GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 21, 2031, doi:10.1029/2002GL015685, 2002

Pacific warm pool excitation, earth rotation and El Niño southern oscillations

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Received 21 July 2002; revised 21 August 2002; accepted 26 August 2002; published 12 November 2002.

[1] The interannual changes in the Earth's rotation rate, and hence in the length of day (LOD), are thought to be caused by the variation of the atmospheric angular momentum (AAM). However, there is still a considerable portion of the LOD variations that remain unexplained. Through analyzing the non-atmospheric LOD excitation contributed by the Western Pacific Warm Pool (WPWP) during the period of 1970–2000, the positive effects of the WPWP on the interannual LOD variation are found, although the scale of the warm pool is much smaller than that of the solid Earth. These effects are specifically intensified by the El Niño events, since more components of the LOD-AAM were accounted for by the warm pool excitation in the strong El Niño years. Changes in the Earth's rotation rate has attracted significant attention, not only because it is an important geodetic issue but also because it has significant value as a global measure of variations within the hydrosphere, atmosphere, cryosphere and solid Earth, and hence the global changes. *INDEX TERMS:* 1223 Geodesy and Gravity: Ocean/Earth/atmosphere interactions (3339); 1239 Geodesy and Gravity: Rotational variations; 1724 History of Geophysics: Ocean sciences. **Citation:** Yan, X.-H., Y. Zhou, J. Pan, D. Zheng, M. Fang, X. Liao, M.-X. He, W. T. Liu, and X. Ding, Pacific warm pool excitation, earth rotation and El Niño southern oscillations, *Geophys. Res. Lett.*, *29*(21), 2031, doi:10.1029/2002GL015685, 2002.

1. Introduction

[2] The Earth's rotation rate changes continually on a variety of time scales due to the influences of many physical factors that originate from both inside and outside the Earth [*Lambeck*, 1980]. The application and development of recent space based geodetic techniques has provided impetus for Earth rotation studies. The decadal to secular variations in the Earth's rotation rate, and hence in the length of day (LOD), are attributed to core-mantle interactions, tidal dissipation, and post-glacial rebound. The LOD variations on the intraseasonal to subdecadal time scales are largely caused by the atmospheric angular momentum (AAM) variation [*Eubanks*, 1993]. In particular, the interannual LOD change is linked to the El Niño Southern Oscillation (ENSO) and interannual variation of the atmospheric angular momentum (AAM) [*Stefanick*, 1982; *Rosen et al.*, 1984; *Chao*, 1984; *Chao*, 1988; *Chao*, 1989]. Simulation results of oceanic general circulation models have detected global oceanic effects on the interannual LOD variation that have not been accounted for by the atmosphere [*Marcus et al.*, 1998; *Johnson et al.*, 1999; *Ponte and Stammer*, 2000]. This research focuses on the effect of large-scale ocean anomalies on the interannual LOD, determined from satellite observations of the movement of the WPWP.

[3] *Yan et al.* [1992a; 1992b] first tracked the movement of the WPWP with satellite sea-surface temperature observations. The WPWP is an extensive water body located in the tropical Pacific Ocean that varies in location and size. The WPWP covers approximately 2.9×10^7 km^2 on average and has a temperature consistently higher than 28°C, about 2° to 5°C higher than that of other equatorial waters. In addition, the WPWP has been closely linked to the early stage of ENSO events [*Cane*, 1983; *Philander*, 1983; *McPhaden and Picaut*, 1990; *Yan et al.*, 1992a; *Yan et al.*, 1993; *Yan et al.*, 1997]. The WPWP represents a large volume of water whose density is lower than that of the surrounding water and so represents a wandering anomaly with respect to the distribution of mass within the ocean. Thus, when this water body migrates through the tropical ocean, it contributes to the earth's angular momentum. A natural question to raise is whether the WPWP movements excite variations in LOD appreciably. In this research, we calculate the warm pool excitation in order to analyze the effects of the warm pool migration on the Earth's rotational changes, namely the LOD, especially during the El Niño and La Niña years. The interannual components of the WPWP excitation and LOD-AAM were extracted by the empirical mode decomposition (EMD) [*Huang et al.*, 1998]. Subsequent analyses of the relationship between the interannual LOD-AAM and the warm pool excitation were conducted using a method we developed in this study, the moving window short-term correlation technique.

2. Analysis Procedures and Results

[4] Reconstructed monthly historical sea surface temperature data with Empirical Orthogonal Functions (EOF) analysis was used to determine the WPWP size. The data, received from the NOAA's National Centers for Environ-

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0094-8276/02/2002GL015685

mental Prediction (NCEP), has a spatial coverage of 2 Degrees Longitude times 2 Degrees Latitude resolution, and a temporal coverage spanning January 1950 to December 1998. Monthly NCEP SST analyzed fields of 1 Degree Longitude times 1 Degree Latitude resolution was also used to extend the former data to the year 2000. The grided monthly temperature of the global upper ocean (T000~T400, 5 Degrees Longitude × 2 Degrees Latitude for the year 1955 to 2000 with depths at: 0, 20, 40, 60, 80, 120, 160, 200, 240, 300, 400 meters), obtained from the Joint Environmental Data Analysis Center (http://jedac.ucsd.edu/JEDAC/DATA/index.html), was used to obtain the thermocline depth where the temperature gradient is the largest.

[5] *Ho et al.* [1995] suggested a simple method to calculate the volume of the WPWP and the centroid movement of WPWP. The volume of the WPWP is expressed as the product of the WPWP area, the sea surface height derived from altimeter data and a constant. The centroid of the WPWP is the geometric center in SST imagery of the warm pool (where Temperature >= 28°C). An important assumption was the existence of a homogeneous water mass.

[6] In this study, however, these methods were modified. Upper ocean layer temperature data (T000~T400), were used to determine the thermocline depth even though the spatial and temporal resolution is somewhat lower. Thus, we considered the thermocline depth and its locational variation in our calculation of the WPWP centroid and volume. Because we used *in situ* data and calculated the thermocline depth, we consider the WPWP volume determined in this study to be more realistic than that using the non-steric sea level height from satellite altimeter reported by *Ho et al.* [1995].

[7] The daily LOD series for 1970~2000 (Figure 1) used in this paper was obtained by International Earth Rotation Service (IERS), through the combination of modern space-geodetic and optical observational results. The tidal terms were removed from all the LOD series according to Yoder's formula for tides [*Yoder et al.*, 1981], and then converted into monthly averaged series in order to compare them with the WPWP excitation.

[8] The atmospheric angular momentum (AAM) function was first introduced by *Barnes et al.* [1983] concerning the excitation of the Earth's rotation. The axial component of the NCEP/NCAR 6-hourly reanalysis AAM for 1970–2000 is employed [*Kalnay et al.*, 1996]. The wind is integrated to the pressure level of 10 mb and the pressure term is computed based on the inverted barometer (IB) assumption [*Salstein et al.*, 1993]. The IB assumes that the ocean responds to atmospheric loading isostatically. The monthly average for the AAM series was taken, and then converted to the units of ΔLOD using the transfer factor of 0.0168 ms/10^{24} kgm^2 s^{-1} [*Rosen*, 1993]. The result is shown in Figure 1.

[9] The WPWP excitation function Ψ due to the WPWP movement is computed based on the Liouville equation [*Lambeck*, 1980], which is derived from the conservation of angular momentum.

$$\Psi = -\frac{0.998\dot{\lambda} r^2 \cos^2\theta}{\Omega C} M$$

where r is the Earth's mean radius, C is the polar moment of inertia for the mantle, Ω is the Earth's mean rotational rate, λ and θ are longitude and latitude of the centroid of the WPWP, and M is the total mass of the WPWP upper layer. The numerical coefficient of 0.998 accounts for the effect of rotational deformation. Two assumptions have been made: (i) the WPWP upper layer, with its mass much smaller than that of the solid Earth, is treated as a point mass; and (ii) the thermal effect related to the variation of the mass of WPWP was taken to be "purely dynamical". Because we study the excitation of the length of day variation due to the WPWP movement (so-called "motion" term), using the mean density of seawater. The thermal effect on density is one or two orders smaller and therefore can be neglected. The resulting WPWP excitation during 1970–2000, which has been converted into equivalent LOD, is shown in Figure 1.

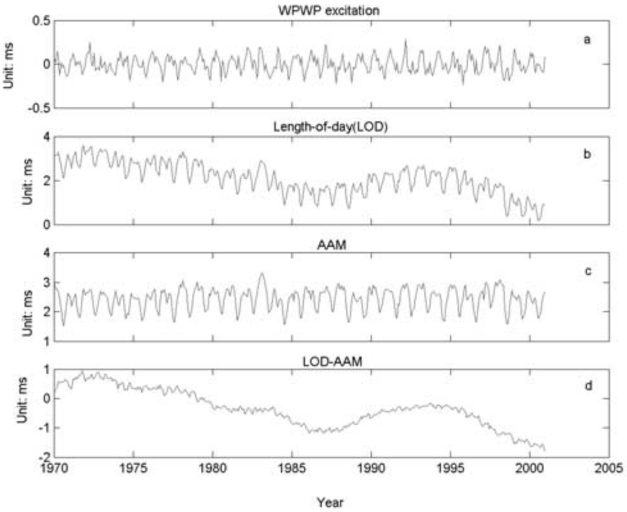

Figure 1. The WPWP excitation and the LOD. From top to bottom: the West Pacific Warm Pool (WPWP) excitation (1a), the length-of-day (LOD) variation (1b), the atmospheric angular momentum (AAM) (1c), and LOD-AAM (1d) during 1970–2000.

[10] In order to remove the atmospheric effects on the LOD, we subtracted the atmospheric angular momentum (AAM) from the raw LOD data. Figures 1a and 1d show the time series of the warm pool excitation and LOD-AAM, respectively. We can see from this figure that the warm pool excitation, with the magnitude of 0.5 milli-seconds (ms), contains the main frequency components of the seasonal and interannual cycles, while the LOD-AAM is dominated by a long-term trend and an interannual cycle. The interannual cycle of the LOD-AAM has the magnitude of 0.6 ms. In order to clarify characteristics of the cycles with different periods in the undulations of the warm pool excitation and the LOD-AAM, we used the EMD [*Huang et al.*, 1998] for a decomposition of the cycles with the different time scales. Here, the EMD was applied for extracting the interannual variation. The EMD can separate the different intrinsic signals with different time scales, and also is not subject to the Gibbs phenomenon, which most filtering methods possess.

[11] Empirical mode decomposition decomposes a complicated data set into a finite and often small number of intrinsic mode functions (IMF) [*Huang et al.*, 1998]. The IMF is defined as any function that (a) in the whole data set, the number of extrema and the number of zero-crossings is

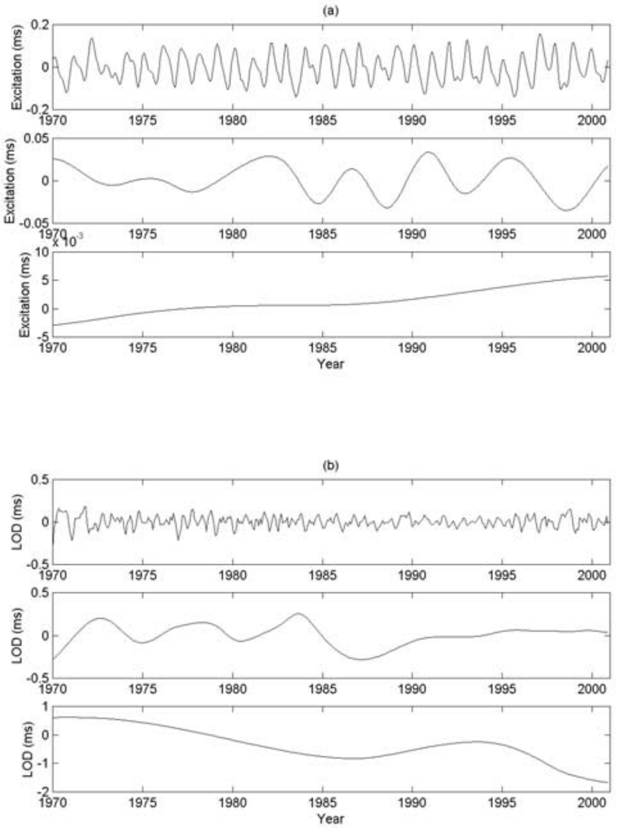

Figure 2. (a) Three components of the WPE extracted using empirical mode decomposition method. Mode 1, mode 2 and mode 3 (from top to bottom) represent oscillations with different time scales. (b) Three components of the LOD-AAM extracted using empirical mode decomposition method. Mode 1, mode 2 and mode 3 (from top to bottom) represent oscillations with different time scales.

either equal or differs at most by one, and (b) at any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero. The EMD method is adaptive, and, therefore, highly efficient. Since the decomposition is based on the local characteristic time scale of the data, it is applicable to nonlinear and nonstationary processes.

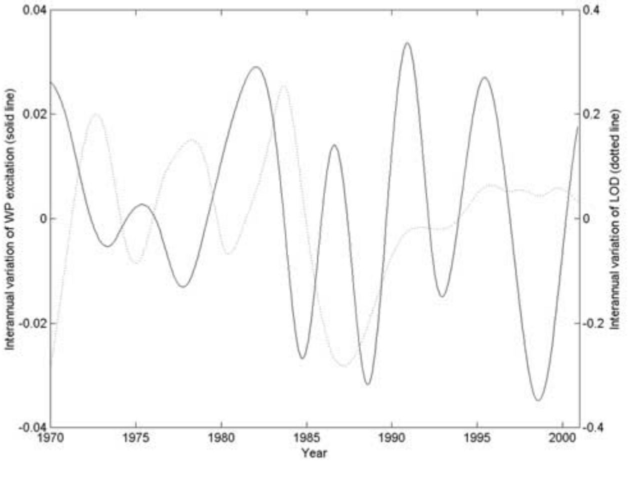

Figure 3. The comparison between mode 2 of the WPE (solid line) and that of the LOD-AAM (dotted line).

[12] The EMD decomposes the warm pool excitation and the LOD-AAM (seasonal terms removed) into three components, which represent the high frequency oscillation (IMF-1), interannual oscillation (IMF-2), and long-term trend (IMF-3) (Figures 2a and 2b). The long-term trend may be caused by tidal dissipation and core-mantle interactions, which have the temporal scales of more than 10 years. By focusing on the undulations in the interannual scale range, we limited our analysis to two time series of IMF-2, which are shown together in Figure 3. In order to reveal the relationship between the two time series, we calculated the short-term correlation coefficients (STCC) between them. The STCC method was implemented by calculating the cross correlation coefficient between the two time series within a window moving in the temporal range of the data, which resulted in a two-dimensional time dependent correlation between the two data sets, and is useful for analysis of the time-dependent correlation between the two data sets. Figure 4 shows the correlation in which the window width was 4.0 years, corresponding to the average length of the quasi-ENSO cycle. High correlation was found in the strong El Niño years of 1975–76, 1986–87, and 1997–98. The time lag between the LOD-AAM and warm pool excitation decreases from 2 months in 1986–87 to no lag in 1997–98, suggesting that the effects of the warm pool are intensified by El Niño events. Thus, more components of the LOD-AAM will be accounted for by the warm pool excitation in the strong El Niño years. In order to verify the confidence of the STCC results, we applied a significance test to the STCC. The method is based on the t distribution statistic (*Gregory*, 1978). Figure 5 shows the correlation coefficients at the 95% confidence level. The correlation coefficients in the strong El Niño years of 1975–76, 1986–87, and 1997–98 are all larger than 0.6 (Figure 4), whereas the 95% confidence level

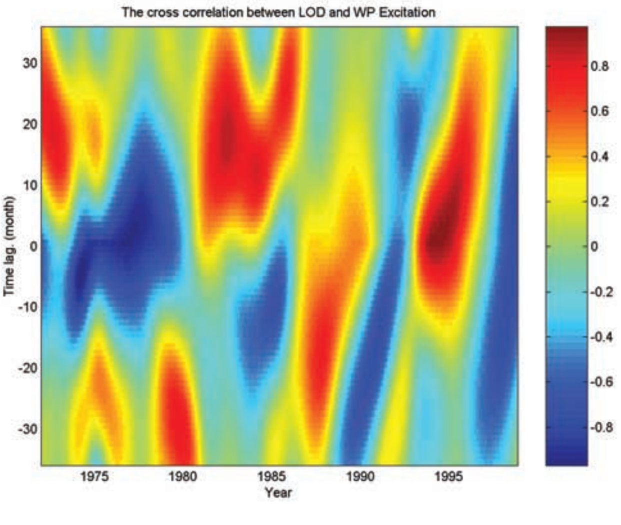

Figure 4. The moving window short-term correlation. The cross correlation of IMF-2 between the WPE and the LOD-AAM is plotted against time. The width of window for calculating the cross correlation is 4 years.

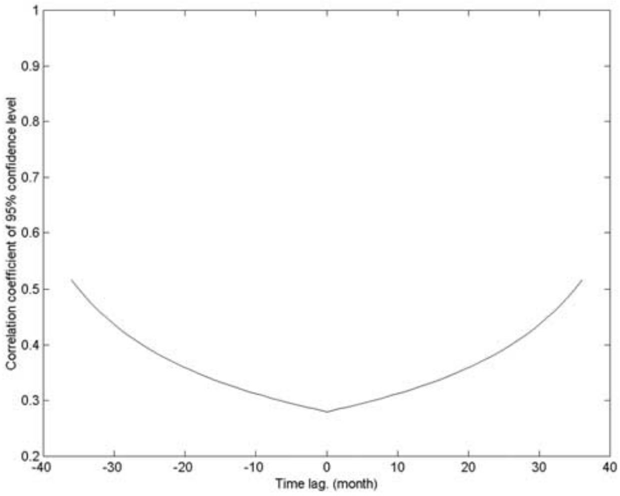

Figure 5. The 95% confident correlation coefficients at different time lag.

threshold is less than 0.52 (Figure 5), which suggests the correlation in the El Niño years is significant.

3. Summary

[13] In this study, the Western Pacific Warm Pool was found to be positively correlated with the interannual variation of the LOD after removing the atmospheric effect, although the scale of the warm pool is much smaller than that of the solid Earth. Thanks to the recent advancements in the space based geodetic techniques, even small changes in the Earth rotation can be monitored and analyzed. Our EMD and STCC analyses suggest that the interannual variation of the WPWP excitation and that of the LOD have relatively high correlation in strong El Niño years in 1975–76, 1986–87, and 1997–98. Hence, the migration of the WPWP plays an important role in contributing to the interannual variation of the LOD, and therefore, in the Earth's rotation rate. This may be the first effort to report the influence of a large water mass on the rotation of the Earth. Finally, although we have shown a positive correlation between the WPWP behavior, and variations in the LOD, a strong correlation does not always guarantee a cause and effect relationship. It is possible that some other factor or factors with similar time scales (perhaps related to El Niño) may also contribute to what we have observed. We wish this will stimulate further study on a very important question of how much of the LOD is explained by the WPWP excitation.

[14] **Acknowledgments.** We thank R. W. Garvine, N. Huang and C. Wunsch for reading the manuscript; B. F. Chao for suggestions and discussion. This research was support partially by the National Aeronautics and Space Administration (NASA) through Grant NAG5-11773, and by the National Science Foundation (NSF) through the Presidential Faculty Fellow award to X-H. Yan (OCE-9453499). W. T. Liu was supported by the NASA Physical Oceanography Program. Y. Zhou, D. Zheng and X. Liao were supported by the National Natural Science Foundation of China (Grant No. 10273018, 19833030, 10133010) and Shanghai Science and Technology Development Foundation (No. 01JC14058). We thank both reviewers for their valuable comments, suggestions, and encouragements.

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