# Correlation Analysis of Length-of-Day Variation, Atmospheric Angular Momentum, and ENSO Interannual Signals: The Indo-Pacific Region After the 2020–2021 La Niña Event

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## Abstract

As the strongest climate variability on interannual scales, the occurrence of El Niño-Southern Oscillation (ENSO) exerts significant influences on global weather and climate, and is also closely associated with variations in Earth' s rotation and interannual signals of atmospheric angular momentum (AAM). Utilizing the reanalysis dataset (R1) from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) covering the period from January 1962 to January 2021, atmospheric angular momentum functions were computed and compared with concurrent interannual-component length-of-day variation ($\Delta$LOD) data, as well as with Oceanic Niño Index (ONI) and Southern Oscillation Index (SOI) data that characterize ENSO: the relationships among ENSO, AAM, and $\Delta$LOD were analyzed through statistical methods including cross-correlation analysis and wavelet transform, with corresponding physical interpretations provided. Additionally, by applying these relationships and potential physical processes, signals of the ongoing moderate La Niña event during 2020-2021 were detected in the interannual component of length-of-day variation, during which the interannual $\Delta$LOD has already undergone a change of approximately 0.18 ms.

## Full Text

## Preamble

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# Correlation Analyses among ΔLOD, AAM and ENSO, and the 2020-2021 La Niña Event

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## Abstract

As the strongest climate variability at interannual timescales, the El Niño-Southern Oscillation (ENSO) exerts significant influence on global weather and climate patterns and is closely linked to interannual signals in both Earth's rotation variations and atmospheric angular momentum (AAM). Based on the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis-1 (R1) dataset from January 1962 to January 2021, we calculated the atmospheric angular momentum excitation function and compared it with interannual components of length-of-day variation (ΔLOD) data and ENSO indices—including the Oceanic Niño Index (ONI) and Southern Oscillation Index (SOI). Using statistical methods such as cross-correlation analysis and wavelet transform, we examined the relationships among ENSO, AAM, and ΔLOD and provide physical interpretations of the associated processes. Furthermore, leveraging these relationships and underlying physical mechanisms, we detected the signal of the ongoing moderate-intensity La Niña event of 2020-2021 in the interannual component of ΔLOD, which has produced a variation of approximately -0.18 ms during this period.

**Keywords:** length-of-day variation; atmospheric angular momentum; ENSO; La Niña; wavelet analysis

## 1 Introduction

The El Niño-Southern Oscillation (ENSO) represents an interannual oscillation of the climate system occurring approximately every 2–7 years in the tropical Pacific region. As a coupled ocean-atmosphere phenomenon, ENSO manifests as warm or cold sea surface temperature (SST) anomalies in the central and eastern equatorial Pacific Ocean, with El Niño corresponding to warm anomalies and La Niña to cold anomalies. In the atmosphere, ENSO appears as the Southern Oscillation—a seesaw pattern in sea-level pressure between the eastern and western tropical Pacific.

Variations in Earth's rotation reflect not only external torques from solar, lunar, and planetary gravitational forces but also internal interactions between the core and mantle, as well as coupling processes within fluid envelopes such as the oceans and atmosphere. At interannual and higher frequencies, atmospheric and oceanic activities constitute the primary drivers of Earth’ s rotation rate changes. Among these, ENSO represents the dominant climate variability at interannual scales and serves as a crucial factor influencing interannual LOD variations.

In the absence of external torques, the solid Earth and its fluid envelopes (atmosphere and oceans) can be approximated as a conservative dynamical system. According to the principle of total angular momentum conservation, angular momentum changes induced by atmospheric and oceanic dynamics must be compensated by opposite changes in the solid Earth’ s angular momentum, thereby altering Earth’ s rotation rate or length of day (LOD). Consequently, ΔLOD exhibits a close relationship with ENSO events.

Numerous studies have investigated the connections among ΔLOD, AAM, and ENSO. Langley et al. [6] first established a quantitative relationship between AAM and ΔLOD. Stefanick [7] demonstrated similarities among LOD variations, AAM, and the Southern Oscillation Index (SOI) at interannual timescales using data from 1963–1973. Following the 1982–1983 super El Niño event, Rosen and Salstein [8] detected the strong warm event signal in both AAM and ΔLOD. Eubanks et al. [9] and Chao [10] found that the SOI leads interannual LOD variations by 1-2 months, indicating that interannual ΔLOD is primarily driven by ENSO. Subsequent work by Dickey et al. [11-13] showed that interannual ΔLOD is mainly excited by the axial component of AAM ( $_3$) and noted a tendency for AAM anomalies to originate in the tropics and propagate toward mid-to-high latitudes in association with ENSO. They also proposed that low-frequency SST variations may excite AAM changes at interannual and decadal timescales, and that the tropical temperature gradient (TTG) peaks 1–2 months after maximum SST anomalies in the central Pacific (Niño-3.4 region), suggesting that TTG-induced thermal wind anomalies drive the wind term of AAM and thus explain ENSO’ s forcing of interannual ΔLOD. More recently, de Viron and Dickey [14] investigated two distinct types of El Niño events (eastern and central Pacific types) in relation to ΔLOD, finding that the AAM signal for eastern Pacific ENSO is more than twice as large as that for central Pacific events, which they explained through torque dynamics. They concluded that eastern Pacific ENSO generates larger mountain and friction torques; while larger mountain torque indicates stronger AAM anomalies, the associated surface winds produce strong negative friction torques that partially offset these anomalies. Lambert et al. [15] analyzed AAM, torques, and ΔLOD during three super El Niño events since 1980, concluding that mountain torque dominated ΔLOD during the 1982–1983 and 1997–1998 eastern Pacific events, whereas friction torque compensated for weaker mountain torque during the 2015–2016 mixed eastern-central Pacific event.

Building upon these studies, we employ IERS ΔLOD observations from January 1962 to January 2021, atmospheric angular momentum functions derived from

NCEP/NCAR Reanalysis-1 (R1), and ENSO indices including ONI and the modified Southern Oscillation Index (MSOI) to comprehensively analyze the interannual relationships among Earth's rotation, AAM, and ENSO. We attempt to provide physical interpretations of the underlying processes and detect the signal of the 2020–2021 La Niña event in the interannual ΔLOD component.

## 2 Data and Methods

### 2.1 El Niño-Southern Oscillation

Due to the inherent diversity and complexity of ENSO [16, 17], accurately defining its episodes and quantifying their duration and intensity presents considerable challenges. The operational criteria established by the National Oceanic and Atmospheric Administration (NOAA) divide the tropical Pacific into Niño-1+2, Niño-3, Niño-3.4, and Niño-4 regions (Figure [Figure 1: see original paper]), with Niño-3.4 representing the central tropical Pacific [18]. NOAA defines ENSO based on seasonal (3-month running mean) SST anomalies in the Niño-3.4 region: anomalies $\geq$ +0.5°C indicate El Niño, while anomalies $\leq$ -0.5°C indicate La Niña. The timing and intensity of ENSO events are primarily determined using the Oceanic Niño Index (ONI), which consists of 3-month running means of Niño-3.4 SST anomalies. A continuous period of at least five months with ONI anomalies exceeding $±$0.5°C constitutes an El Niño or La Niña event, respectively. Notably, the current ONI is based on NOAA' s Extended Reconstructed SST version 5 (ERSSTv5), which updates its climatology every five years to minimize the influence of long-term warming trends in the Niño-3.4 region on ENSO monitoring [19].

The Southern Oscillation Index (SOI) measures the atmospheric manifestation of the Southern Oscillation as a standardized monthly mean sea-level pressure difference between Tahiti (eastern tropical Pacific) and Darwin (western tropical Pacific) (Figure [Figure 1: see original paper]). The SOI also serves as an indicator of equatorial Pacific easterly wind strength, with positive values corresponding to La Niña-related easterly anomalies and negative values to El Niño-related westerly anomalies [20]. Figure [Figure 2: see original paper] compares monthly SOI and Niño-3.4 SST anomalies from January 1962 to January 2021 (data from NOAA), revealing a negative correlation with pressure changes exhibiting higher-frequency noise than SST anomalies. While both indices generally synchronize temporally, they differ in intensity representation: during the three super El Niño events of 1982–1983, 1997–1998, and 2015–2016, SOI shows a decreasing trend whereas Niño-3.4 SST anomalies display an increasing trend. Figure [Figure 3: see original paper] illustrates the correlation between various ENSO indices under different processing methods, showing maximum negative correlations for monthly SOI versus Niño-3.4 SST anomalies (green dot-dashed line), 3-month running mean SOI versus ONI (red dot-dashed line), and interannual (1–10 year) components of SOI and ONI (blue dot-dashed line). Correlation coefficients strengthen sequentially to -0.73, -0.84, and -0.92 as smoothing increases.

To align with ONI' s representation of ENSO phases, we invert the SOI to obtain the Minus Southern Oscillation Index (MSOI). To mitigate edge effects during filtering, we first extend the time series by 30 months on each end using an autoregressive (AR) model, then apply a second-order Butterworth bandpass filter (1-10 year period), and finally remove the AR-extended portions where edge effects are significant [21].

### 2.2 Length-of-Day Variation

Variations in Earth' s rotation rate about its axis are expressed as length-of-day changes (ΔLOD):

$$\Delta LOD = -\frac{\Delta\omega}{\omega_0} \times 86400 \text{ s}$$

where ΔLOD represents the change in length of day, $\Delta\omega$ is the change in Earth' s angular velocity, and $\omega_0$ is Earth' s mean angular velocity. Equation (1) shows that ΔLOD is inversely proportional to changes in Earth' s rotation rate [22].

The International Earth Rotation and Reference Systems Service (IERS) provides daily observations of Earth orientation parameters (EOP), including ΔLOD, since January 1, 1962. Early data were obtained through optical astrometry, while modern measurements since the 1970s employ space geodetic techniques including Lunar Laser Ranging (LLR), Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), Global Navigation Satellite Systems (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) [23]. The latest EOP 14 C04 series achieves microsecond-level precision for ΔLOD measurements.

We analyze ΔLOD time series from January 1, 1962, to January 31, 2021. To enforce angular momentum conservation within the Earth system, we remove tidal external torques by calculating and subtracting the contribution of solid Earth tide zonal harmonics to LOD according to IERS conventions, yielding non-tidal ΔLOD daily data that are then converted to monthly means [24, 25]. Figure [Figure 4: see original paper] displays the decomposed LOD variation sequences, where panel (a) shows non-tidal multi-scale ΔLOD (light blue line) and the decadal-scale component obtained through polynomial fitting (pink line); panel (b) presents the interannual ΔLOD time series (red line) derived by removing decadal and seasonal components from non-tidal ΔLOD, followed by AR model extension, Butterworth filtering, and edge effect removal; panel (c) shows the seasonal component (green line) fitted by summing annual, semiannual, and terannual terms; and panel (d) displays subseasonal high-frequency components (dark blue line).

### 2.3 Atmospheric Angular Momentum

To investigate atmospheric excitation of LOD variations, we employ Eubanks' formulation for the axial atmospheric angular momentum function (AAMF) $_3$, expressed separately for pressure ( $^3$) and wind ( $^3$) terms [26]:

$$\chi_3 = \chi_p^3 + \chi_w^3$$

$$\chi_p^3 = \frac{0.753R^4}{gC_m\Omega} \iint p_s \cos^3\phi \, d\lambda d\phi$$

$$\chi_w^3 = \frac{0.998R^3}{gC_m\Omega} \iiint u \cos^2\phi \, dp d\lambda d\phi$$

where $u$ is zonal wind speed, $p$ is surface atmospheric pressure, $R$ is Earth' s radius, $\Omega$ is Earth' s mean rotation rate, $g$ is gravitational acceleration (9.8 m $s^{-2}$), $C$ is the axial moment of inertia of the mantle, $\lambda$ is longitude, and $\phi$ is latitude.

The required meteorological fields—surface pressure and horizontal wind—are obtained from the NCEP/NCAR Reanalysis-1 dataset, with 6-hourly temporal resolution (starting at GMT 00:00), 2.5° × 2.5° horizontal grid spacing, and 17 vertical levels from 1000 to 10 hPa [27, 28]. For the pressure term calculation using long-term data (1962-2021), we account for sea-level variations due to atmospheric pressure changes by applying the inverted barometer (IB) approximation, which assumes oceanic response to atmospheric pressure fluctuations [29, 30]. For the wind term, we incorporate topographic effects by vertically integrating from the surface corresponding to terrain elevation up to 10 hPa [31]. The axial AAM function ( $_3$) is the sum of pressure and wind terms. To match ΔLOD observation units (ms), we multiply $_3$ by a conversion factor of $8.64 \times 10^7$ ms · rad$^{-1}$. Finally, we remove a fitted seasonal component similar to that for ΔLOD, apply AR model extension, bandpass filtering (1-10 year period), and edge effect removal to obtain the interannual AAM component corresponding to ENSO indices and ΔLOD.

## 3 Comparative Analysis Results

Figure [Figure 5: see original paper] compares interannual components of ΔLOD, AAM, and MSOI, revealing similar fluctuation patterns with prominent amplitude peaks during the super El Niño events of 1982-1983, 1997-1998, and 2015-2016. Figure [Figure 6: see original paper] presents lead-lag correlations among these interannual time series, with all correlation coefficients exceeding the 99% significance level [32]. MSOI leads both AAM (blue line) and ΔLOD (red line) by approximately one month, with maximum correlation coefficients of 0.69 and 0.55, respectively. Conversely, AAM and ΔLOD are synchronous (green line) with a correlation coefficient of 0.70. This reflects strong coupling between the solid Earth and surface fluid envelopes at interannual timescales and verifies the instantaneous angular momentum exchange between the atmosphere and solid Earth under zero external torque. These results are consistent with previous studies [7, 11–13, 33].

To further analyze the time-frequency characteristics of interannual LOD variations, AAM excitation, and the Southern Oscillation, we employ the regularized Morlet wavelet transform [34]. For a time series $f(t)$, the wavelet transform is defined as:

$$W_\phi(f)(a,b) = \int_{-\infty}^{+\infty} f(t)\Psi^*\left(\frac{t-b}{a}\right) dt$$

where $\Psi(t)$ is the mother wavelet, $a$ is the dilation scale factor determining frequency characteristics, $b$ is the translation factor in the time domain, and the wavelet transform simultaneously analyzes quasi-periodic time series in both time and frequency domains. Figure [Figure 7: see original paper] shows wavelet spectra for interannual components of ΔLOD, AAM, and MSOI, where red indicates positive phase, blue indicates negative phase, and darker colors represent stronger intensity. The three variables exhibit similar time-frequency distribution structures.

These statistical results demonstrate the process by which ENSO influences Earth’ s rotation rate through atmospheric angular momentum changes. During El Niño events, positive MSOI values (negative SOI) indicate weakened trade winds and anomalous westerlies in the equatorial region, which reduce the strength of the zonal Walker circulation. Simultaneously, anomalous atmospheric heating from warm Pacific waters enhances the meridional Hadley circulation, strengthening the subtropical westerly jet. Figure [Figure 6: see original paper] shows that interannual MSOI leads AAM and ΔLOD by about one month, likely reflecting the time required for tropical air-sea interactions to generate anomalous responses in the subtropics through meridional atmospheric transport. The combined effects of equatorial westerly anomalies and enhanced subtropical jets increase the westerly wind component, thereby strengthening AAM. Conservation of total angular momentum in the Earth-atmosphere system requires that increased AAM be compensated by decreased angular momentum of the solid Earth, causing Earth’ s rotation to decelerate and ΔLOD to increase. As El Niño events peak and subsequently decay through Bjerknes feedback [35], the associated atmospheric circulation anomalies gradually diminish, leading to reduced AAM and ΔLOD values. Consequently, AAM and ΔLOD typically reach their maxima during the mature phase of El Niño. Previous studies have described similar feedback processes [8, 36, 37].

Conversely, during La Niña events, cold SST anomalies in the eastern equatorial Pacific strengthen equatorial easterlies, enhance the zonal Walker circulation, and weaken the meridional Hadley circulation and subtropical westerly jet. Enhanced easterly components in the tropics and subtropics reduce AAM, and by angular momentum conservation, increase Earth' s rotation rate and decrease ΔLOD. As La Niña decays, AAM and ΔLOD typically increase relative to their minima.

Although ENSO represents the strongest interannual climate variability and a major driver of interannual LOD variations, it cannot fully explain all interannual LOD changes due to the complexity of factors affecting Earth' s rotation rate. Other climate modes such as the Quasi-Biennial Oscillation (QBO) and various internal geophysical processes may also contribute to interannual LOD variations [26, 38].

Figure [Figure 8: see original paper] compares interannual ΔLOD with ONI. As of late January 2021, ONI values from July 2020 to January 2021, calculated as 3-month running means of Niño-3.4 SST anomalies, had satisfied the La Niña criterion of at least five consecutive months with anomalies ≤ -0.5°C. ONI peaked in November 2020 (OND average) at -1.3°C, constituting a moderate-intensity La Niña event according to NCAR standards [18]. Comparison of interannual ΔLOD with ONI sequences (El Niño events in red shading, La Niña events in blue shading) reveals that ΔLOD does not perfectly correspond to ENSO warm/cold events in terms of timing and intensity, likely due to differences in data resolution, processing errors, and the complexity of factors influencing ΔLOD. Nevertheless, when these error sources are ignored, nearly all El Niño and La Niña events produce corresponding maxima and minima in interannual ΔLOD. For the ongoing moderate La Niña event from summer 2020 to spring 2021, interannual ΔLOD shows a variation of approximately -0.18 ms during the corresponding period (right side of Figure [Figure 8: see original paper]a). We will continue monitoring the evolution of this event.

## 4 Summary and Discussion

This study analyzes the interannual relationships among astronomically observed length-of-day variations, atmospheric angular momentum, and ENSO indices (SOI and ONI), provides physical process descriptions, and detects the 2020–2021 La Niña signal in interannual ΔLOD.

Cross-correlation analyses among ENSO, AAM, and ΔLOD verify the strong correlation and synchrony between ONI and MSOI, while revealing the lead-lag statistical relationships among ΔLOD, AAM, and MSOI. The near-synchrony between ΔLOD and AAM reflects instantaneous angular momentum exchange between the atmosphere and solid Earth under conservation of total system angular momentum. The approximately one-month lead of MSOI over AAM and ΔLOD statistically demonstrates that ENSO serves as an important excitation source for interannual ΔLOD.

Based on available observations from January 1962 to January 2021, 19 El Niño events and 17 La Niña events have occurred. Since El Niño and La Niña induce anomalous atmospheric circulations in the tropics and subtropics (manifested as AAM changes), they produce corresponding LOD variations. The moderate La Niña event from summer 2020 to spring 2021 accelerated Earth' s rotation rate, generating an interannual ΔLOD variation of approximately -0.18 ms. As of late February 2021, this La Niña event continues, and we will maintain monitoring of associated astronomical and meteorological developments.

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*Note: Figure translations are in progress. See original paper for figures.*