about 1 ms/Day. This increase was followed by a decrease, as El Nino begat La Nina. The 1997-98 El Nino exhibits both similarities and differences from the 1982-83 El Nino. At its peak the 1997-98 El Nino resulted in a 0.8 ms increase in LOD.

Although the size of this event was not as large as the earlier one, it lasted much longer. Like the earlier event, it has been followed by a La Nina.

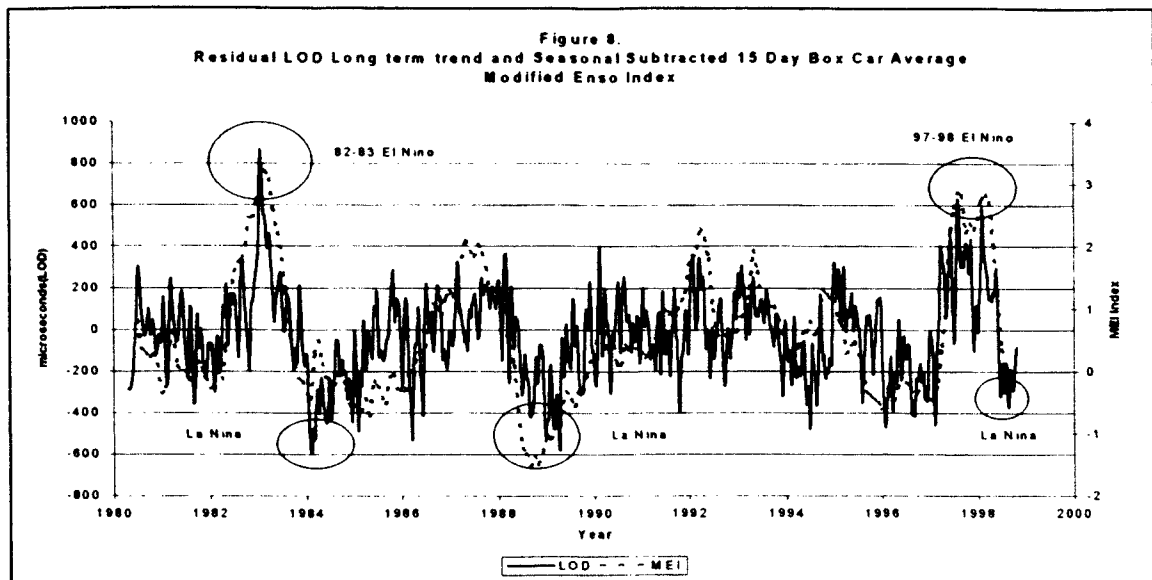


We have focused our discussion on LOD, that is the rate of rotation of the Earth. It is also interesting to look at the integrated effect of the LOD. If we view the Earth as clock, LOD corresponds to how fast or slow the clock is, that is how much time the clock gains or loses in a day. When we integrate this we find how far off the clock is in keeping perfect time. Figure 7 plots the integrated effect of variations in LOD. The 1982-83 El Nino led to a total integrated effect of 0.12 s, while the latest El Nino was slightly higher, at 0.125 s. As we transition from El Nino to La Nina the Earth slows down, and we lose the time we have gained.



In the discussion above we identified various excursions in the residual LOD with El Nino and La Nina events. However, we gave no evidence for these excursions actually being caused by the El Nino or the La Nina. One way of demonstrating that this is the case is to show that an index associated with the El Nino/La Nino is correlated with LOD. We show this in Figure 8 below, which plots the Multivariate ENSO Index. [Wolter, 1998]. This index uses two months of data, so it is smoothed compared to the LOD measurements. Also plotted on this figure are

15-day averages of the residual LOD. The correlation between the two series is high and obvious.



ACKNOWLEDGEMENTS

It is a pleasure to acknowledge conversations with Tom Clark who originally suggested this research, and David Salstein who suggested detrending the LOD data to make comparison with AAM easier. John Gipson was supported under NASA grant NAS5-32331.

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EL NIÑO IMPACT ON ATMOSPHERIC AND GEODETIC EXCITATION FUNCTIONS OF POLAR MOTION

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An El Niño phenomenon is the prominent interannual fluctuation in the atmosphere-ocean system in the tropical Pacific. During El Niño epochs there are disturbances of the normal tropical easterly wind causing the dominant extensive meteorological disruption. Differences of ocean temperatures between different regions of the tropical Pacific known as the Niño 1+2, Niño 3, Niño 4, Niño 3.4 regions, extending westward from South America (see NOAA Climate Diagnostics Bulletins) and the Southern Oscillation Index (SOI), which is the standardized difference of atmospheric surface pressure between Tahiti in the central Pacific and Darwin, Australia, characterize these phenomena. The combination of El Niño-Southern Oscillation is known as ENSO.

Motion and redistribution of masses within the atmosphere are accompanied by variations in the solid Earth rotation. Influences of ENSO on Earth rotation, on variations of length of day (LOD) and polar motion have been investigated in many papers. Mostly, though, El Niño influences on LOD have been investigated (Chao, 1989; Dickey, 1993; Dickey et al., 1994; Eubanks et al., 1986; Franquis et al., 1994; Gambis, 1992; Gipson et al., 1998; Nastula et al., 1990; Rosen et al., 1984 and others) and two papers dealing with this problem are included in this volume (Dickey et al. and Gipson et al.). An example of the strength of the connection between ENSO and LOD is the maximum correlation coefficient - 0.67, between LOD and SOI, obtained with a one month lag for the time interval of 1965 - 1990 (Dickey et al., 1994).

Influences of El Niño on polar motion have already been found through correlations between geodetic and atmospheric excitation functions of short period variations of polar motion with period ranges of 20 - 150 days (Kosek et al., 1995a; Kolaczek et al., 1998; Nuzhdina et al., 1997). The correlation coefficients between temperatures in the Niño regions (NINO data) and the correlation coefficients between short period variations of atmospheric and geodetic excitation functions computed for several El Niño epochs reach values on the order of 0.5 - 0.7. (Kolaczek et al., 1998; Nuzhdina et al., 1997. Fig.1a is given as an example).

Here, computation of correlations between the NINO data and correlation coefficients of short period oscillations (20 - 150 days) of atmospheric and geodetic excitation functions were carried out again taking into account the additional new data for the epoch of the last, strong El Niño 1997/1998 and results are presented in Fig. 1b.

Similar data series, but longer, than in our previous paper (Kolaczek et al., 1998) used here include:

- IERS Earth Orientation Parameters EOP (IERS) 97C04 (IERS, 1998);
- Equatorial Components of Atmospheric Angular Momentum χ_1 , χ_2 of the reanalysis data of the NCEP/NCAR (U.S. National Center for the Environmental Prediction/National Center for Atmospheric Research) (IERS, 1998; Salstein et al., 1993, 1995);

- set of NINO temperature 4 data; (NOAA/NCEP [National Oceanic and Atmospheric Administration/NCEP])
- SOI Indices (NOAA/NCEP)
- Equatorial Components of geodetic excitation functions of polar motion ψ_1 , ψ_2 computed by the deconvolution formula (Barnes et al., 1983) from the EOP (IERS) 97C04 pole coordinates data.

It was shown previously (Kolaczek et. al., 1998) that correlation coefficients between NINO 4 data and variations of correlation coefficients of geodetic and atmospheric excitation functions are higher than in the case of other NINO data series. Thus, correlation coefficients between equatorial components of atmospheric and geodetic excitation functions χ_2 , ψ_2 were computed and correlated with NINO 4 data (Fig. 1b). Each correlation coefficient C was computed for a one year span with steps of 45 days. The correlation coefficient between NINO 4 data and variations of correlation coefficients of atmospheric and geodetic excitations functions for different time periods containing one or two El Niño events in the years 1986 - 1998 are given in Fig.1b. They are variable and reach in maxima the value of 0.7 - 0.9. Fig. 1a shows such correlation coefficient for El Niño phenomena in 1983/84 and 1986/87 (Kolaczek et al. 1998). The significance levels were estimated taking into account only independent correlation coefficients between atmospheric and geodetic excitation functions, that is, one point per year. It is worth mentioning that, as shown earlier, an influence of each El Niño on Earth Rotation is different. Correlation coefficients CC and time delays depend on the period of time of data taken for computations.

There are irregular variations or disturbances of polar motions in El Niño epochs, too. They are related to the transfer of perturbations of Atmospheric Angular Momentum (AAM) into correlations between geodetic and atmospheric excitation functions of polar motion (Kosek et al. 1995b, 1998). Such irregular variations are seen in Fig. 2, where differences between short period variations of the x pole coordinate and their autocovariance predictions by autocovariance methods are shown. These differences are greater than the level of values of three times the standard deviation during El Niño epochs in 1979/1980, 1983/1984, 1985/1986, 1988/1989, 1995/1996.

The MESA spectra of correlation coefficients variations between ψ/χ excitation functions, NINO and SOI data in the years 1975 - 1997 indicate two strong oscillations with periods of 4-5 years, and 2-3 years (Figs. 3,4). The period of 4-5 years is connected with El Niño phenomena, the period of 2-3 years is the period of the Quasi-Biennial Oscillation (QBO). Such spectra suggest the existence of ENSO and QBO impacts on the correlation between the ψ and χ considered excitation functions.

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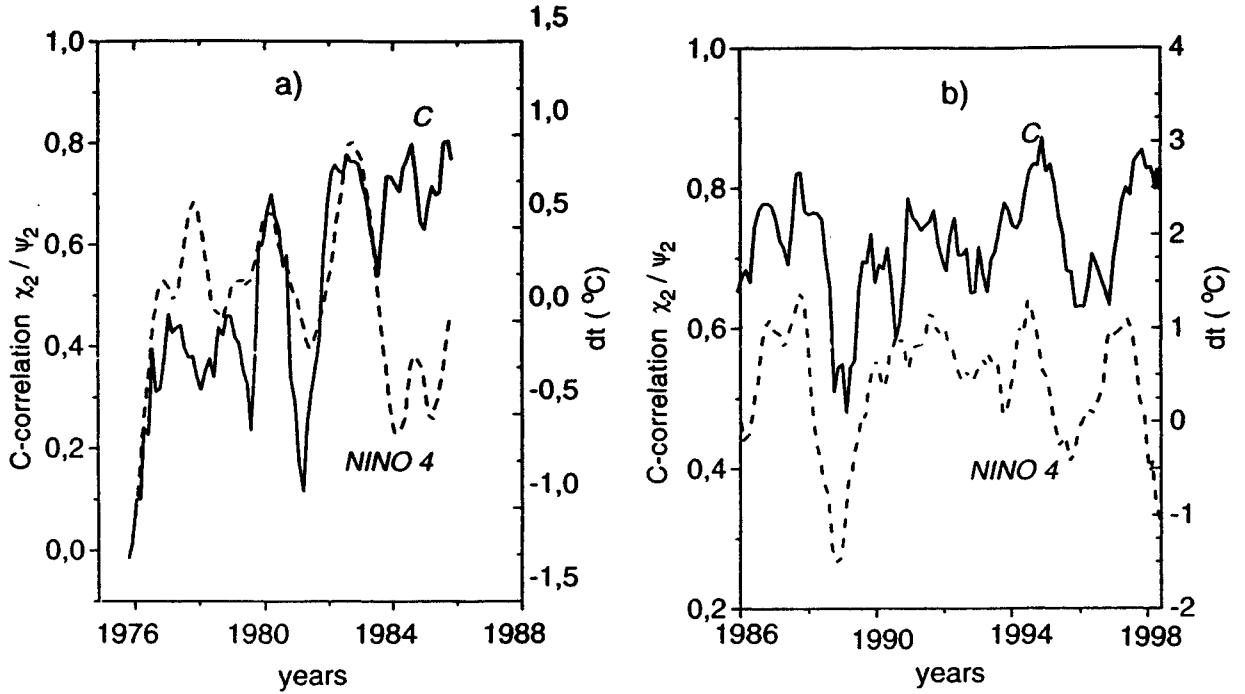


Fig. 1. Diagrams of the NINO 4 data and the correlation coefficient C between short period variations of χ_2 , ψ_2 for the period range of 20 - 150 days.

- a) $CC = .80$ (time delay = 292 days) for the period 1976-1984 (Kolaczek et al., 1998)
 - b) $CC = .74$ (time delay = 0 days) for the period 1985-1990.5; One El Nino event.
 - $CC = .67$ (time delay = 0 days) for the period 1985-1995.5; Two El Nino events.
 - $CC = .86$ (time delay = 0 days) for the period 1993-1998.5; Two El Nino events.
 - $CC = .96$ (time delay = 0 days) for the period 1995-1998.0; One El Nino event
- significance level of 95%.

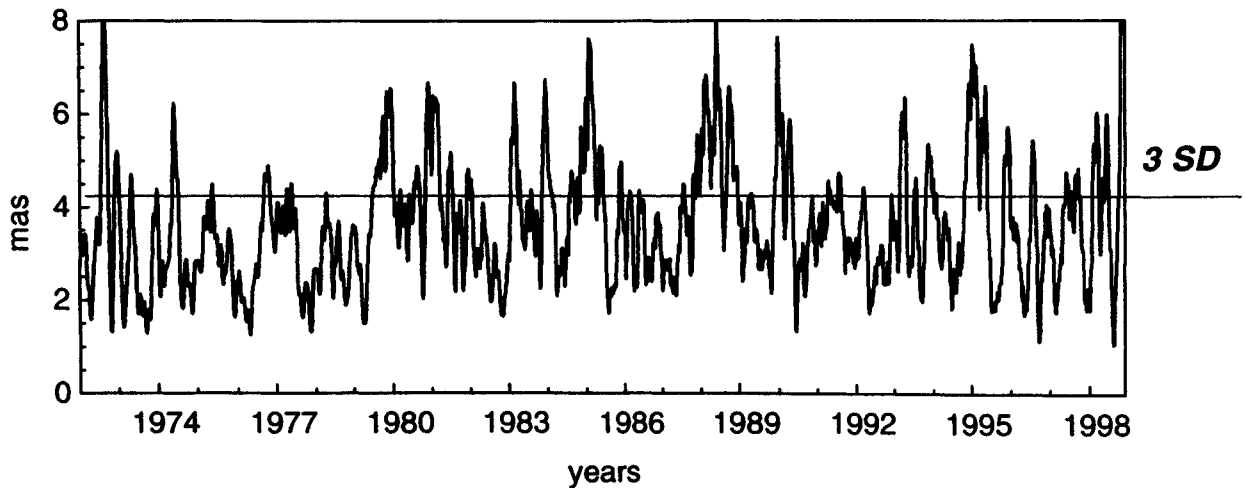


Fig. 2. The smoothed 30 point average, absolute value of the difference between x IERS (97 CO4) filtered by the Butterworth HPF with the cut-off period of 270 days and its autocovariance 14-day prediction.

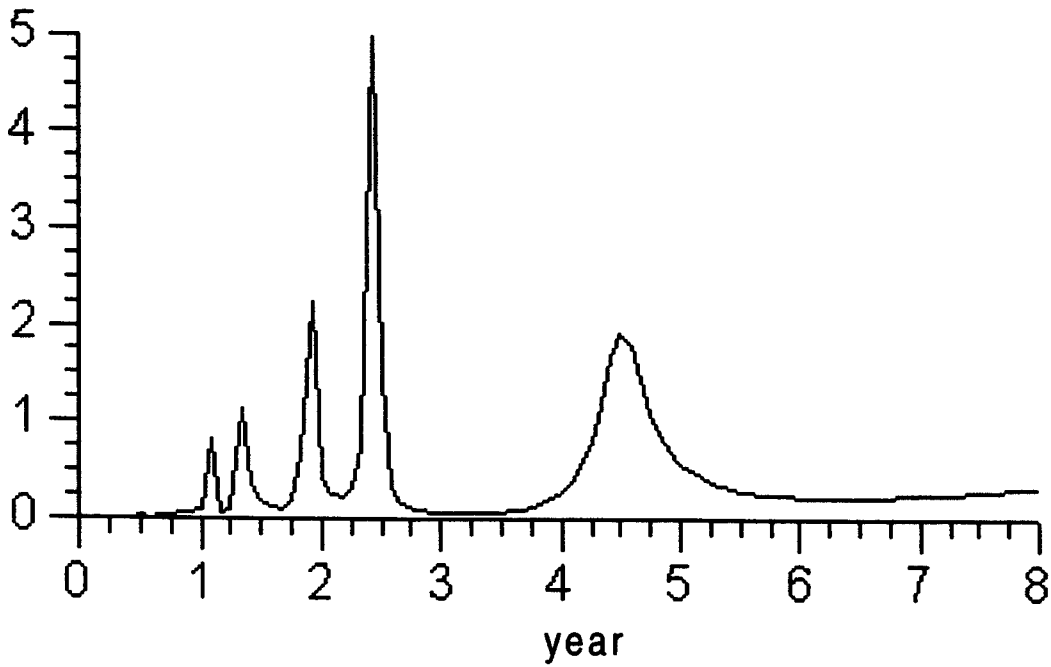


Fig. 3. MESA spectra of variations of correlation coefficients between atmospheric and geodetic excitation functions χ_2 , ψ_2 for the years 1975 - 1997 in the period range 20 - 150.

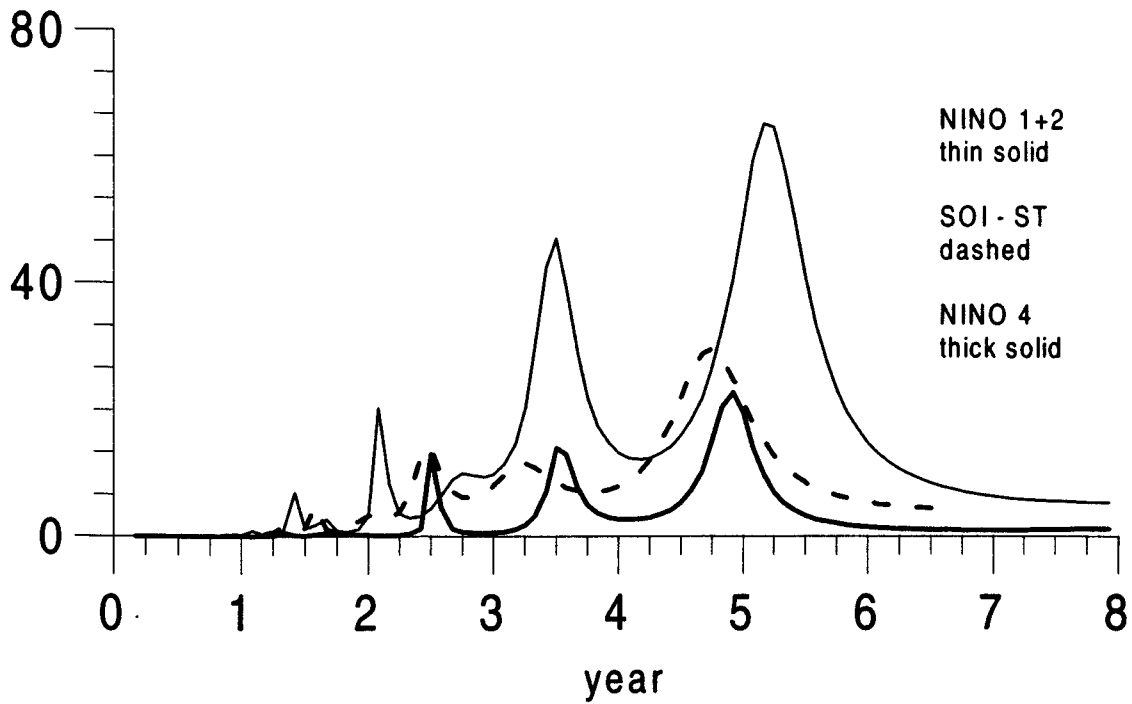


Fig. 4. MESA spectra of NINO and SOI data for the years 1975 - 1997.

THE 1997-1998 EL NIÑO EVENT: INSIGHT VIA SPACE GEODESY

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The impact of the 1997-1998 El Niño Southern Oscillation (ENSO) event is examined in context of angular momentum exchange utilizing length of day (LOD), Southern Oscillation Index (SOI) and Atmospheric Angular Momentum (AAM) (both global and latitudinally belted) data from 1970 to 1998. Comparisons are made with previous events.

The El Niño Southern Oscillation (ENSO), a climate fluctuation that recurs on a 2-7 yr. time scale, is associated with persistent large-scale variations in the dynamical behavior of the global atmosphere-ocean system. Comparisons between length of day (LOD) and the strength of the ENSO cycle, represented by the Southern Oscillation Index (SOI, the difference in sea level pressure between Darwin and Tahiti) have indicated striking agreement, with high interannual values of LOD generally coinciding with ENSO events [see *Chao*, 1984, 1988, 1989; *Dickey et al.*, 1992, 1993 and 1994, *Eubanks et al.*, 1986; *Gambis*, 1992, *Rosen et al.*, 1984, *Salstein and Rosen*, 1986]. During an ENSO event, the SOI reaches a minimum, leading to an increase in atmospheric angular momentum (AAM) associated with the collapse of the tropical easterlies. Further increases in AAM may result from a strengthening of westerly flow in the subtropical jet streams. Conservation of total angular momentum then requires the Earth's rate of rotation to slow down, thus increasing LOD.

The LOD series analyzed is the Jet Propulsion Laboratory (JPL) Kalman-filtered series, designated as COMB97 [*Gross et al.*, 1998], which is derived from a Kalman filter-based combination of independent Earth rotation measurements utilizing the techniques of optical astrometry, very long baseline interferometry (VLBI) and lunar laser ranging (LLR). For the SOI, we use a modified version of the Southern Oscillation Index based on Tahiti and Darwin sea level pressure (SLP) data provided by the National Center for Environmental Prediction. The time series is obtained by first removing the annual cycle (this is done by subtracting from both series the mean SLP value at that location for the corresponding month), dividing the monthly anomalies so obtained by the corresponding standard derivation, and then taking the Darwin-minus-Tahiti differences. Note the series used here, the "Modified Southern Oscillation Index" (MSOI), is opposite in sign to that which is commonly used [e.g., *Trenberth and Shea*, 1987], so as to be positively correlated with the LOD (see Fig. 1). For the atmospheric angular momentum, National Center for Environmental Prediction (NCEP) Reanalyses for the period 1970 - 1998 [*Kalnay et al.*, 1996] are investigated.

The focus of this note is the most recent ENSO event. With this goal, it is imperative that a method be developed to extract the longer term decadal signal and the dominant seasonal terms

from all series. A composite annual cycle is removed from both the LOD and AAM, as was done for the MSOI. The decadal variability is obtained by taking the difference between the LOD and AAM (with composite seasonal cycle removed) and approximating its longer term behavior with the leading dominant modes as determined by singular spectrum analysis (SSA -- see *Vautard and Ghil, 1991*). The residual series of LOD with the composite annual cycle and decadal signal removed shows both strong interannual as well as intraseasonal variability, and is compared with the AAM and MSOI in Fig. 1. Similarity among the three series is striking, with strong peaks evident in 1982-83 and during the recent event. All three series had a sharp rise in early 1997, with maxima still evident in the latest values shown.

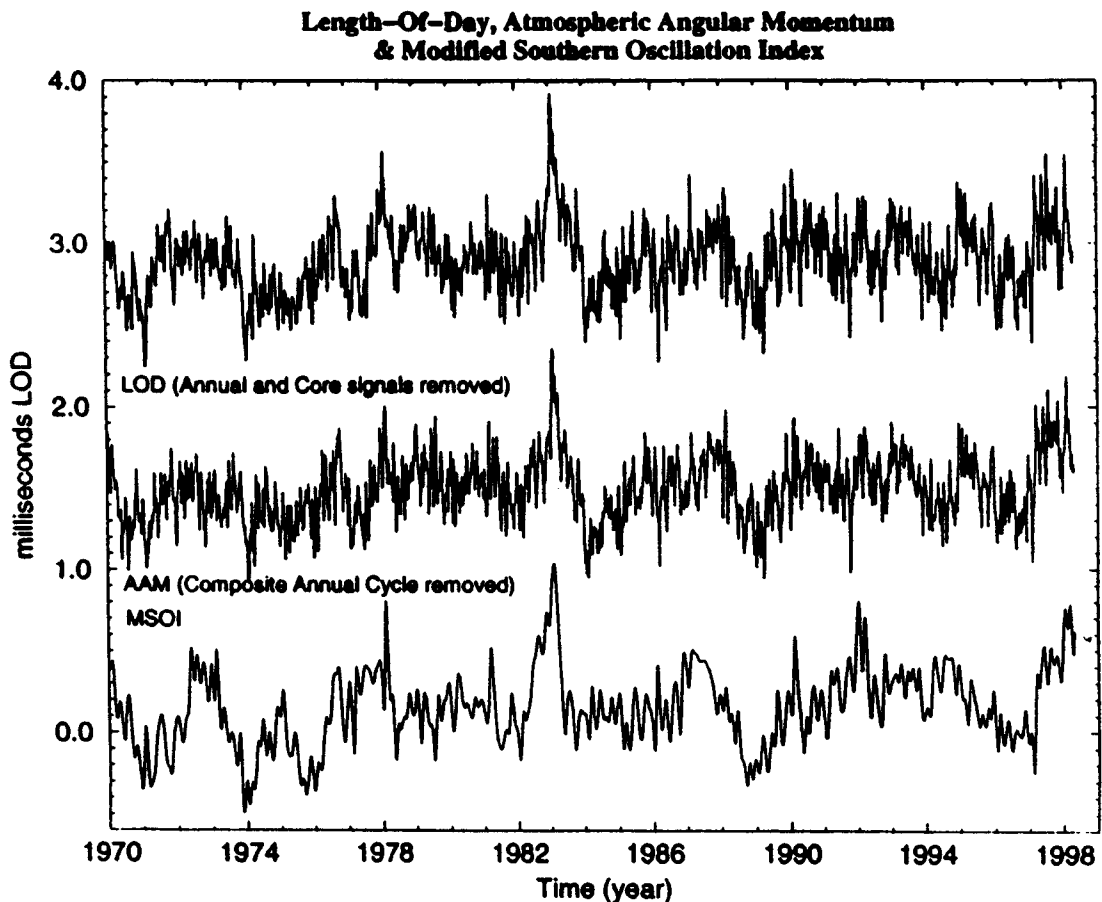


Fig. 1 A comparison among LOD, AAM, and MSOI (top, middle and bottom curves, respectively). The strong 1982-83 and 1997-98 ENSO events are clearly evident.

Additional insight into the origin of interannual rotational fluctuations can be gained through the examination of the latitudinal structure of the associated atmospheric variation [*Dickey et al., 1992* and *Black et al., 1996*]. The AAM obtained by integrating atmospheric data up to 100 mb over 46 equal-area belts is considered, with interannual variations obtained using a recursive filter [*Murakami, 1979*] with three different bands: ENSO (20-65 months), low frequency (LF - 35-65 months), and the quasi-biennial (QB --20-36 months) bands (see Fig. 2). The resulting pattern of interannual variability is evident, with V-like structures emerging from the tropics and propagating poleward.

Atmospheric Angular Momentum

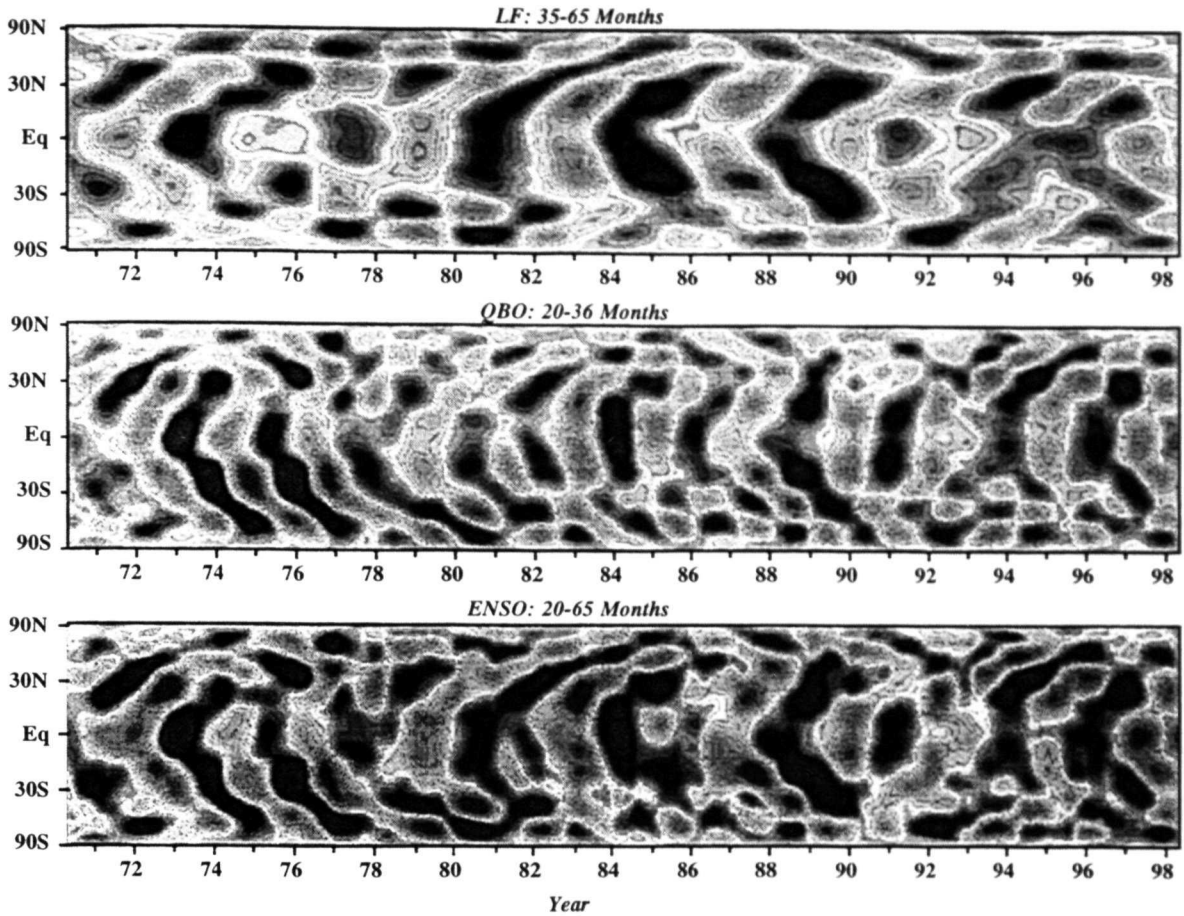


Fig. 2 Latitude-time (Hovmöller) plot of interannual atmospheric angular-momentum variations. We use the NCEP reanalysis series integrated over 46 separate equal-area latitude bands, based on atmospheric wind data up to 100 mbar. Interannual variations are obtained by recursive-filtering in the three interannual bands: the ENSO (20-65 months) band; the low-frequency (LF) band (35-65 months); and the quasibiennial (QB) band (20-36 months). Regions with darker shades represent easterly AAM anomalies and lighter shades represent westerly AAM anomalies.

The 1982-1983 event is associated with positive AAM (that is anomalous eastward winds) beginning at the equator in late 1980/early 1981 and propagating to high latitudes in both hemispheres over the course of several years. During the mature phase of the ENSO event (mid-1982 to mid-1983), strong positive anomalies are located in the northern subtropics with moderate anomalies in the southern subtropics. These anomalies diminish in strength and propagate poleward as the ENSO events decays. A similar scenario can be seen for the 1986-87 event, with strong modulation on the QB time scale [Dickey *et al.*, 1992]. The strong ENSO events in 1972-73, 1982-83 and 1997-98 are especially robust in the LF band, compared with additional episodes in 1977 and 1987. The complex multi-year events in the early 1990's have features visible in both the QB and LF bands.

For the most recent event, a V-like structure is visible in all three bands; activity began in the summer of 1996 in the LF band and in late 1996 in the QB band. Constructive interference is evident in the ENSO band with strong tropical activity in early 1997 propagating poleward to produce enhanced activity in the mid-latitudes in late 1997/early 1998. Already in late 1997/early 1998, signs of the coming La Niña event are evident, with easterlies developing in the tropics. Unlike the 1982-83 event, which had a dominant maximum in the northern hemisphere mid-latitudes, the current event has its strongest activity in the tropics, and is more comparable in its latitudinal development to the 1972-73 event.

ACKNOWLEDGEMENTS

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ANGULAR MOMENTUM AND TORQUES DURING THE 1982-83 EL NIÑO

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In January 1983, during the mature phase of the major 1982-83 El Niño event, atmospheric angular momentum (AAM), or more precisely its relative component M_r associated with the zonal circulation, reached the highest values on record (Rosen et al. 1994). From angular momentum conservation principles, the observed positive anomalies in M_r implied a source of AAM at the lower boundary. Mechanisms available for AM exchanges include the friction torque T_f , associated with tangential stresses at the lower surface, and the mountain torque T_m , related to pressure gradients acting on topography (e.g., Ponte et al. 1994). Wolf and Smith (1987), based on a limited pressure dataset, concluded that mountain torques on the Rockies were responsible for the sharp rise in M_r during January 1983, but they could not explain the subsequent decay of M_r values to normal levels. Ponte et al. (1994), based on output from climate model simulations of the 1982-82 El Niño, found both T_f and T_m to be important in general, but differences in the details of simulated and observed AAM evolutions precluded definite conclusions on the nature of the AAM transfers.

Using recently available M_r estimates based on the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Salstein and Rosen 1997) and a concurrent torque dataset produced by K. Weickmann and his group at NOAA's Climate Diagnostics Center in Boulder (Huang et al. 1999), we have reexamined the AAM evolution during the 1982-83 El Niño, with a focus on determining the torque mechanisms involved in the AAM anomalous behavior. Values of M_r , T_f , and T_m for the El Niño period (June 1982-June 1983) are shown in Figure 1, together with their respective climatological values obtained by averaging 29 years of data (1968-96).

Anomalies in M_r are mostly positive for the period examined, but they more than double in amplitude during a rapid, 2-week increase in mid January 1983. Values of M_r in late January 1983 are more than 3 standard deviations above climatological levels for the period. After reaching its peak value, M_r gradually decreases to near normal values by April 1983. The anomalous torque mechanisms responsible for this behavior can be discerned by examining the time series of T_f and T_m in Figure 1. Anomalies in T_m change sign on weekly or shorter time scales. There is, however, an approximate 2-week period with sustained large positive anomalies that coincides with the January rise in M_r . Anomalies in T_f are mostly positive for this period, but substantially weaker than those in T_m . In contrast, the decrease of M_r to near normal values by April 1983 is clearly related to sustained negative anomalies in T_f .

The complex interplay of torque mechanisms apparent in Figure 1 is explored in greater detail by Ponte and Rosen (1999). In particular, their regional analysis of the torque data confirms the importance of mountain torques on the Rockies to the January 1983 increase in AAM, as seen by Wolf and Smith (1987), but finds evidence for equally important contributions from mountain torques on Eurasian topography. Similarly, the negative anomalies in T_f responsible for the decay of M_r from February to April are mainly due to signals in the northern subtropics. A discussion of the relation between

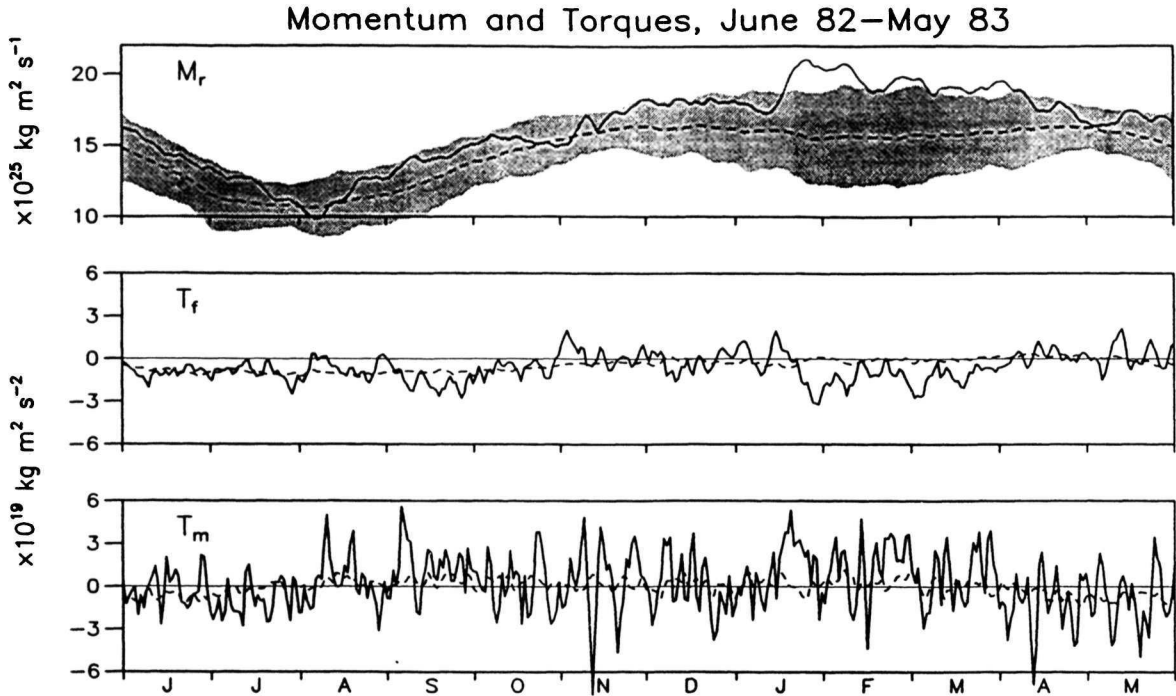


Figure 1. Time series of daily averaged M_r , T_f , and T_m , from top to bottom, displayed as solid lines, for the 1-year period starting on June 1, 1982, together with respective climatological means plotted as dashed lines. Shading around mean M_r curve represents anomalies smaller than ± 2 standard deviations.

M_r and torque anomalies and the general state of the atmosphere during the 1982–83 El Niño is provided in Ponte and Rosen (1999). A comparison of the 1982–83 El Niño event to the most recent 1997–98 event should prove useful in establishing any potential common aspects of the evolution of AAM during the strongest two El Niño events of recent decades.

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FLUCTUATIONS OF THE EARTH ROTATION AND EL NINO EVENTS

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1. MOTIVATION

We investigate the characterization of nonlinear low dimensional deterministic processes in the rapid fluctuations of Earth Rotation. We then analyze their intrinsic stability by computing the associated global and local Lyapunov exponents.. We see how the variations of that stability are related to El Niño phenomena.

The first step of our work is to apply nonlinear time series analysis techniques to daily observations $x(t)$ of the length of day (LOD) and polar motion components (PMX, PMY) spanning over more than 27 years and filtered so to keep the period range $[\approx 2day - 100days]$. Using time delay coordinates, we embed each EOP time series in a low dimensional pseudo-phase space. The dimensional and stability characteristics of the underlying dynamical process (which induces the rapid fluctuations of the Earth rotation) are then extracted from the reconstructed orbit (see below). We decide to treat those time series in a new manner because, first of all, atmospheric and oceanic flows generate the main perturbations in the Earth's Orientation Parameters (EOP) for such periods (see e.g. Eubanks 1993). The dynamics of the oceanic/atmospheric system are nonlinear and exhibit chaotic attractors on various time scales (see e.g. Nicolis and Nicolis 1984, Tziperman et al. 1994). Thus we ask the question of the transmission of these interacting complex dynamics to the short term fluctuations of the Earth Rotation. More over, the power spectrum associated to each EOP time series analysed here, is broadband: a broadband spectrum is not only revelant of a high-dimensional noise process but is also typical of a nonlinear low dimensional chaotic process (ex: the Lorenz attractor, Ruelle 1991).

2. EMBEDDING

The main idea of the non-linear time series analysis is to take a univariate time series $x(t)$ and to build from it a multidimensional object (the attractor) embedded in a multidimensional space (the embedding space), (Takens 1981). From the geometrical properties of this object, we can recover dynamical properties of the underlying process which has generated the time series.

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Embedding time delays are obtained from the Average Mutual Information function (Fraser and Swinney 1986). They are of 10 days for *LOD*, 15 days for *PMX* and 18 days for *PMY*.

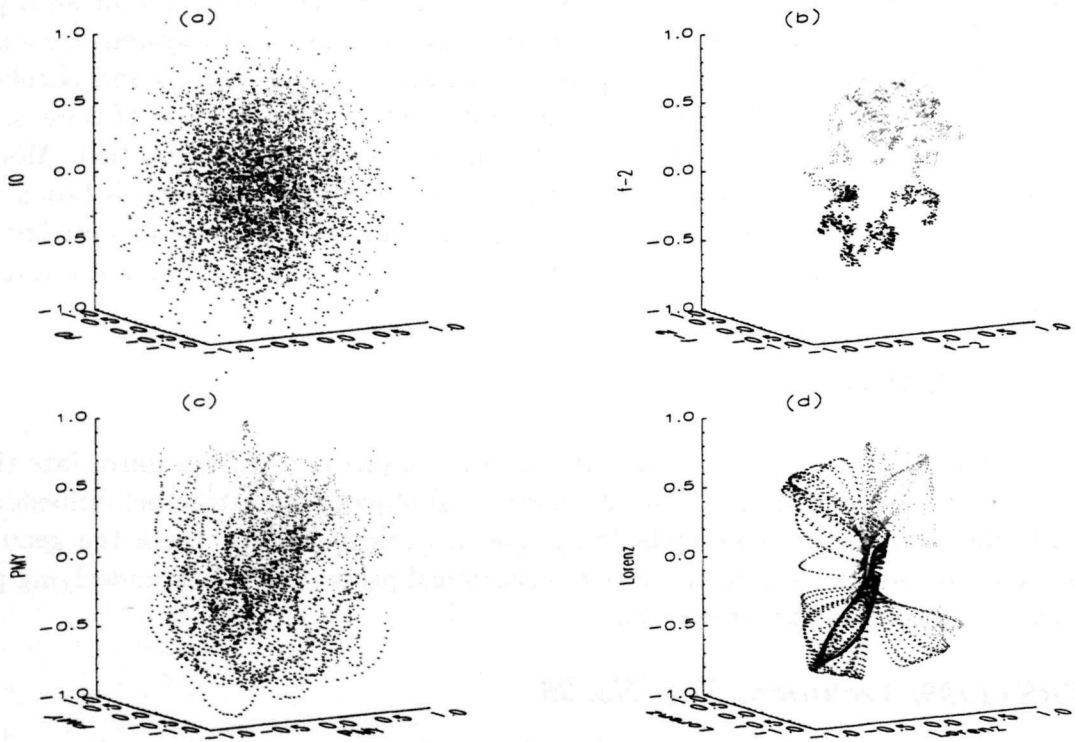
They are used to construct the multidimensional vectors with delayed coordinates:

$$\tilde{y}(t) = [x(t), x(t + \tau), \dots, x(t + (D_E^* - 1)\tau)] \quad (1)$$

The dimension of the embedding space, $D_E^* = 5 - 7$ is determined from both the percentage of global false neighbours and from the correlation integral methods (Grassberger and Procaccia 1983).

In order to have an idea about the phase space behaviour of the reconstructed systems, we draw 3D projections of delayed coordinates of the *EOP* data vectors; they are clearly different from stochastic power law noises (infinite dimensional processes) and seem to be issued from a smooth dynamical system.

Indeed the following figure shows the 3D projection of a 6-dimensional reconstruction of delayed vectors for : a) a time series of white noise, b) a time series of a random walk, d) a chaotic time series c) the time series of *PMY*. The results for *PMX* and *LOD* are similar. We clearly see the erratic distribution of points for the white noise, the fractal structure of the curves for the random walk and the continuous orbits for the chaotic system. For *PMY*, the orbits are continuous, self-crossing because the dimension required to unfold the attractor is superior to 3, (note the presence of noise in the centre of the figure). All these results can be found in details with complete discussion in Frede and Mazzega (1998a).



3. GLOBAL STABILITY ANALYSIS

The previous part of the analysis was devoted to dimensional characterizations of the *EOP* short terms fluctuations. A stability characteristics of the underlying dynamics can also be drawn from the embedded time series. This analysis recovers the development of instabilities in the system and puts hard bounds on the time interval over which it is impossible to reliably predict the system evolution (whatever might be the method used for such prediction). First of all, the dynamical dimension indicates the exact number of active dynamical variables of the system and also gives the number of Lyapunov exponents to be determined.

Using a local false neighbours algorithm (Abarbanel and Kennel 1993) and an analysis of the data local covariance matrix eigen-spectrum, we find a local dimension $D_L = 5$ for the three *EOP* series.

The global Lyapunov exponents are indicators of the system stability. They are calculated from the eigen values of the jacobian matrix along the orbit (Abarbanel 1996). They measure the rate of contraction or expansion of an orbit perturbation taken on a local eigen-direction of the system dynamics (see below). A negative exponent implies a contraction of the orbit perturbation lying on the corresponding stable manifold. On the contrary if the system possesses at least one positive Lyapunov exponent λ_i , its time evolution is sensitive to the choice of initial conditions in a particular direction. Any small perturbation $\delta(0)$ exerted on the orbit at $t = 0$ along that direction grows exponentially with time, so that:

$$\delta(t) = \delta(0)exp(\lambda_i t) \quad (2)$$

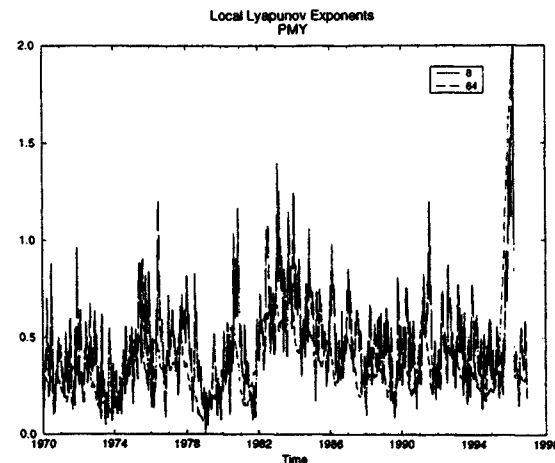
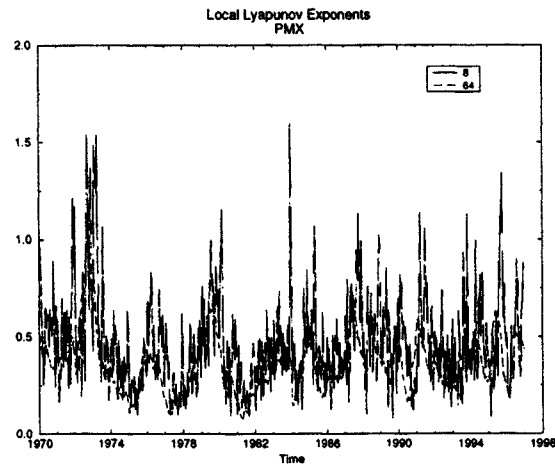
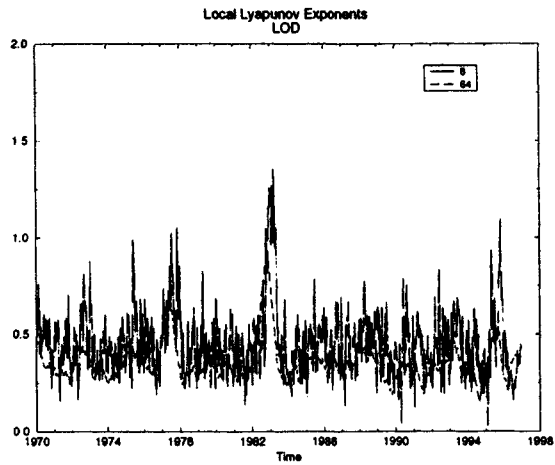
A zero Lyapunov exponent is always associated with a continuous dynamical system (a flow). Indeed it corresponds to the absence of both contraction and expansion if the perturbation is exerted along the orbit itself (neutral manifold). Systems whose sum of the Lyapunov exponents is negative are dissipative. Any volume of the n-dimensional phase space will shrink with time, though some directions may remain unchanged (along neutral manifolds) or even stretch (along unstable manifolds). The existence of positive exponents is typical of the chaotic nature of the system regime. Perturbations taken "outside" from the attractor will be damped but two orbits will rapidly separate from each other on the attractor because of the unstability.

For each *EOP* time series, we found two negative exponents, a null one with an accuracy of five per cent and two positive exponents. The principal Lyapunov exponents averaged over 1970-1997 being positive, this result unambiguously indicates the chaotic nature of the Earth's rotational dynamical regime in this period range of fluctuations. As a consequence, some theoretical prediction horizons can not be passed beyond by any tentative forecast of the the *EOP* evolution. Horizons of 11.3 days for *LOD*, 8.7 days for *PMX* and 8.1 days for *PMY* are found beyond which prediction errors will be of the order of the *RMS* of the filtered *EOP* series.

4. LOCAL STABILITY ANALYSIS

The previous evaluations are global ones, but locally, there can exist variations of the stability induced by the own dynamics of the system or by external solicitations. The stability variations of the reconstructed orbits are analyzed by the determination of their local Lyapunov exponents. These exponents are computed from the eigenvalues of local jacobian matrices retrieved from the embedded *EOP* time series.

The following figure shows the Local Lyapunov exponents for a) *LOD*, b) *PMX* and c) *PMY* respectively. It is more exactly the temporal variations of the principal Lyapunov exponent.



We have chosen two windows for its evaluation: the first one of 8 days gives us the rapid fluctuations of stability while the 64 days gives us a sort of smoothing of the stability over 2 months. This is done to obtain a compromise between the noise level and short expected variations. We remark the same event appears earlier for the second window. This is due to the fact that on the one hand the algorithm evaluates 8 jacobian matrices while 64 on the other hand. So the same phenomena at a time t will be seen earlier in the second case (because of the larger window of the moving average).

We see that the Earth's rotational state experiences large changes in stability with regard to the average chaotic regime. Moreover the local prediction horizons, as deduced from the local Lyapunov exponents, occasionally drop down to about 3.3 days for *LOD* in the years 1982 - 1984, 2.6 days for *PMX* in 1972-1973 and 2.6 days for *PMY* in 1996-1997. The main momentary stability perturbations of the Earth rotation are clearly related to El Niño and La Niña events (e.g. 1982-1984, 1972-1973). The 1996 loss in stability for the *PMY* lacks an obvious source mechanism.

This means that the observed loss of predictability of the Earth Orientation Parameters is directly related to the stability loss of the ocean/atmospheric system.

We must keep in mind that it is not surprising that a same El Niño does not have the same effect on the 3 *EOP* time series stability, the stability of a system depending on the system state. More over another source of excitation may happen at the same time masking partially an El Niño forcing. We musn't confuse the time series itself with the time series of the stability variations. Here we are not looking at the correlation between El Niño events and the *EOP* time series but at the repercution in term of predictability of geophysical forcings on the short term fluctuations (less than 100 days) of the *EOP*. The following table gives dates of events and associated horizons of prediction (in days) for the *EOP* time series (see Frede and Mazzega (1998b) for more details).

Series	LOD	PMX	PMY
Date of events			
1972-73	7.8	3.3	10.2
1976-77	11.8	7.8	7.8
1977-78	5.6	19.5	6.5
1979-80	11.8	5.2	10.2
1982-84	2.7	9.8	4.9
1987-88	11.8	6.5	7.8
1991-92	11.8	5.6	4.9
1995-97	6.5	4.3	1.9
Global mean values	11.8	11.5	10.2

5. CONCLUSION

Dimensional and dynamical characteristics of the nonlinear processes inducing the rapid fluctuations of the Earth rotation have been extracted from the *LOD* and Polar Motion filtered time series. It is in particular shown that some instabilities develop in the Earth rotation under a chaotic regime. Moreover these instabilities are magnified in those period of ENSO activity of the ocean-atmosphere system. As a consequence, the horizon of predictability of the *EOP* time series in this frequency band, is limited to 10-12 days in the average but to only 2-3 days when El Niño and La Niña events perturb the Earth rotation. It will be interesting to perform the same analysis when longer and more precise *EOP* time series are available and look then at the repercution of the 1997-1998 recent El Niño on the *EOP* stability.

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TROPICAL PACIFIC OCEAN LONG WAVES CONTRIBUTION TO LENGTH OF DAY DURING ENSO IN 1980-1997

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1. INTRODUCTION

Theoretical studies showed in the early 80s that the low frequency variability associated with ENSO in the tropical Pacific ocean could be explained to a large extent by the contribution of long wavelength equatorial waves (Cane and Sarachik, 1981; Cane, 1984). Such predictions were only confirmed for the whole basin about 10 years later from observations, in particular, from altimetry. Thus, several authors used sea level data derived from satellite measurements to estimate the Kelvin and Rossby wave contributions in the tropical Pacific ocean (Delcroix et al., 1994; Boulanger and Menkes, 1995; P rigaud and Dewitte, 1996 [hereafter PD96]) and showed that they could explain to a large extent the observed thermocline displacements and zonal current low frequency variability.

Whereas the classical delayed oscillator theory (Schopf and Suarez, 1988) considers that the main source (sink) of heat during El Ni o (La Ni a) is due to the deepening (rising) of the thermocline depth in the eastern Pacific, recent studies have highlighted the importance of zonal advection in displacing the warm pool (Picaut and Delcroix, 1995) and consequently in warming or cooling of the eastern Pacific during ENSO (Picaut et al., 1997). This zonal displacement of a huge water mass associated with the oceanic zonal current raises the question of its impact on the Earth's length of day (LOD), which has been shown to have interannual variations similar to El Ni o since Stefanick (1982) and Chao (1984). Although the main share of the signal in LOD at interannual frequencies can be attributed to zonal winds variations (Eubanks, 1993), the study at these time scales of the effect of oceanic zonal currents, and especially the equatorial ocean variability has, for instance, not been undertaken and deserves special attention.

We propose in this study to estimate from the analysis of sea level observations the contribution of the interannual variability of the equatorial Pacific ocean to global angular momentum and to compare it to LOD and atmospheric angular momentum (AAM). We take advantage of a technique used to derived zonal current anomalies from sea level variations (PD96; Dewitte, 1998). Expendable Bathythermograph (XBT) measurements are used as a proxy of sea level over 1980-1998. Sea level data derived from TOPEX/POSEIDON are also used over the period September 1992-May 1998. We first present the data sets and briefly detail the computations and assumptions realized in the study. The last section is devoted to the analysis of the results.

2. DATA AND COMPUTATIONS

The XBT data set was provided by N. Smith from Bureau of Meteorology Research Center (see Smith et al. [1995]). Thermocline depth anomalies are estimated from the ocean heat content in the upper 400 meters as described in PD96. They are further converted into sea level anomalies assuming that the averaged thermocline depth is 150m and that the ocean vertical structure can be approximated to the first baroclinic mode. This latter assumption is necessary to carry on the computation (see PD96) and is to a large extent acceptable for the tropical Pacific (Zebiak and Cane, 1987). Anomalies are relative to the mean over the period January 1982-December 1995. Sea level anomalies are also derived from TOPEX/POSEIDON

measurements (provided and pre-processed by the University of Texas) over the period September 1992-May 1998. Anomalies are relative to the mean over the period January 1993-December 1996.

The length of day (LOD) data from January 1982 to December 1997 on a mean monthly basis was provided by IERS. The AAM data over the same time-span, up to 10 hPa, also on monthly means were computed from four time daily series derived from the reanalyses of NCEP/NCAR (Kalnay et al., 1996) from 1982 to 1983, as from JMA (Japan Meteorological Agency) daily AAM series from 1983 to 1997. Both series were provided by the Atmospheric Special Bureau for the Atmospheres of the IERS established jointly by AER and NOAA (Salstein et al., 1993). Before being compared to the Oceanic Angular Momentum (OAM) series the LOD and AAM series are seasonally filtered using the well-known X11 seasonal filter (Schip and Stier, 1995). Therefore in both series intraseasonal and interannual variability is kept.

Following PD96, sea level anomalies are projected at each longitude onto the meridional structures associated with the first baroclinic mode. The contributions of the Kelvin and the first meridional Rossby modes are derived. The surface baroclinic zonal current anomalies are reconstructed. For the TOPEX period, they differ very little from another estimation using a different technique (Delcroix et al., 1998). The vertical structure of currents and the phase speed are obtained from the vertical mode decomposition of an averaged equatorial density profile taken from a forced OGCM simulation of the tropical Pacific (Dewitte et al., 1998). The mean stratification of this simulation is in very good agreement with the Levitus data set at the equator, which would provide similar results for the first baroclinic vertical structure. The vertical structure is made zonally varying depending on the local stratification to take into account that the thermocline is tilted from west to east. Thus a measure of the overall strength of the zonal anomalous circulation in the equatorial Pacific is given by the relative oceanic angular momentum (OAM) about the rotation axis relative to Earth's surface

$$OAM = \frac{R^3}{g} \int_{x_1}^{x_2} \int_{y_1}^{y_2} \int_{z_1}^{z_2} u(x, y) \cdot F(x, z) \cos^2(y) dx dy dz$$

where R is the radius of the Earth, g the acceleration due to gravity, $u(x, y)$ the surface zonal current anomalies, $F(x, z)$ the first baroclinic mode vertical structure, with the integral performed between $x_1=140^\circ\text{E}$ and $x_2=270^\circ\text{E}$, $y_1=10^\circ\text{S}$ and $y_2=10^\circ\text{N}$, and $z_1=0\text{m}$ and $z_2=600\text{m}$. Note that for $z_2>600\text{m}$, $F(x, y)$ is very small and OAM is almost unchanged if the integration is performed up to the ocean bottom.

3. THE RESULTS

Figure 1A presents the difference between LOD and AAM (LOD-AAM). The residual presents intraseasonal and important quasibiennial and quadrennial periods (spectra not shown). Figure 1B presents the OAM anomaly from seasonal climatology time series derived from the XBT and TOPEX data. The OAM series are the total variability from both Kelvin and Rossby waves, but with the Kelvin waves contributing up to 80% of the total variance (not shown). The OAM time series is characterized by a large interannual variability associated with ENSO because the derived zonal current anomalies are themselves strongly correlated to ENSO (Delcroix et al., 1994, DP96). The residual and OAM anomalies are on the same order of magnitude, suggesting that the tropical Pacific Ocean contributes significantly to the closure of the global oceanic angular momentum budget. This is consistent with a recent study based on model outputs (Marcus et al., 1998). To get rid of the intraseasonal variability that is much larger in the atmosphere than in the ocean and in order to extract contributions to the interannual variability in the quasibiennial and quadrennial time scales, we respectively band pass the series on two frequency bands: 1.2 to 2.8 years and 2.8 to 5 years. The results are

presented respectively in the OAM series in Figure 1C and Figure 1D, and they are compared with the residual between the LOD and AAM series there.

The amplitude is on the same order of magnitude for both frequency bands, with a correlation at the 45% level (above the 90% level of significance) for the quasibiennial signals (Figure 1C). Of particular interest is the main agreement of both curves during El Niño 1997. Although the curves are generally slightly phase shifted over 1982 to 1986, they are often in phase after. The main reason for this may be due to that the XBT data prior to 1986 are quite sparse and this results in a larger uncertainty onto the derived zonal current anomalies.

The agreement of the amplitudes is encouraging, mostly because the OAM is here only computed from latitudes going from 15°S to 15°N. Therefore the quasibiennial oscillation in OAM must have a significant variability along the equator. Consequently in the quadrennial band an important variability must also arise from the tropics.

Figure 1B presents also the OAM calculated using the availability of high quality TOPEX/Poseidon satellite measurements of sea level variability. Over the overlapping period (September 1992 to December 1997), both signals are highly correlated, encouraging to use XBT data for OAM computation.

4. CONCLUSIONS

The contribution of the equatorial Pacific low frequency current variability to the global angular momentum of the Earth-atmosphere-ocean system was estimated from observations. Although LOD and AAM at interannual time scales are highly correlated, their difference presents quasibiennial and quadrennial periods. The oceanic angular momentum calculated from the equatorial Pacific Ocean is shown to have the same order of magnitude as the LOD-AAM residual. Although other tropical oceans are not considered, their interannual variability is much less and is then unlikely to significantly alter our result. Note also that it is much more difficult to derive zonal current from observations in the other tropical oceans. However although this estimation is largely dependent onto the approximations made to derive the oceanic zonal current anomalies (mostly the one baroclinic mode approximation), the result suggests a large impact of the upper oceanic variability in the tropics associated to ENSO onto the LOD. The correlation at the quasibiennial period is highly promising, since the quasibiennial period plays an important and complex role on LOD at interannual time scales. Although the OAM must be computed using all the oceanic variability, the tropical Pacific Ocean variability is shown here to be playing a dominant role at interannual time scales.

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FIGURE CAPTIONS:

Figure 1a: Difference between length of day (LOD) and atmospheric angular momentum (AAM). The data have first been seasonally filtered. Unit in Milliseconds (ms).

Figure 1b: Oceanic Angular Momentum (OAM) calculated from XBT data (dashed line) and Topex Poseidon data (solid line). Units in milliseconds (ms).

Figure 1c: Comparison at the quasibiennial band (1.2 to 2.8 years) of LOD-AAM residual (solid line) and OAM from XBT data (dashed line). Units in milliseconds (ms).

Figure 1d: Comparison at the quadrennial band (2.8 to 5 years) of LOD-AAM residual (solid line) and OAM from XBT data (dashed line). Units in milliseconds (ms).

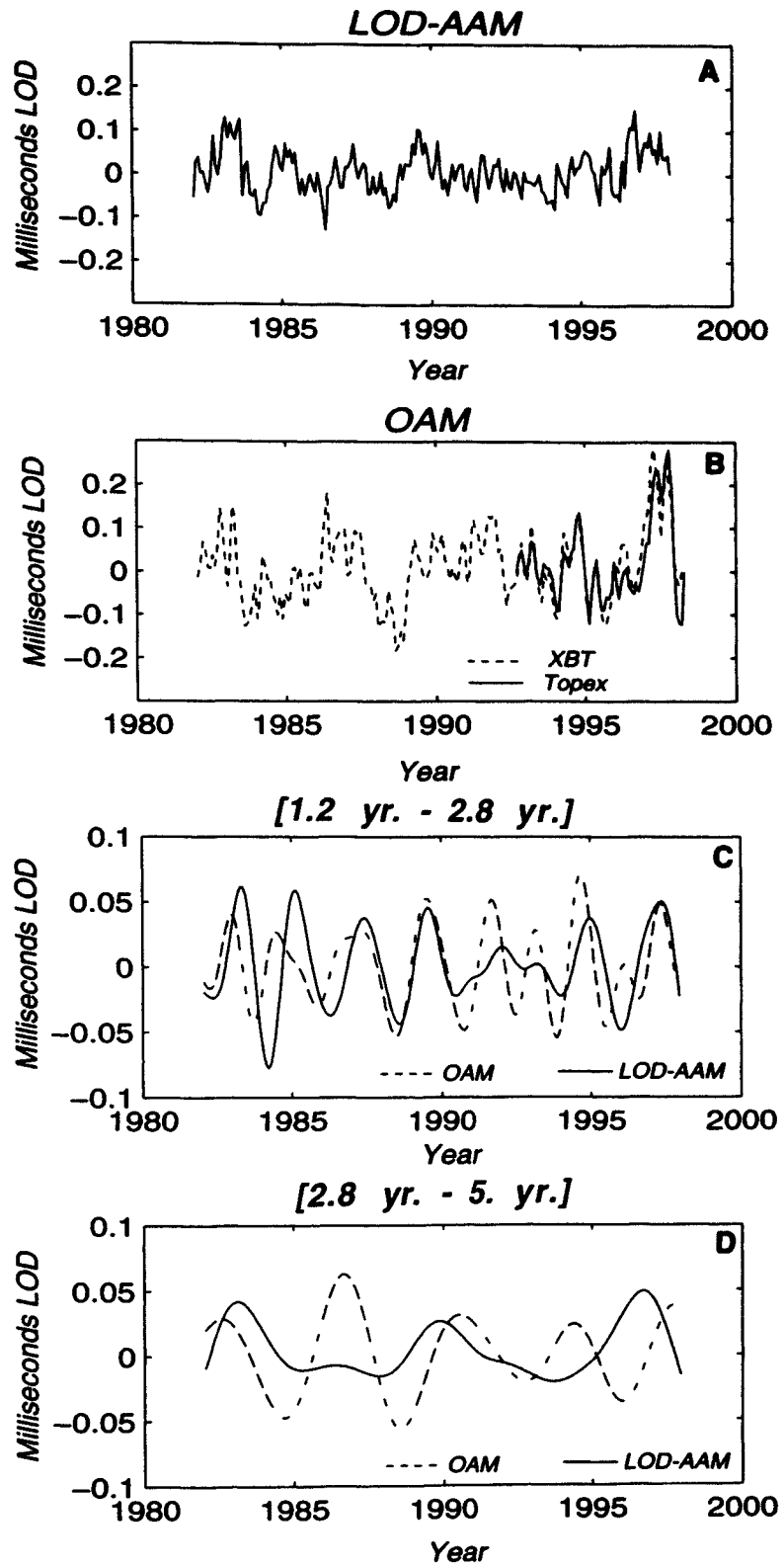


Fig. 1

EL NIÑO SIGNAL IN LOCAL AND GLOBAL ATMOSPHERIC TORQUES

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1. INTRODUCTION

The atmosphere exchanges angular momentum with the solid Earth, inducing changes in the Earth's orientation parameters (e.g., Burnes et al., 1983) and in the Earth's rotation by means of interaction torques. Those torques are due to the pressure acting upon both the topography and on the Earth's bulge, to the gravitational attraction between the masses of the solid Earth and the atmosphere, and to frictional forces related to the wind stress in the atmosphere. Here we wish to determine if the presence of an El Niño event has an influence upon the various torques that effect the dynamic interactions between atmosphere and solid Earth.

In de Viron et al. (1998), the mathematical expression of the pressure and the gravitational torque are given. It is shown that only the effect of the bulge of the potential induce a non negligible torque. The gravitational torque induced by the flattening of the potential is proportional to the pressure torque on the equatorial bulge. So, the analysis of the gravitational torque will not give additional information, and will not be considered here.

We have investigated the three quantities for the equatorial components (related to polar motion). In this case we compute the pressure torque on the local topography, the friction torque, and the pressure torque on the Earth's bulge. For the axial component (related to length of day fluctuations) we only compute the pressure torque on the local topography and the friction torque because the bulge will not induce an effect for this component.

We have computed torques between 01 March 1980 and 30 November 1995 from the surface data of the NASA Goddard Earth Observing System Data Assimilation System (GEOS-1 DAS; Schubert et al., 1993). During this study period, four different El Niño events occurred. The subject of this paper is to observe torques during the El Niño periods, and to determine if they are significantly different from other events.

2. DATA ANALYSIS

To see if the torque presents abnormal variation during an El Niño event, we have computed the mean variance of the torque as a function of the day in the year. We have drawn separately the mean variance during El Niño years and non-El Niño years for the X and Y components (polar motion) in Figs. 1 and 2 and for the Z component (length of day) in Fig. 3.

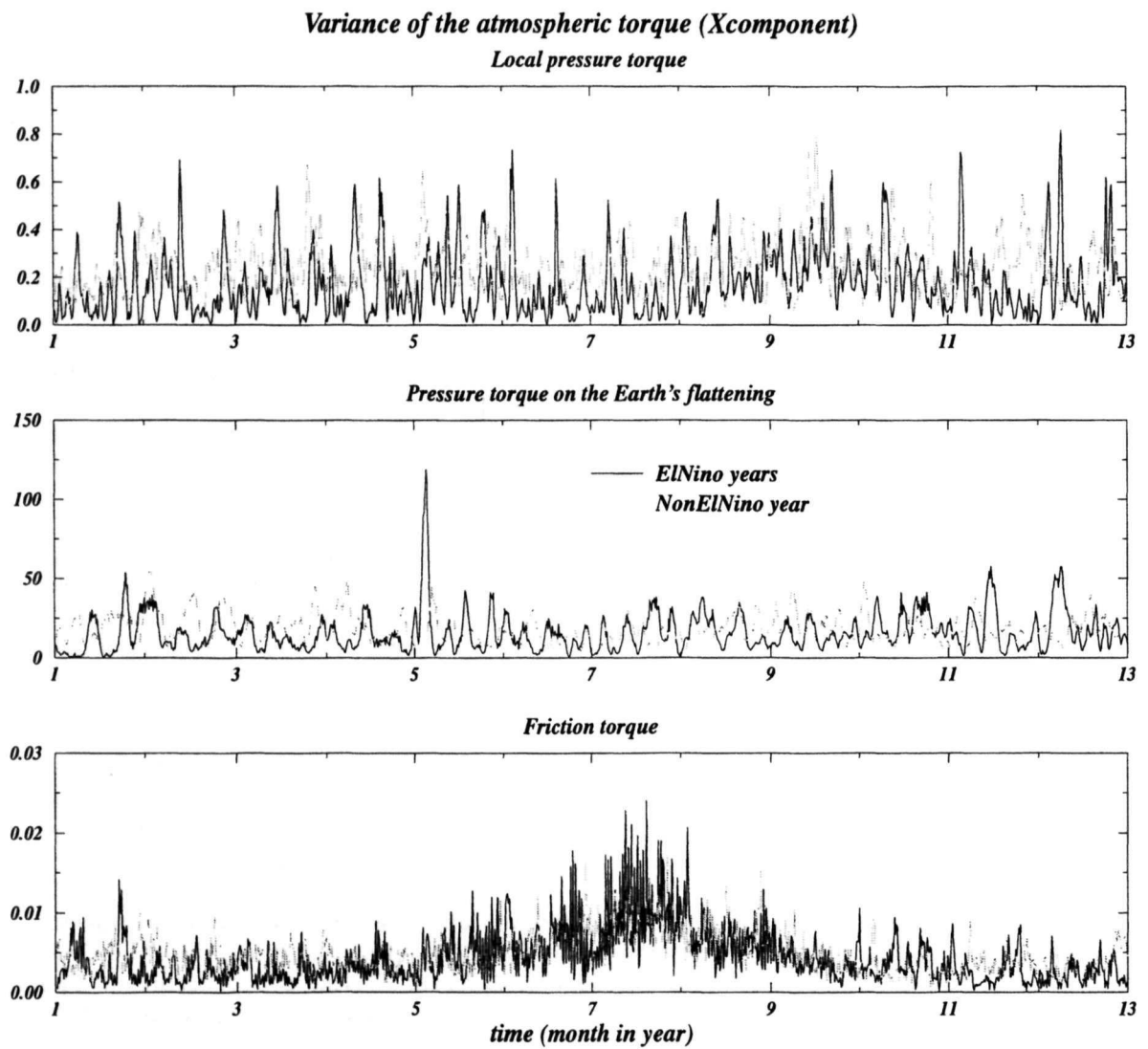
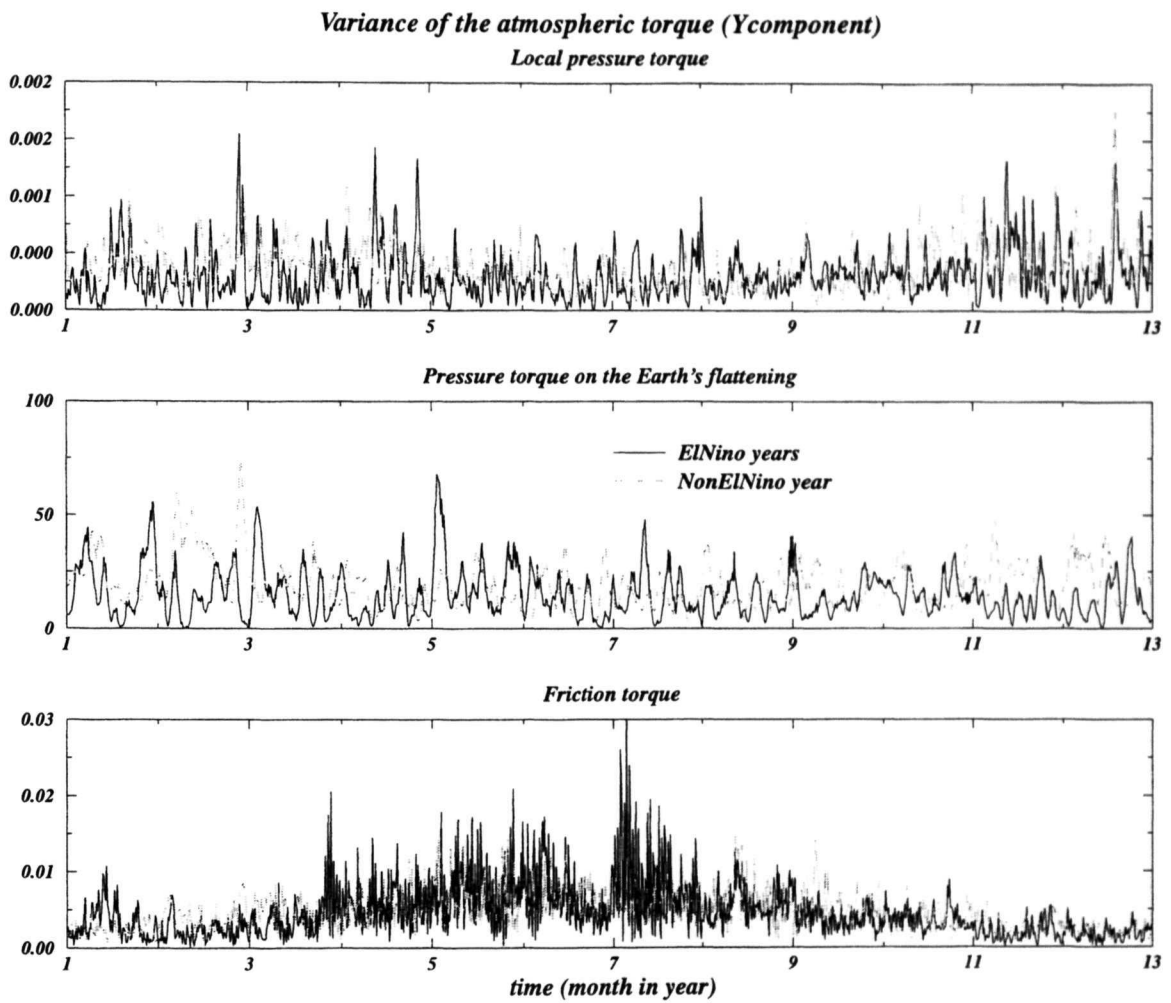


Fig. 1

**Fig. 2**

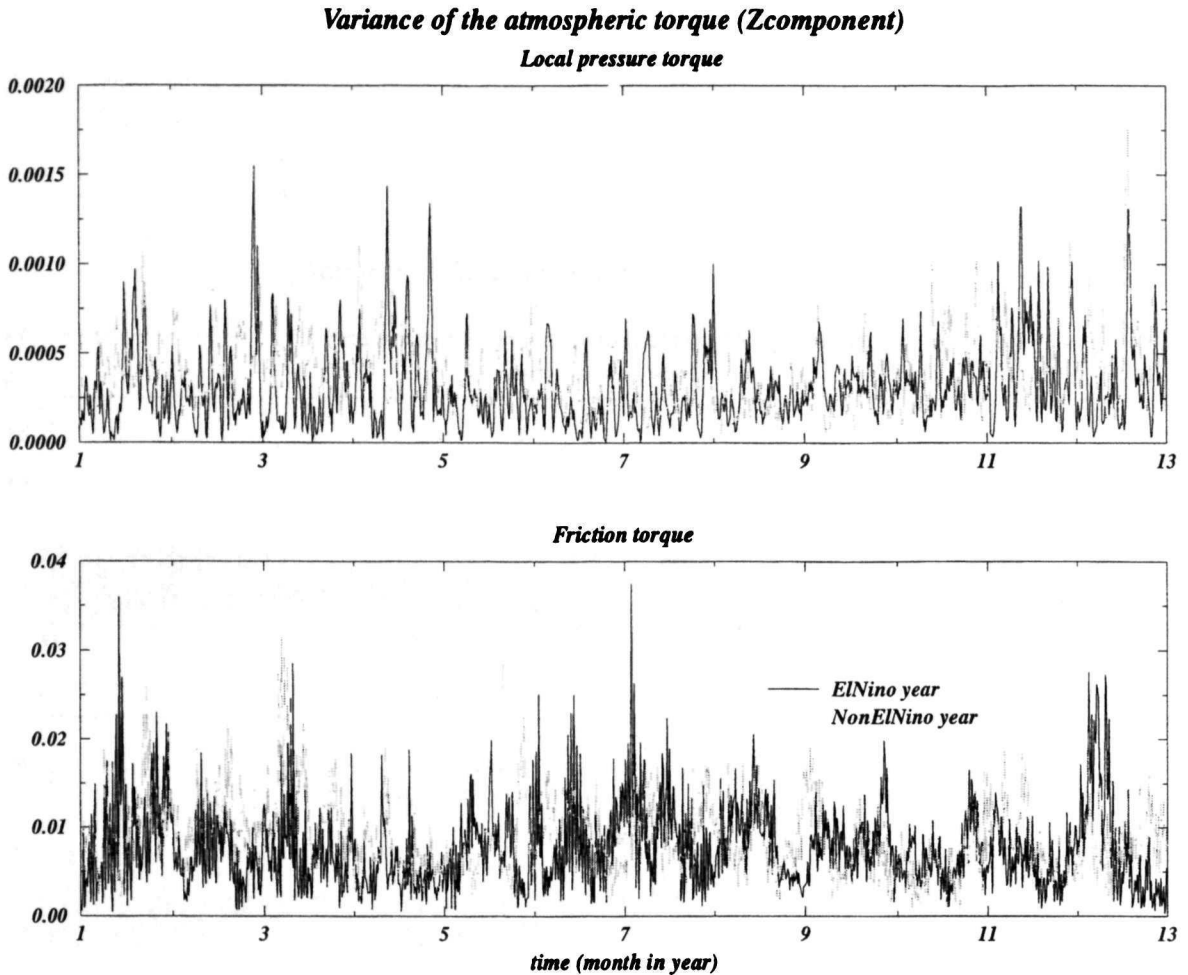


Fig. 3

In Figs. 1, 2, and 3, we can see that there are some peaks in the variance of the pressure torques, but these peaks show little distinction between years with and without an El Niño event.

It seems that the El Niño event does not produce a large anomaly in the equatorial pressure torques, both in local (pressure on local topography) and in global (pressure on ellipticity) forcing of the Earth. For the friction torques it is different; indeed the variations in the friction torque are much larger during the El Niño years than during the others, mostly during Northern Hemisphere summer (July and August).

3. CONCLUSION

There is no particular signal due to the El Niño event in the pressure torques, but El Niño seems to produce abnormally large values of the friction torque in all the three components. However, the friction torque is non-negligible only for the axial component.

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ATMOSPHERIC-OCEANIC INFLUENCE ON INTERANNUAL LENGTH-OF-DAY VARIABILITY LINKED TO EL NIÑO/SOUTHERN OSCILLATION

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Variations in the rotation rate of the Earth, or equivalently in LOD (Length-Of-Day), consist in a number of free and forced oscillations superimposed on a "red noise" background (Eubanks, 1993). They are important quantities closely related to many geophysical phenomena. On a time scale longer than or about 10 years, it is usually accepted that the secular variation and the decade fluctuation are caused by core-mantle coupling and tidal energy dissipation (Lambeck, 1980).

On time scale of about one year and shorter, the seasonal and short-term variations (including annual and semiannual components) have been established beyond any doubt to be caused by meteorological and solar lunar tidal effects. Many authors (Barnes et al., 1983, Rosen and Salstein; 1983, Chao, 1988, 1989; Dickey, 1989,1993) have been confirmed the relationship between seasonal LOD variations and variations in the polar component of the atmospheric angular momentum.

A less studied spectral band takes into account LOD variations in the time scales shorter than 10 years and longer than 1 year. These kinds of variations are usually called interannual components. It is well accepted that they are linked to El Niño–Southern Oscillation (ENSO) atmospheric global-scale events (Stefanick, 1982; Chao, 1984).

El Niño (EN) effect historically refers to a massive warming of the coastal waters of Peru and Ecuador. Unusual warm temperatures in the equatorial Pacific Ocean characterize it.

In normal non-El Niño conditions cool water is typically observed in the eastern part of the tropical Pacific Ocean (phenomenon called "cold tongue").

Cold tongue temperatures vary seasonally being warmest in the northern hemisphere springtime and coolest in the northern hemisphere fall. El Niño can be thought as an exaggeration of the usual seasonal cycle (TAO project, 1998).

During typical El Niño conditions, warm water spread from the eastern Pacific Ocean towards the east (in direction to South America). The "cold tongue " became weak and the usually weak winds in the western Pacific blow strongly towards the east pushing the warm water (TAO Project, 1998).

El Niño phenomenon is fairly well known since long time ago, however the atmospheric component of ENSO phenomenon, the Southern Oscillation, is a recent discovery. Specifically, this effect consists in an oscillation in surface temperature between southeastern tropical Pacific and Australian-Indonesian regions (Cane, 1992).

The Southern Oscillation Index (SOI) is a measure of the strength of tropical Pacific atmospheric circulation, based on sea level pressure difference between Tahiti (French Polynesia) and Darwin (Australia). Low SOI is associated with weaker than normal trade winds and El Niño conditions (Chao, 1984; TAO Project, 1998).

The strong connection between SOI and Sea Surface Temperature (SST) is immediately apparent: when the waters of the eastern tropical Pacific are abnormally warm (El Niño event) sea level pressure drops in the eastern Pacific and rises in the west (low SOI) (Cane, 1992).

Through MEM spectral analysis, we will be able to evince an unexpected feature of the ENSO phenomenon due to the presence of at least two La Niña episodes during the last

10 years. For that, the oceanic influence might cause a light departure in LOD variability from the classical 36-month period associated with the life cycle of individual atmospheric ENSO event (Black et al., 1996).

DESCRIPTION OF THE DATA

We utilized a 3811 days long LOD time series in the period January 1988 - June 1998 from the EOP C04, daily combined series of Earth Orientation Parameters from the IERS (International Earth Rotation Service). Our goal is an interannual LOD time series to examine empirically the relationship between ENSO and interannual LOD variations. To perform it, we removed well-known long and short-period variations trying do not damage the interannual signal as follows:

First at all, we removed the tidal effects produced by the gravitational attraction of the Sun and Moon predicted in the model of Yoder (Yoder et al., 1981). Nevertheless, annual and semiannual components are particularly strong and therefore hard to remove. Thus, we modeled long period (decade) and remaining seasonal variations as in LOD as a sum of sine functions. The parameters were estimated using a least-squares adjustment.

We then subtract from LODR time series the estimated sum obtained above. The resultant is called interannual LOD series. Finally, in order to perform the cross-spectral analysis, we averaged the interannual signal in monthly values.

Analysis were performed using SOI data as well as four regional SST data sets: El Niño 1+2 (SST1-2 in the successive) includes observational data from the area 0° to 10° S and 90° W to 80° W, El Niño 3 (SST 3) extends from 5° N to 5° S and 150° W to 90° W, El Niño 4 (SST4) takes the same belt in latitude but extends from 160° E to 150° W and finally El Niño 3.4 (SST 3.4) spans the area from 5° N to 5° S and 170° W to 120° W.

The SST and SOI series are provided by the Climate Prediction Center (CPC) of the National Center for Environmental Prediction (NCEP). They were taken along the same period as LOD but they provide only one data per month.

SPECTRAL ANALYSIS

The maximum entropy method for spectral analysis was first suggested by Burg in 1967. Its application to problems of geophysical and astronomical interest has met with considerable success due to the advantage of being able to find sharp spectral peaks where other classical methods fail (Andersen, 1974; Marple, 1987).

Since its outset, MEM has been a tool in the development of parametric or modeling approaches to high-resolution spectral estimation. The maximum entropy spectrum is very closely related to autoregressive (AR) spectral analysis. In fact, MEM and AR power spectral density are identical for Gaussian processes and a known autocorrelation sequence of uniform spacing (Marple, 1987).

The MEM estimates the power spectral density (PSD) function after determining a set of model coefficients based on a procedure to obtain AR spectral estimates.

When the appropriate AR model is not known, many different orders must be tried and compared for to select a suitable order. To carry it out, we compute the first error criterion developed by Akaike (1969) that indicates which model to choose. It is called final prediction error (FPE). According to the principle of parsimony, the order selected is the one for which FPE is minimum (Jones, 1976; Marple, 1987).

FPE criterion was used to search the wright order before applying MEM for power spectra estimation. The FPE plot as a function of the length of the autorregressive process involved is shown in Figure 1.

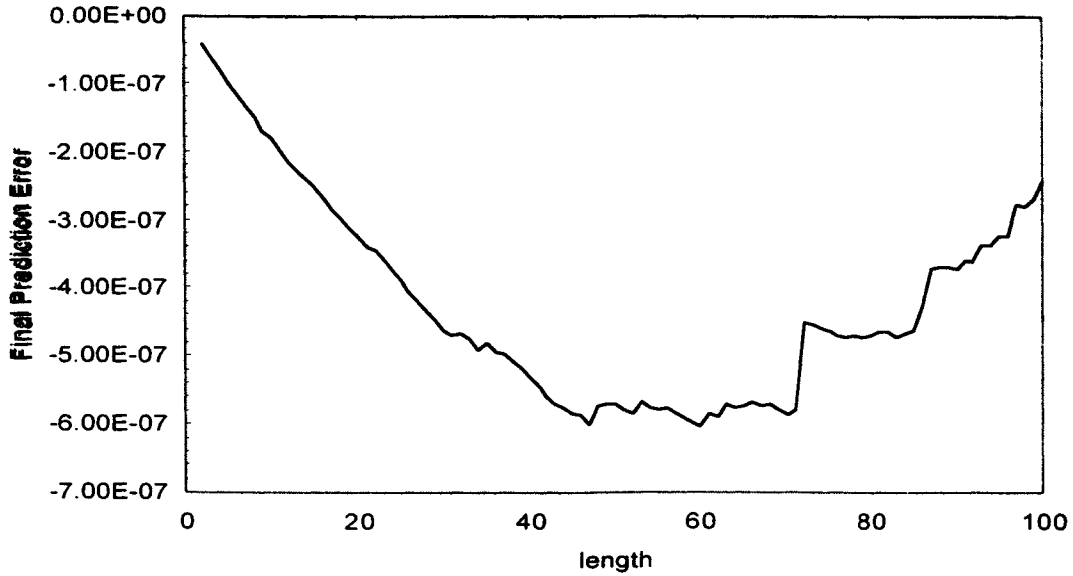


Figure 1. Final Prediction Error of the autoregressive process computed for LODR series

Power spectral density values for different autoregressive orders are given in Table 1. Note that when the order for the AR process is increasing, the power spectrum estimates becomes rough and both, wide and heights of the spectral peaks change dramatically. Nevertheless, in this case amplitudes for the principal components remains being almost the same values.

Table 1. Power spectral density values estimated from the maximum entropy method apply to LODR. Only 32-month and 2.1-month period is considered. These values correspond to different AR orders between 31 and 100. Optimal values in the sense of FPE criterion are highlighted.

	AR order	31	60	83	100
32-month	PSD (dB)	-7.56	-2.8	-5.25	-4.48
	A (mas.)	63.5	65.7	63	61.6
2-month	PSD (dB)	-1.1	2	-8.74	-6.1
	A (mas.)	250.4	250.5	213	234

Interannual LOD series was utilized as input data in the calculus of the power spectral density function using MEM method. The corresponding power spectrum shown in Figure 2 a. The interpretation of this plot needs some care and has rather a qualitative character for the following reasons: 1) even large values of MEM PSD do not necessarily mean an important excess of power in the true PSD function and 2) it is difficult to estimate the detected spectral peak "by eye" because the relative height of two peaks says nothing about the relative amplitude (Brzezinski, 1995).

This draw exhibits important peaks expressing: a 32-month period component and three other peaks in 63, 69 and 116 days. Despite 63 and 69 days are very close, we neglect the possibility it might be the same peak because the same feature appears in different AR orders.

Once the maximum entropy coefficients of $\hat{P}_{MEM}(f)$ have been estimated, we can derive the corresponding integrated power spectrum estimation in order to calculate the mean amplitude of oscillation. Amplitude definition depends on the choice of the arbitrary edge frequencies and is exactly valid in the case of a harmonic term.

Numerical values of these parameters at the highlight peaks of the power spectral density estimated by MEM are shown in Table 2.

Table 2. Significant peaks of the maximum entropy power spectra applied to LODR. These values correspond to 60 in AR order and they are optimal in the sense of final prediction error (FPE).

Frequency (cpy)	0.38	3.14	5.32	5.8
Period (months)	32.02	3.88	2.29	2.1
PSD (dB.)	-2.8	-6.9	-7.3	2.
A (mas.)	65.7	110.6	145.4	250.5

We also applied MEM algorithm to estimate maximum entropy cross power spectrum following Brzezinski's (1995) procedure to compare interannual LOD time series, Southern Oscillation Index (SOI) and Sea Surface Temperature (SST) time series respectively.

In order to implement the procedure some assumptions have been made. The two series we want to compare must be a representation of two stationaries in the wide sense, zero-mean stochastic processes. Obviously, both are taken in the same temporal limits and have to be sampled at the same time interval.

Although all our time series are real-valued, CSD is a complex quantity by definition. It can be proved (Ulrych and Jensen, 1974; Brzezinski, 1995) that the cross power spectrum of a given two series z_1 and z_2 can be obtained as a combination of the power spectra of z_1 , z_2 and two auxiliary series $\bar{z} = z_1 + z_2$ and $\tilde{z} = z_1 + iz_2$ as

$$P_{z_1 z_2}(f) = \frac{1}{2} \left\{ \left[P_{\bar{z}}(f) - P_{z_1}(f) - P_{z_2}(f) \right] + i \left[P_{\tilde{z}}(f) - P_{z_1}(f) - P_{z_2}(f) \right] \right\}$$

where f refers to the frequency $f \in (0, f_N)$ for two real-valued time series and f_N is the Nyquist frequency. Hence combining these four MEM PSD functions, we obtained the MEM Cross Power Spectrum Estimation $(\hat{P}_{z_1 z_2})$.

RESULTS

An estimation of the power spectral density function using MEM was performed according with the procedure described above, on SOI data. Correspondingly, we used the same value for the autoregressive process involved using the FPE criteria. This condition is also necessary to perform the cross-spectral estimation by MEM in order to compare the behavior of both as a function of the frequency into the same spectral window.

Three important peaks can be identified both in the individual power spectra density function (figure 2b) and in the cross-power spectrum (figure 2c) with different amplitudes. Some numerical results are given in Table 3.

Table 3. Power spectral density values (in dB) estimated from the maximum entropy method applies to interannual LOD and Southern Oscillation Index (SOI). All these values correspond to 60 in AR order and they are optimal in the sense of final prediction error (FPE).

Peaks in common (months)	LOD free	SOI
32	-2.80	61.70
3.88	-6.93	---
2.29	-7.30	74.20
2.1	-9.22	64.00

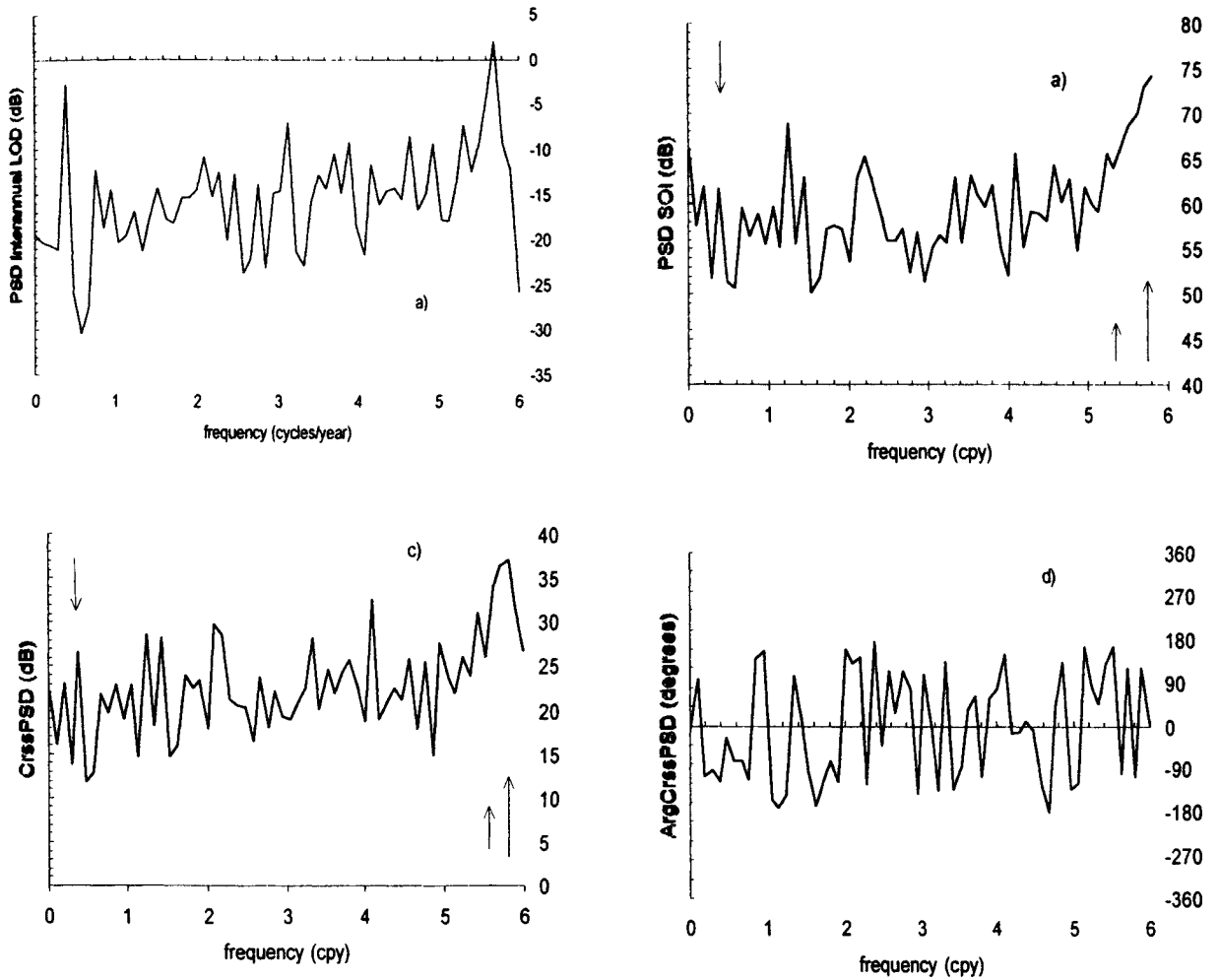


Figure 2. MEM Power and Cross-Power Spectrum of interannual LODR series and SOI series. Units of PSD are decibels.: a) Power Spectrum of the LODR, b) Power Spectrum of SOI, c) Cross Power Amplitude Spectrum, d) Cross Power Phase Difference Spectrum. Arrows indicated remarkable peaks in both.

Comparing SOI with interannual LOD, the phase difference is on average about 108 degrees. Many authors have related interannual LOD variation with ENSO as its excitation mechanism. Consequently, we expected to find such agreement from the comparison between LOD and SOI only for periods upper than 1 year. This event is shown in the 32-month period peak in both PSD functions. This result is relatively close to the primary oscillation period of 36 months for the Angular Atmospheric Momentum (AAM), with phase strongly linked to ENSO phenomena (Black et al., 1996).

In order to identify possibly distinct sources or confirm ocean-atmospheric influence on interannual LOD variations, the NCEP SST data were analyzed separately with some detail for regions along the tropical Pacific Ocean corresponding to the data sets previously defined as SST 1-2, SST3, SST4 and SST3-4 (D. Salstein, personal communication, 1998). Numerical values of the PSD function by MEM are given in Table 4.

Table 4. Power spectral density values (in dB) estimated from the maximum entropy method applied to interannual LOD and Sea Surface Temperatures (SST) in different regions along the tropical Pacific Ocean. All these values correspond to 60 in AR order and they are optimal in the sense of final prediction error (FPE).

Peaks in common (months)	LOD free	1+2	3	4	3. 4
32	-2.80	46.64	42.42	36.67	42.36
3.88	-6.93	63.13	54.85	49.6	36.91
2.29	-7.30	67.2	59.89	49.42	59.05
2.1	-9.22	76.28	71.28	70.73	71.16

Again, despite 63 and 69 days are very close peaks, we neglect the possibility that they be the same peak due to the fact that the same feature appears in different AR orders. In addition, all remarkable peaks between 40 and 60 days can be attributed to the Madden-Julian oscillation (Madden, 1987). However, one unexpected peak rises in the 4-month period for LOD. Such a peak can not be explained as a residual in the interannual LOD time series building because SOI and SST series have not any processes at all besides MEM application.

Cross-power spectrum values on different regions where SST is available are plotted in figure 3, where also LOD power spectral estimates are given to contrast. The phase difference between interannual LOD and different regional SST data sets is about 122 degrees on average.

Although large values of MEM PSD function do not necessarily mean a real important excess of power in the true spectrum (Brzezinski, 1995), a fairly good agreement was reached in both comparisons.

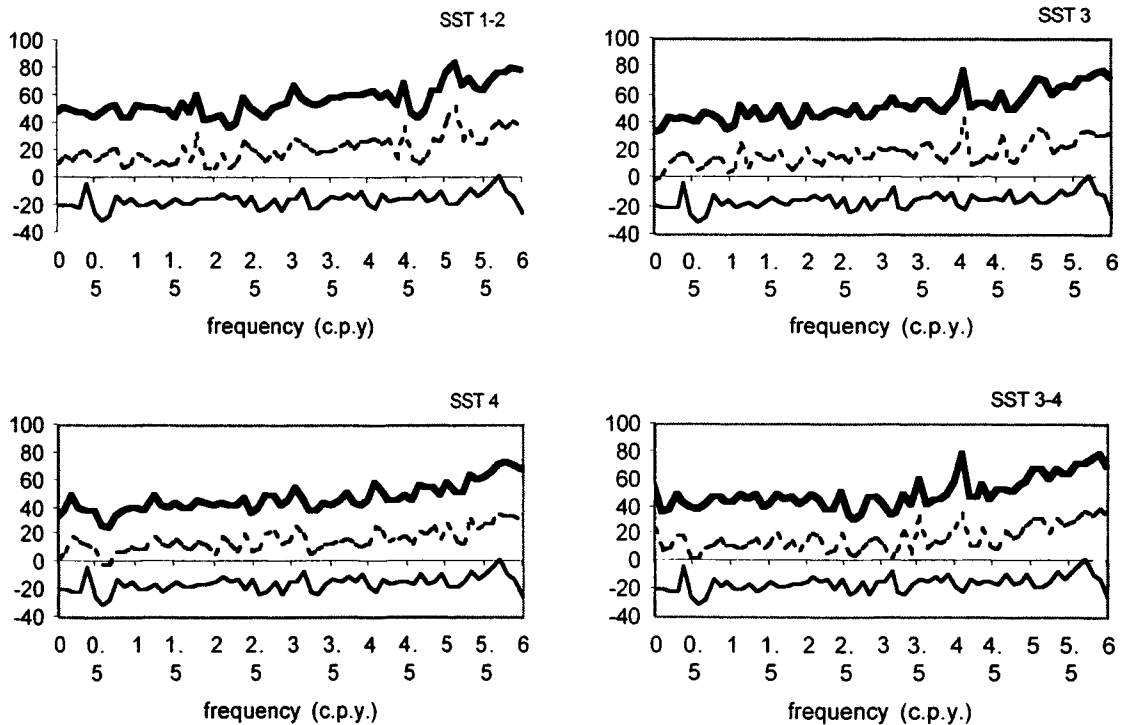


Figure 3. MEM Power spectral estimates of interannual LOD (solid line) and SST (bold solid line) in regions 1-2, 3, 4 and 3-4 respectively. The Cross-Power Spectra estimate (dotted line) is also shown. Units are dB.

Classical Power spectra was also used to compare time series of interannual LOD and its atmospheric-oceanic inferred excitations. We operate directly on the data sets yielding a PSD

estimate. Such a periodogram uses a Hamming window to reduce the side lobes in the spectral estimate. In order to produce a statistically stable spectral estimate, the data must be segmented into possibly overlapping intervals and the sample spectrum of each segmented averaged (Marple, 1987).

Over a total number of 128 samples, we selected 16 samples per segment and 10 samples to shift to the beginning to the next segment. These quantities were taken to reach an agreement between stability and spectral resolution. The results were smoothed using a Gaussian-shaped low pass filter with a window with in the time domain of about 43 months (full width to half maximum, FWHM).

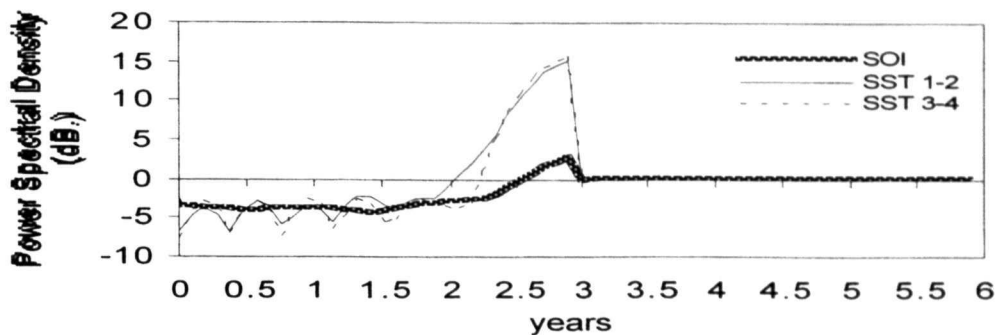


Figure 4. Power spectral density plot of SOI and SST in two different regions of the tropical Pacific Ocean for the period 1988 through 1998 after a low pass filtering.

A significant peak either in SOI and the regional SST spectra are found close to coincide with the 32-month peak showed above in the cross-power spectra by MEM. This is presented in Figure 4 when we plotted SOI and only two regional SST spectra. The peak is clearly seen if we plot the same data using a logarithmic scale (Figure 5).

CONCLUDING REMARKS

The maximum entropy method (MEM) has been widely applied for polar motion studies taking advantage of its performance on the management of complex time series. Despite mostly of the applications were developed to this field, MEM showed to be a powerful tool when it is used in real time series.

Estimations of the Cross-Power Spectrum density applying MEM were performed in order to compare LOD with SOI and SST time series, which are close related to El Niño-Southern Oscillation (ENSO) events.

Through that, we could evince a good agreement in the period of almost 32-month and 2-months whereas an agreement in unexpected periods of 4 months. This would be a non-predicted feature of the ENSO phenomena though the reasons that might cause this effect are yet under study.

The remarkable accordance we found near a 2-month period in all the data sets analyzed agrees well with the almost 50-day period fluctuations in LOD related to meteorological events (Langley et al., 1981). More specifically, we refer to the eastward propagating global scale Madden-Julian oscillation in the tropical troposphere. Such a phenomenon also has a characteristic period of 40 – 50 days and this feature is associated with observed large scale variations in pressure, wind and convective activity near the equator (Madden and Julian, 1972; in Eubanks, 1993).

Complete studies relating tropical winds, precipitation, SST and convective variations processes over the ocean, indicate that Madden-Julian oscillations probably result from tight coupling between wind and SST over equatorial regions of the eastern Indian Ocean and the western Pacific Ocean (Eubanks, 1993). Space geodetic data and meteorological data agreed very well during the hardest El Niño periods of 1982-1983. Because of that the 1982-83 El Niño event was

associated with an increase in the power of the 40-50 days oscillation (Eubanks, 1993) although such a relationship is disputable (Gambis, 1992).

Even though a 36-month period is consistent with the time scales associated with the life cycle of individual atmospheric ENSO event (Black et al., 1996), the variation of about 32-month we found in interannual LOD series might be linked as well through the ocean

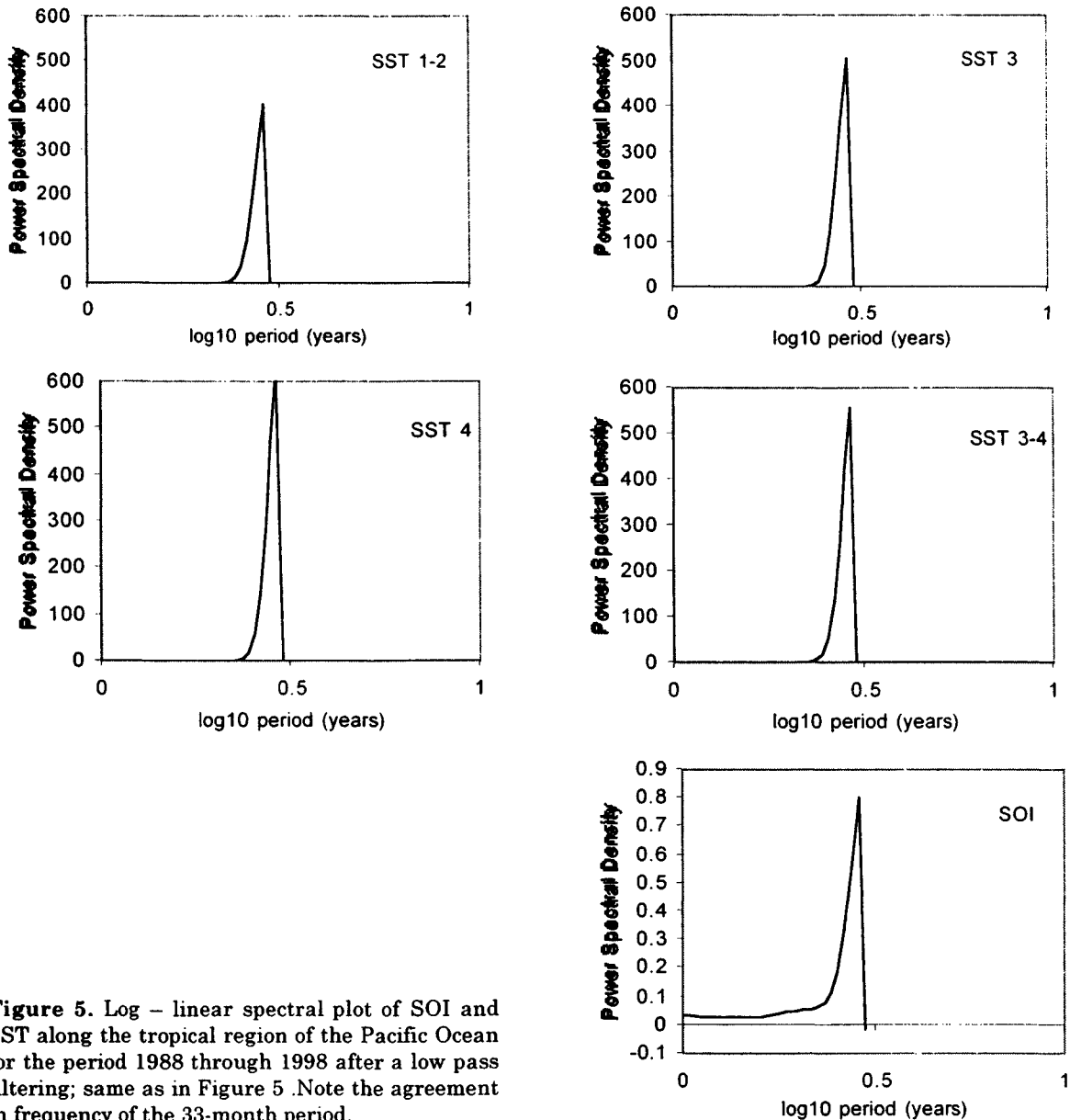


Figure 5. Log – linear spectral plot of SOI and SST along the tropical region of the Pacific Ocean for the period 1988 through 1998 after a low pass filtering; same as in Figure 5 .Note the agreement in frequency of the 33-month period.

mechanism that push this phenomenon. In fact, our data set includes not only three El Niño events (1991-92; 1993-94 and 1997-98) but also at least two La Niña events (1988 and 1995) (TAO Project, 1998).

El Niño and La Niña (or El Viejo) are opposite phases of ENSO cycle. La Niña events occur after some (but no all) El Niño phenomena and refer to the cold phase of ENSO. Unusual cold ocean temperatures in the equatorial Pacific characterize it (TAO Project, 1998).

ACKNOWLEDGEMENT

The authors thank David A. Salstein for the interesting comments and suggestions. This work was carried out at La Plata Astronomical Observatory, under contract with La Plata University.

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CORRELATION OF INTRASEASONAL LENGTH OF DAY AMPLITUDE MODULATION WITH ENSO

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ABSTRACT

The Hilbert transform is used to extract the amplitude modulation signals for the intraseasonal variation of Length of Day ranging from 1962 to 1996. The results reveal that the intraseasonal Length of Day amplitude modulation variation has not only a positive secular trend, but also an interannual variation which is ahead of the ENSO evolution. The amplitude modulations for the quasi-50-day oscillation and the quasi-120-day oscillation have been studied separately. This shows that the peaks of the quasi-50-day oscillation amplitude modulation always occur longer than one year before happening of each ENSO event and seem to be the precursor of the ENSO event, and this is the same with the atmospheric research results. They also indicate the dominant correspondence between the quasi-120-day oscillation amplitude modulation and ENSO events since 1976 and absolutely negatively correlation with ENSO before 1972 because of phase change 180 degree in the evolution of the quasi-120-day oscillation amplitude modulation time series during the beginning of the 1970's.

Key words Hilbert transform, ENSO, intraseasonal LOD variation

INTRODUCTION

El Nino/Southern Oscillation (ENSO) is the most dominant dynamic variation of interannual scale in the system of atmosphere, oceans and the solid Earth, and it refers to a warm ocean current that flows along the coast of south-east Pacific Ocean and also influences weather patterns in the rest of the world. The high precision Earth rotation data currently observed by space geodesy could play a key role in understanding the process of atmosphere through angular momentum conservation. Most previous studies show that interannual length of day (LOD) variation is highly correlated with ENSO events (Figure 1)⁽¹⁾ and the Global Circulation Modal(GCM) simulation results indicate that intraseasonal atmospheric oscillation obviously interacts with ENSO⁽²⁾. So the behavior of intraseasonal LOD variation and its correlation with ENSO, are important for better understanding the mechanics of ENSO and the prediction of the occurrence and effects of this event .

DATA PROCESSING

The rotational rate of the solid mantle has been astronomically observed as the LOD derived from “Comb95” data set for nearly 34 years from January 1962 to January 1996 (courtesy of R.S.Gross,1995)⁽³⁾. They are very rich in signal content.

The decadal, seasonal, and long-period tidal signals are the most prominent, and are superimposed on broad-band interannual, intraseasonal and rapid variation as the thin solid line ΔLOD_g in Figure 2.

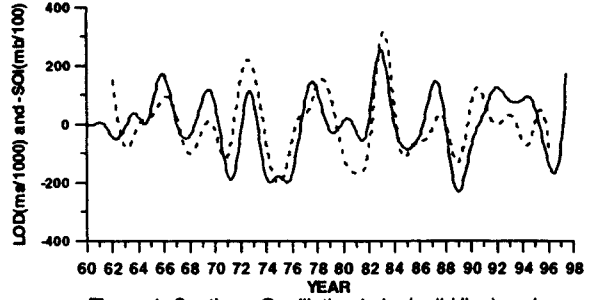


Figure 1. Southern Oscillation Index(solid line) and LOD Variation (dashed line) all at interannual scale

The first step is to use a least-squares fit to the entire excess LOD series ΔLOD_g as indicated by Formula (1) to remove the dominant seasonal signals by annual and semiannual sinusoids as well as the secular trend. The bold solid line in figure 2 represents the fitted excess length of day ΔLOD_f .

$$\Delta LOD_f(t) = c + bt + \sum_{i=1}^2 A_i \sin\left[\frac{2\pi}{T_i}(t + P_i)\right] \quad (1)$$

$$\Delta LOD = \Delta LOD_g - \Delta LOD_f$$

Here A_i, T_i, P_i are, respectively, the amplitude, period and phase of the annual and semiannual variation of excess LOD, b is the coefficient of the secular trend, c is a constant term, ΔLOD is the difference between the geodetic excess LOD and the fitted excess LOD. A band-pass filter, whose frequency response function is given by Formula (2)⁽⁴⁾, was chosen to obtain the intraseasonal variation of excess LOD with periods between 40 days and 150 days and this is represented by the solid line in Figure 3.

$$R(f_1, \epsilon_1; f_2, \epsilon_2) = A(f_1, \epsilon_1) \cdot C \cdot [1 - A^N(f_2, \epsilon_2)]^M \quad (2)$$

where $A(f, \epsilon) = \frac{\epsilon}{\epsilon + (2\pi f)^6}$ is the Vondrak low-pass-filter frequency function, f is the cut-off frequency while N, M are positive integers.

To extract the amplitude modulation signals for the intraseasonal variation, we then use the Hilbert transform defined as⁽⁵⁾

$$\hat{y}(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{y(\tau)}{t - \tau} d\tau \quad (3)$$

where $y(t)$ is the band-pass-filtered excess LOD time series, that is the intraseasonal LOD oscillation, $\Delta LOD_n = R \cdot \Delta LOD$.

We define a new analytic function $n(t) = y(t) - i\hat{y}(t) = a(t)\exp[i\phi(t)]$, where $a(t) = (y^2 + \hat{y}^2)^{\frac{1}{2}}$ is the amplitude modulation(AM) of ΔLOD_n . Performing these above steps yields a new

intraseasonal LOD amplitude modulation(AM) time series data set from January 1962 to January 1996, as represented by the dashed line in Figure 3.

RESULTS AND DISCUSSION

From the intraseasonal LOD amplitude modulation time series, we used the Vondrak low-pass filter to filter out the high frequency components with periods shorter than two years. So a new amplitude modulation time series for intraseasonal LOD variation has been obtained and compared to interannual negative Southern Oscillation Index time series (Figure 4).

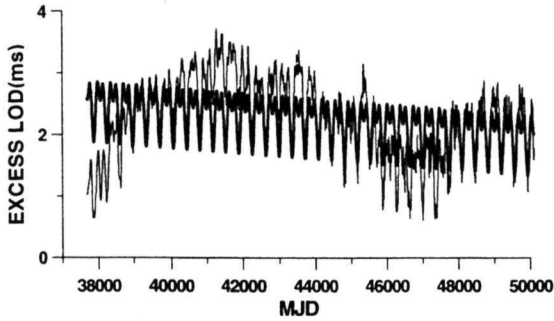


Fig.2 The geodetic excess LOD (thin solid line) and the fitted excess LOD (bold solid line)

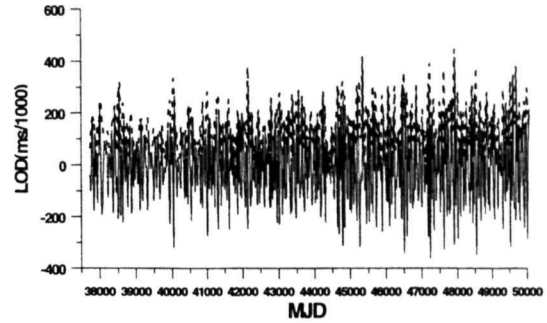


Fig. 3 The intraseasonal Length of Day variation (solid line) and its amplitude modulation time series(dashed line)

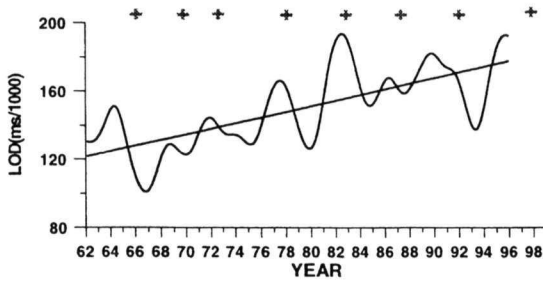


Fig.4 The intraseasonal LOD amplitude modulation with frequencies lower than one cycle per year

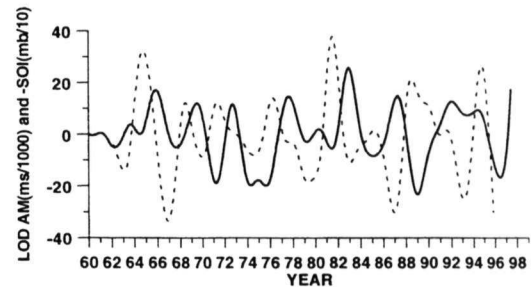


Fig.5 The quasi-50-day oscillation amplitude modulation at interannual scale (dashed line) and -SOI (solid line)

In Figure 4, the symbol '+' represents the occurrences of ENSO events. It's interesting to note the correlation between the occurrence of the AM peaks of intraseasonal LOD variation and the evolution of ENSO events. This reveals that the intraseasonal LOD strong AM peaks occur ahead of each ENSO event with different phases and sometimes almost the same phase. It implies at least that the intraseasonal variation is obviously modulated by ENSO oscillation in nonlinear modulation, where the modulation signals exist in the form of amplitude modulation of short waves. Furthermore, a positive secular trend in intraseasonal LOD AM variation exists, which means that the intraseasonal oscillation becomes slightly stronger and stronger with time. The clues provided by this result seem to indicate that the gradually stronger intraseasonal variation could cause ENSO to occur more frequently, and this needs to be further studied in atmospheric and oceanic researches.

As shown by the wavelet spectrum for intraseasonal LOD variation⁽⁶⁾, the variation

includes the quasi-50-day oscillation and the quasi-120-day oscillation, which are different in time evolution. With the same data process of different parameters, we also get the AM time series at interannual scale for the well known quasi-50-day oscillation and the quasi-120-day oscillation (Figure 5, Figure 6). Figure 5 explicitly shows that there is always a stronger peak

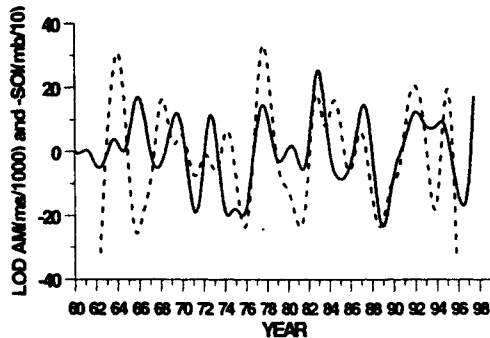


Fig.6a The quasi-120-day oscillation amplitude modulation at interannual scale (dashed line) and -SOI (solid line)

of the quasi-50-day variation amplitude modulation occurring longer than one year before happening of each ENSO event and looking like the precursor of the event. Figure 6 (a) indicates that the dominant correspondence between the quasi-120-day oscillation AM and ENSO events since 1976 is the same as the wavelet result ⁽⁶⁾. At the beginning of 1970's, the quasi-120-day oscillation became weaker and before 1972 the evolution for the quasi-120-day oscillation AM is absolutely negatively correlated with ENSO events, and this is different from that correlation between these two signals since 1976. This may imply that the quasi-120-day oscillation AM time series has a 180 degrees reversion in phase. It can be recognized in Fig.6 (b) that the evolution of the interannual LOD variation is always the same with ENSO variation, but the quasi-120-day oscillation amplitude modulation variation because of the phase change of 180 degrees at the beginning of the 1970's. Of course, to verify this conclusion, further studies and more data are necessary.

From the behavior of the intraseasonal length of day variation, a conclusion can be made that the intraseasonal variation apparently interacts with ENSO dynamical variation in the system of atmosphere, oceans and the solid Earth.

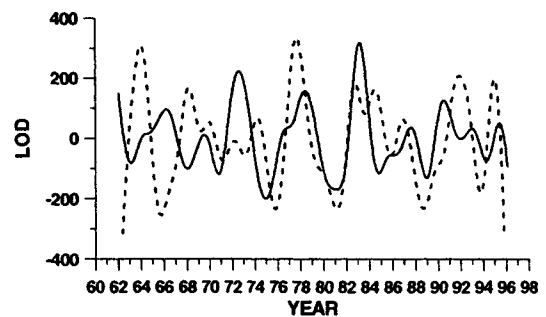


Fig.6b The quasi-120-day oscillation amplitude modulation at interannual scale (unit:ms/10000,dashed line) and interannual LOD variation(unit:ms/1000,the solid line)

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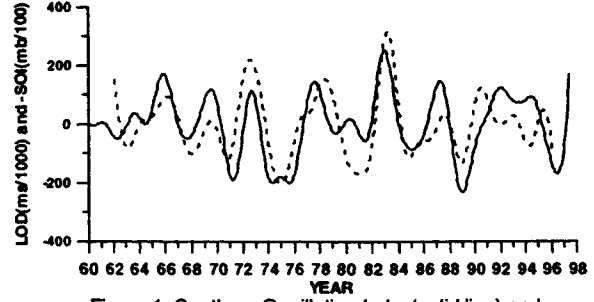


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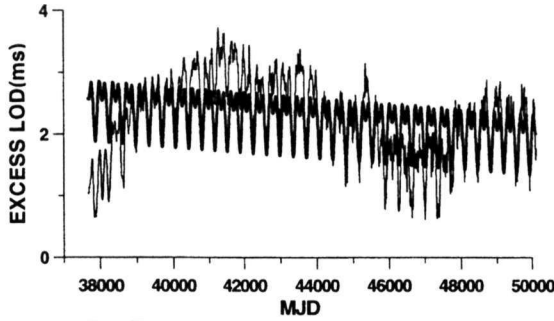


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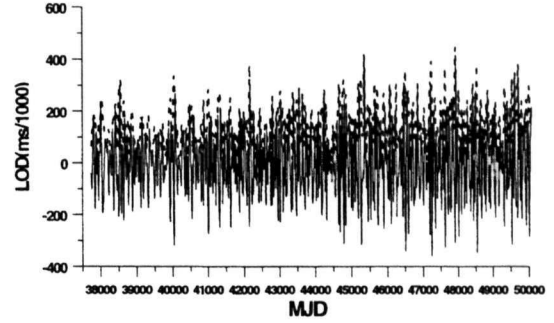


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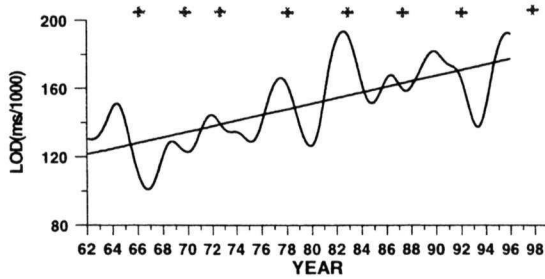


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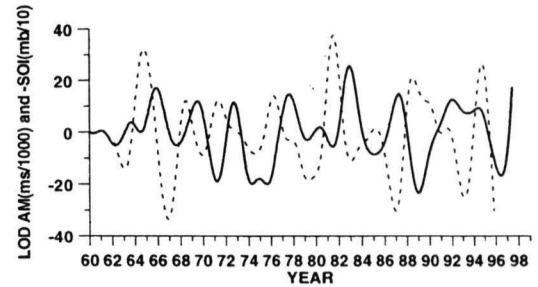


Fig.5 The quasi-50-day oscillation amplitude modulation at interannual scale (dashed line) and -SOI (solid line)

In Figure 4, the symbol '+' represents the occurrences of ENSO events. It's interesting to note the correlation between the occurrence of the AM peaks of intraseasonal LOD variation and the evolution of ENSO events. This reveals that the intraseasonal LOD strong AM peaks occur ahead of each ENSO event with different phases and sometimes almost the same phase. It implies at least that the intraseasonal variation is obviously modulated by ENSO oscillation in nonlinear modulation, where the modulation signals exist in the form of amplitude modulation of short waves. Furthermore, a positive secular trend in intraseasonal LOD AM variation exists, which means that the intraseasonal oscillation becomes slightly stronger and stronger with time. The clues provided by this result seem to indicate that the gradually stronger intraseasonal variation could cause ENSO to occur more frequently, and this needs to be further studied in atmospheric and oceanic researches.

As shown by the wavelet spectrum for intraseasonal LOD variation⁽⁶⁾, the variation

includes the quasi-50-day oscillation and the quasi-120-day oscillation, which are different in time evolution. With the same data process of different parameters, we also get the AM time series at interannual scale for the well known quasi-50-day oscillation and the quasi-120-day oscillation (Figure 5, Figure 6). Figure 5 explicitly shows that there is always a stronger peak

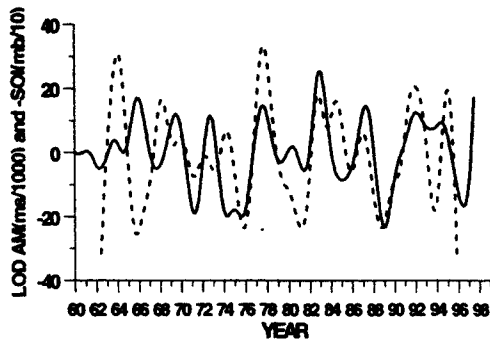


Fig.6a The quasi-120-day oscillation amplitude modulation at interannual scale(dashed line) and -SOI(solid line)

of the quasi-50-day variation amplitude modulation occurring longer than one year before happening of each ENSO event and looking like the precursor of the event. Figure 6 (a) indicates that the dominant correspondence between the quasi-120-day oscillation AM and ENSO events since 1976 is the same as the wavelet result⁽⁶⁾. At the beginning of 1970's, the quasi-120-day oscillation became weaker and before 1972 the evolution for the quasi-120-day

oscillation AM is absolutely negatively correlated with ENSO events, and this is different from that correlation between these two signals since 1976. This may imply that the quasi-120-day oscillation AM time series has a 180 degrees reversion in phase. It can be recognized in Fig.6 (b) that the evolution of the interannual LOD variation is always the same with ENSO variation, but the quasi-120-day oscillation amplitude modulation variation because of the phase change of 180 degrees at the beginning of the 1970's. Of course, to verify this conclusion, further studies and more data are necessary.

From the behavior of the intraseasonal length of day variation, a conclusion can be made that the intraseasonal variation apparently interacts with ENSO dynamical variation in the system of atmosphere, oceans and the solid Earth.

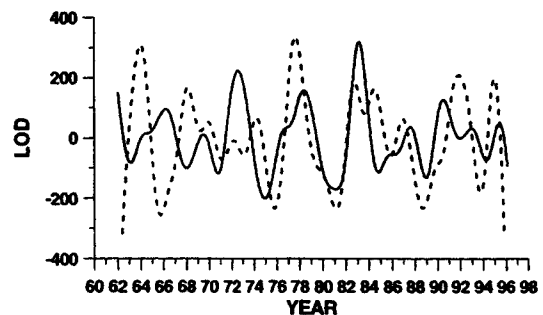


Fig.6b The quasi-120-day oscillation amplitude modulation at interannual scale (unit:ms/10000,dashed line) and interannual LOD variation(unit:ms/1000,the solid line)

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