Geophysical Fluid Contributions to Intradecadal Length of Day Variations

Alexandra Mohn[1], Isobel Howard[1], Imogen Buckroyd[1], Frederik Dahl Madsen[1,2]

[1] School of Geosciences, University of Edinburgh
[2] Lyell Centre, British Geological Survey

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Abstract

Variations in length of day (LOD) are a result of mass movements in the Earth's fluid envelope and deep interior. Previously, a six (SYO) and eight year (EYO) oscillation have been inferred to arise from fluid motions in the core; however, these signals are masked by other geophysical fluid contributions. This work focuses on assessing the impact of atmospheres, oceans, and hydrology on studying the SYO and EYO. To isolate these oscillations for further study, we subtracted angular momentum contributions originating from zonal tides, the atmosphere, oceans, and hydrology. Zonal tides are subtracted based on a synthetic model utilising a sum of harmonic waves. Atmospheric contributions are subtracted to isolate the SYO and EYO, as a result of atmospheric interference within the four- to seven-year range. Oceanic contributions made little difference to the analysis of the LOD signal; removal of these contributions is therefore not required within the intradecadal timescale. Hydrologic contributions were not removed for our analysis of the SYO and EYO because including hydrologic contributions resulted in a cleaner isolation of the SYO and EYO. We conclude that studies analysing intradecadal LOD variations should remove tidal and atmospheric contributions, whereas oceanic contributions have minimal impact, and hydrological contributions mask our signal.

Introduction

Length of day (LOD) is a measurement of the difference between measured length of day (UT1) and the nominal length of day (86,400 seconds or UTC) (Gross 2015). Variations in LOD are related to the exchange of angular momentum between the solid Earth and external excitation sources (Rekier *et al.* 2022). Geophysical excitation sources include external torques and the exchange of angular momentum between the solid Earth and geophysical fluid components, such as the atmosphere, oceans, and hydrology (Pfeffer *et al.* 2023). These geophysical fluid contributions can mask solid Earth contributions to LOD, particularly at shorter timescales.

Large intradecadal LOD variations occur primarily due to interactions between the core and the mantle (Gross 2015). To analyse these intradecadal variations, we must remove extraneous geophysical fluid contributions which mask solid Earth contributions. At smaller timescales, tidal and atmospheric contributions dominate the LOD signal (Barnes *et al.* 1983; de Viron *et al.* 2002). Chao *et al.* (2010) quantified the contribution of atmospheric and oceanic angular momentum to LOD variations, and found that these contributions are smaller than observed LOD variations by 10–20% at the intra-seasonal and seasonal timescales. Pfeffer *et al.* (2023) also considered the removal of various angular momentum (AM) sources at the intradecadal timescale; in particular, they found hydrologic AM contained unbalanced contributions at interannual periods.

LOD variations occur across a variety of timescales, from intra-annual to 60+ years (Roberts *et al.* 2007; Cazenave *et al.* 2025). Particularly in this article, we focus on the six- and eight year oscillations (SYO and EYO, respectively). Although the origin of these are still a topic of debate, they are both believed to originate from the Earth's core, with the SYO governed by gravitational coupling between the solid inner core and mantle (Mound *et al.* 2006) and the EYO likely related to magnetohydrodynamic waves in the liquid outer core (Duan *et al.* 2020).

This work provides a further investigation of AM contributions at the intradecadal timescale, in an effort to best isolate the SYO and EYO for further time series analysis.

Data

We utilised the Earth orientation parameter (EOP) C04 data series, provided by the International Earth Rotation and Reference Service (IERS) (Bizouard *et al.* 2019), to obtain LOD values. This data series is based on a combined smoothing and weighted average of very long baseline interferometry (VLBI) and global navigational satellite systems (GNSS) from January 1963 to October 2024 (as shown in Figure 1). The C04 solution improves the re-weighting and combination of these techniques with respect to other EOP solutions, improves alignment with the most recent version of the international terrestrial reference frame, and provides better error estimates for the polar coordinates (Bizouard *et al.* 2019).

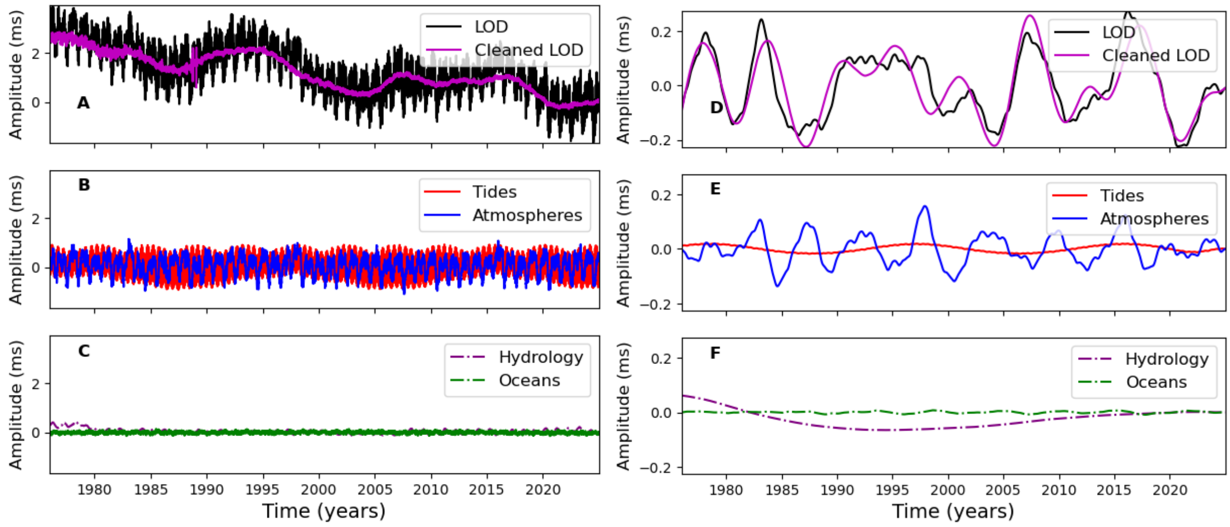

Figure 1: **A–C**: Unfiltered LOD and geophysical fluid time series. **D–F**: 4–10 year bandpass filtered LOD and geophysical fluid time series. **A, D**: LOD and cleaned LOD (LOD − tides − AAM − OAM) time series. **B, E**: Tidal and atmospheric time series. **C, F**: Hydrological and oceanic time series.

Tidal Contributions

Yoder *et al.* (1981) created a model which encompasses the tidal deformation effects on UT1, which forms the basis for the IERS 2010 conventions commonly utilised for LOD analysis. Tidal contributions were determined with a synthetic model, following the Petit *et al.* (2010) IERS conventions, utilising a sum of harmonic waves. These contributions are shown in Figure 1b,e. These contributions dominate over other LOD contributions at periods ranging from a week to a month (Lambeck 1980); however, they contain additional periodic variations in angular momentum ranging from 5 days up to 18.6 years (Petit *et al.* 2010).

Geophysical Surface Fluid Contributions

Atmospheric, oceanic, and hydrologic angular momentum excitation functions (sampled at rates ranging from 3–24 hours) were provided by GFZ (Dobslaw *et al.* 2010), and were averaged over 24 hours to align with the EOPC04 series.

Atmospheric angular momentum (AAM) dominates at shorter timescales, from intraseasonal to interannual (Chao *et al.* 2010). AAM is calculated from the summation of the motion term (calculated from the zonal wind field) and mass term (as a result of pressure variations) (Barnes *et al.* 1983; Chao *et al.* 2010). Most measurements of AAM utilise the inverted-barometer approach to correct for the effect of changing atmospheric pressure distributions on the ocean, which tends to have a small and nearly constant effect on the pressure (mass) term (Barnes *et al.* 1983; Chao *et al.* 2010).

Oceanic angular momentum (OAM) correlates with LOD at the seasonal and intraseasonal oscillation period (Chao *et al.* 2010). OAM is calculated from the summation of the motion term (current) and mass term (pressure), determined from general circulation models (Chao *et al.* 2010). Hydrological angular momentum (HAM) primarily consists of the mass term and is smaller in magnitude (less than 0.05 ms, see Figure 1c,f). The oscillation periods are primarily seasonal, with some interannual variations (Chao *et al.* 2010).

Solid Earth Contributions

Total angular momentum is conserved, so we tested variations of subtracting the aforementioned contributions to isolate core-originated LOD variations. There are two well-established harmonic components of 5.9 and 8.6 years, referred to as the SYO and EYO, respectively (Abarca del Rio *et al.* 2000; Gillet *et al.* 2010; Duan *et al.* 2020; Rosat *et al.* 2023). The cleaned signal is shown in Figure 1a,d. We limited our data analysis range from January 1976 to October 2024, due to the availability of atmospheric, oceanic, and hydrological angular momentum functions from 1976 onwards.

Methods

Filtering and Wavelet Transform

After cleaning the signal of external sources, we applied a first-order Butterworth bandpass filter (Butterworth 1930) of 4–10 years to isolate the intradecadal oscillations within the LOD time series. We then utilised the continuous wavelet transform (CWT, Torrence *et al.* 1998) to extract frequency information from the time series. The CWT is scale independent, which works well for time series that contain a range of dominant frequencies.

The CWT of a discrete time series (x_n) is the convolution of x_n with a scaled and normalised wavelet (ψ), and is represented by the following equation:

$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \psi^* \left[\frac{(n'-n)\delta t}{s} \right] \tag{1}$$

where W_n represents the wavelet transform, s represents the wavelet scale, n represents the localised time index, ψ represents the normalised wavelet equation, the asterisk represents the complex conjugate, and δt represents the time step.

This convolution is done N times for each scale to approximate the CWT, which allows one to do all N convolutions simultaneously in Fourier space with a discrete Fourier transform, where $k = 0, \cdots, N-1$ represents the frequency index. The wavelet transform is simply the inverse Fourier transform of the product, due to the convolution theorem:

$$W_n(s) = \sum_{k=0}^{N-1} \hat{x}_k \hat{\psi}^* (s\omega_k) e^{i\omega_k n \delta t} \tag{2}$$

where the caret represents the Fourier counterpart to the real series, and the angular frequency, ω_k:

$$\omega_k = \begin{cases} \frac{2\pi k}{N\delta t} & : k \leq \frac{N}{2} \\ -\frac{2\pi k}{N\delta t} & : k > \frac{N}{2} \end{cases}$$

In our analysis, we utilised a complex Morelet wavelet, ψ_0 (Morlet *et al.* 1982):

$$\psi_0(t) = \frac{1}{\sqrt{\pi B}} e^{-\frac{t^2}{B}} e^{i2\pi C t} \tag{3}$$

where t represents time, B the bandwidth, and C the centre frequency.

Finally, we normalised this wavelet utilising the following equation:

$$\psi(t) = \left(\frac{\delta t}{s} \right)^{1/2} \psi_0(t) \tag{4}$$

where $\psi_0(t)$ is normalised to have unit energy. We applied the CWT to the filtered LOD time series and investigated a variety of wavelet parameters, as well as the usage of zero-padding the LOD time series.

Typically, zero-padding is used in the CWT as we assume an infinite cyclical time series. We added zeros to each end of the time series before performing the CWT to limit edge effects; however, this introduced discontinuities and resulted in decreasing amplitudes at the ends of the time series. This also limited the range of the CWT we can interpret, as defined by the cone of influence (where edge effects become impactful, and defined mathematically by the e-folding time for the autocorrelation of the wavelet power at each scale). We compared a CWT graph for both a padded and unpadded LOD time series (see Figure 2), which had minimal differences within the interpretable region. Thus, the CWTs in this report were performed on an unpadded time series.

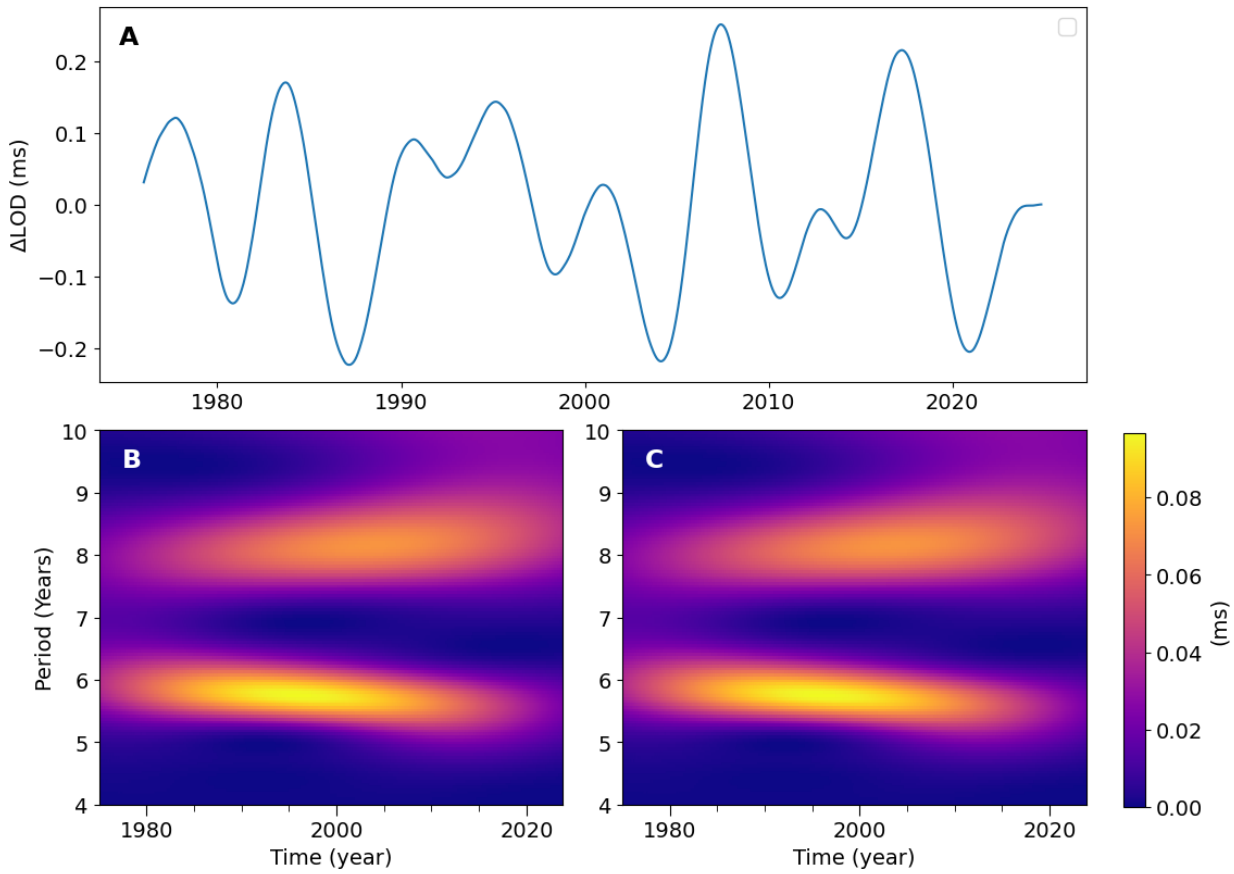

Figure 2: 4–10 year bandpass-filtered CWT LOD − AAM and tides. **A**: LOD − AAM and tides time series. **B**: Unpadded CWT. **C**: Padded CWT.

Results

We iteratively subtracted the angular momentum contributions from our LOD data series before applying the 4 – 10 year bandpass filter, and then applied the CWT to each iteration. We assessed the SYO/EYO in each iteration using 90% and 95% confidence intervals, highlighted in Figure 3 by the dotted and solid lines, respectively.

When we removed only zonal tides (Figure 3a), we find the EYO was very clear in this signal, as shown by the associated CWT (Figure 3e). However, the SYO was unclear in this figure, presumably due to masking from the atmospheres. When we additionally subtracted atmospheric contributions (Figure 3b), we found both the SYO and EYO were clear in this signal, as seen in the CWT (Figure 3f). This further suggests that the atmospheric contributions mask the SYO. When we further removed oceanic contributions (Figure 3c), we found the SYO and EYO were still clear in the CWT (Figure 3g), and show minimal difference to the previous iteration, where only atmospheres and zonal tides were removed (Figure 3f). Finally, we subtracted hydrologic contributions (Figure 3d), and found both the SYO and EYO were still clear; however, the EYO appears to weaken slightly in the CWT (Figure 3h) once hydrological contributions were removed.

Taking the residuals of each iteration (Figure 4) provided a visualisation of the differences between angular momentum iterations. Subtracting AAM (Figure 4a) resulted in a much stronger SYO, further highlighting that atmospheric contributions mask the SYO. We found minor variations in the EYO once we subtracted atmospheric contributions, but these variations are small in magnitude compared to the SYO (residuals of 0.005 versus 0.020 ms, respectively). We additionally subtracted OAM (Figure 4b), which resulted in a stronger SYO and slightly weakened the EYO. Additionally subtracting HAM (Figure 4c) resulted in a weaker isolation of both the SYO and EYO, with a residual of -0.020 ms. It also introduced temporal inconsistencies in the SYO, notably switching from a negative to positive residual around 2000. We found subtracting hydrologic contributions introduced inconsistencies, and worsened the isolation of the SYO and EYO.

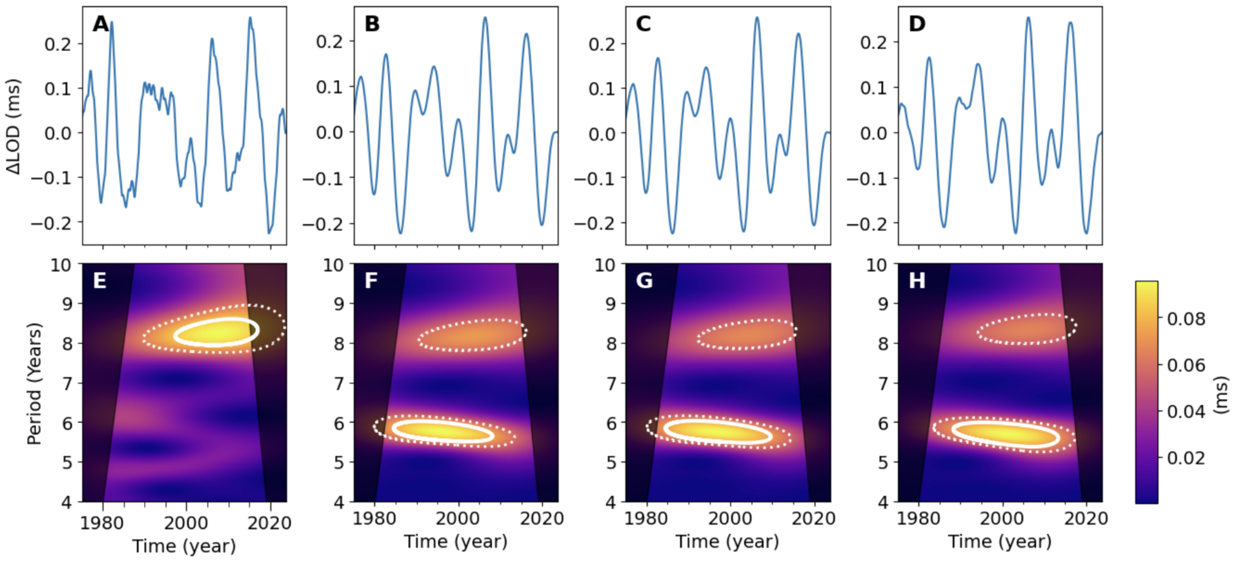

Figure 3: Geophysical fluid contribution iterations CWT, over a 40-year timescale from 1976–2024. Confidence intervals are indicated by a solid line for 95%, and a dotted line for 90%. **A–D**: 4–10 year bandpass-filtered LOD signal, where the y-axis represents the change in LOD in ms. **E–H**: CWT of the above LOD signals, where the y-axis represents the dominant period in years. Brighter colours signify a more dominant period, ranging from 0.02–0.04 ms. **A,E**: LOD — tides. **B, F**: LOD — AAM and tides. **C, G** LOD — OAM, AAM, and tides. **D, H**: LOD — HAM, OAM, AAM, and tides.

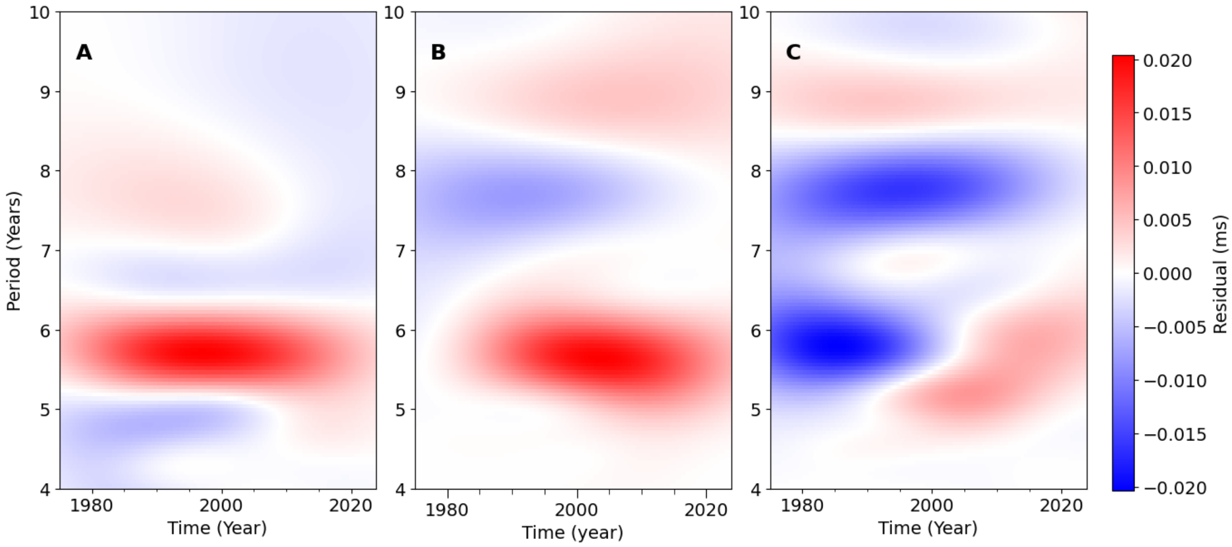

Figure 4: Residuals of 4–10 year bandpass-filtered CWT LOD geophysical fluid iterations. **A**: Residual of (LOD — AAM and tides) — (LOD — tides). **B**: Residual of (LOD — OAM, AAM and tides) — (LOD — AAM and tides). **C**: Residual of (LOD — HAM, OAM, AAM, and tides) — (LOD — OAM, AAM, and tides).

Discussion

Tidal and atmospheric excitation functions contributed significantly to LOD variations, and must be subtracted from the time series for further analysis of core signals, such as the SYO and EYO. Subtracting solely tidal contributions allows for investigations of the EYO at a statistically significant level, but does not reveal the SYO. This is likely due to the interference between the SYO arising from the core (e.g. Mound *et al.* 2006) and the atmosphere (e.g. Pfeffer *et al.* 2023). By additionally subtracting atmospheric contributions, we were able to isolate the SYO and clean residual signals in the 4–6 year period range. The atmosphere contains its own SYO (Abarca del Rio *et al.* 2000), which may act destructively with the core-originated SYO (e.g. Mound *et al.* 2003; Mound *et al.* 2006). This suggests that the atmosphere and LOD are anti-correlated at the SYO period, which aligns with findings in Rosat *et al.* (2023).

Subtracting oceanic contributions had minimal effect on the LOD time series or the CWT once we bandpass filtered within the 4–10 year range. For the purpose of analysing intradecadal oscillations, we therefore recommend removing oceanic angular momentum contributions for completeness, but this is not a necessity as it does not qualitatively affect the results. At shorter timescales (less than intraseasonal), such as those analysed by Chao *et al.* (2010), the effects of oceanic contributions must still be subtracted.

Subtracting hydrologic contributions significantly impacted the residuals in the 6–10 year period range, perhaps due to destructive interference with the core-originated LOD oscillations. This would be of scientific relevance if the angular momentum contributions from the hydrological models were trustworthy. However, as found by Pfeffer *et al.* (2023), current global hydrological models may be insufficient representations of hydrological processes, which may further contribute to the irregularities we observe in the CWT residuals. Due to this interference, potential irregularities, and the small magnitudes of our hydrologic contributions, we suggest that hydrologic angular momentum contributions should not be removed for intradecadal LOD analysis.

Cleaning the LOD signal of these external contributions is crucial for analysis of core-originated contributions. Once our LOD signal was cleaned of atmospheric and oceanic contributions (Figure 2c and g), we noted a general trend across our time series of the EYO slowly increasing in period length. This is contrary to results from Duan *et al.* (2020) and Ding *et al.* (2021) who found the EYO to be increasing in amplitude; however, they assumed a fixed period. The SYO appears to decrease in period length over time, and the 95% confidence interval ends in 2010 because of the interrupted SYO (Madsen *et al.* 2025). This was similarly found by Howard *et al.* (2025). As our time series length increases, the range of interpretable data will increase, allowing for more concrete conclusions regarding these apparent changes in oscillation period.

Conclusion

We investigated the effect of three geophysical surface fluid contributions on intradecadal variations in LOD. We found that subtracting tidal and atmospheric contributions within the intradecadal timescales is crucial for analysis of the SYO and EYO. Additionally subtracting oceanic contributions had minimal effect on our isolation of the SYO and EYO, and we suggest removing this is optional at the intradecadal scale. Given the current state of hydrological angular momentum models, we found that removing these from the LOD signals interferes destructively with known signals, and should therefore not be included in the signal cleaning process, in agreement with Pfeffer *et al.* (2023). After the appropriate signal cleaning (subtracting zonal tides, AAM, and OAM), we found indication that the EYO is slightly increasing in period. This is contrary to previous results from Duan *et al.* (2020) and Ding *et al.* (2021), who found it to be increasing in amplitude, although we note that their analysis considered the period to be fixed. We also found that the SYO has been decreasing in period, and our results show some indication of the SYO changing around 2010, in agreement with Howard *et al.* (2025) and Madsen *et al.* (2025).

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