The First-time Absence of Chandler Wobble since 2015 in the Observation History

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Abstract

The Chandler Wobble (CW) period is considered a single time-invariable constant, ~1.2 years, but the possible time-variability has not been examined using modern space-geodetic data. We first examined whether the Chandler period could vary with time on the assumption of minimum excitation power. Unexpectedly, the estimated Chandler period has been shortened by more than 60 days since about 2005. Moreover, by simple least-squares modeling, we found that CW started to be weaker in 2005 and almost disappeared in 2015. We interpret these results in both excitation and wobble domains as caused by the absence of CW for the first time in the observation history. Assuming no excitations of CW since 2005, the rather abrupt damping suggests the Q-value is below 25. Meanwhile, the analyses of the available atmospheric and oceanic angular momentum (AAM/OAM) functions indicate the significant amplitude of CW even after 2005, implying that the AAM/OAM functions are incomplete.

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Key Points:

- The Chandler Wobble has been weaker since around 2005 and almost disappeared in 2015 without being re-excited as of June 2022.
- Assuming no excitations since 2005, the abrupt damping by ~10 years suggests the smallest Q-value than ever estimated.
- The available atmospheric and oceanic angular momentum data cannot explain the cause(s) of the missing Chandler Wobble.

Abstract

The Chandler Wobble (CW) period is considered a single time-invariable constant, ~1.2 years, but the possible time-variability has not been examined using modern space-geodetic data. We first examined whether the Chandler period could vary with time on the assumption of minimum excitation power. Unexpectedly, the estimated Chandler period has been shortened by more than 60 days since about 2005. Moreover, by simple least-squares modeling, we found that CW started to be weaker in 2005 and almost disappeared in 2015. We interpret these results in both excitation and wobble domains as caused by the absence of CW for the first time in the observation history. Assuming no excitations of CW since 2005, the rather abrupt damping suggests the Q-value is below 25. Meanwhile, the analyses of the available atmospheric and oceanic angular momentum (AAM/OAM) functions indicate the significant amplitude of CW even after 2005, implying that the AAM/OAM functions are incomplete.

Plain Language Summary

Polar motion is a near-circular motion of the position of the Earth's spin axis around the North Pole. It consists of two periodic components, annual wobble (AW) and Chandler wobble (CW), in addition to the slower secular drift of the mean pole. While AW is a forced motion by the seasonal changes in the angular momentum of the Earth's surface fluids around the equatorial axes, CW is considered a free mode with a period of ~1.2 years determined by the Earth's mechanical response properties. Both AW and CW have been continuously observed as astronomical latitude changes since the late 19th century. Here, we show that the CW has been absent since 2015 for the first time in the observation history. Although the atmosphere and ocean have been considered the main excitation sources of CW, we show that the currently available estimates of the atmospheric and oceanic contribution cannot explain the ongoing

CW absence. Moreover, if the un-excitation of CW started from ~2005, as our analyses indicate, we are led to suggest a much quicker damping time for CW than previously thought. We may have to change our views on the excitation dynamics of CW.

1. Introduction

Chandler Wobble (CW) is one of the dominant components of polar motion, a long-period (> 1 day) motion of the Earth's spin axis relative to the rotating solid Earth. Annual wobble (AW) is another significant component of polar motion that is regarded as a "forced motion" by seasonal processes within the Earth's surface fluids. CW's excitation source(s) had been elusive, and earthquakes were once examined as a candidate (e.g., Dahlen, 1973). However, it is now widely accepted that the atmosphere, ocean, and possibly continental water are excitation sources (e.g., Furuya et al., 1996, 1997; Aoyama et al., 2003; Gross, 2000; Nastula et al., 2007). Its roughly 1.2-year period, more precisely estimated to be, e.g., 433.7 ± 1.8 days (Furuya & Chao, 1996), is considered to be constant as a period of "free oscillation" (e.g., Smith & Dahlen, 1981). Although the time-variable hypothesis on the Chandler period has been proposed (e.g., Carter, 1981; Sekiguchi, 1976), Okubo (1982) demonstrated through numerical simulations that the Chandler period could seem to be variable with time depending on the prescribed Q on the assumption of Gaussian random excitation process.

Since the 1970s, precise polar motion data have been accumulated with the advent of space geodetic techniques. However, no previous works on the time-variability of the Chandler period have been performed based on those higher-quality data in terms of precision and temporal resolution. This study thus initially aimed to examine whether the Chandler period could vary over time. However, the estimated "variability" turns out to be unexpectedly large and gets shorter and shorter, which is inconsistent with the previous understanding of the Chandler period. We interpret those results as caused by the absence of CW in the recent period and perform another analysis in the wobble domain, from which we can demonstrate when the CW started to be unexcited. While the CW amplitude is known to have been the smallest in the 1920s (e.g., Vondrák & Ron, 2005), we show that the latest amplitude of CW is much smaller and almost zero. Moreover, we show that the available AAM and OAM cannot reproduce the recent CW anomaly. Finally, we discuss the possible implications of these results for the dynamics of CW.

1. Data and Methods

We use the polar motion data, EOP 14 C04 (IAU 1980), which is provided by International Earth Rotation and Reference Systems Service (IERS) (Bizouard et al., 2017). The period of the data we used is between 1 January 1971 and 28 December 2021. We use Equation (2a) in Wilson (1985) to derive the "geodetic" excitation function. Here, we fix the Q-value with 100.

To examine the possible time-variability of the Chandler period (P), we first clipped the 12 years of polar motion data. After computing the geodetic excitation, we calculated the power spectrum density (PSD) for each excitation time series using the multi-taper method (Thomson, 1982); the quadric long-term trend was removed after the data was clipped. Then, to estimate the P during the clipped period, we searched, within a range of P, such a period that gave the minimum PSD in the frequency band around 0.8 cpy and would correspond to the P conforming to the minimum excitation hypothesis (Wilson & Vicente, 1990). We repeat these procedures by shifting the clipped 12 years of polar motion data daily. In the analysis below, we have also tested other lengths for cutting the data, changing from 12 years to 15 and 18 years, to derive the results independent of the data's clipped length.

To confirm the results in the excitation domain, we perform a simple least-squares analysis, fitting the polar motion data with two different models. The polar motion mainly comprises the AW (clockwise and counterclockwise), CW, and long-term motion. Thus, ignoring the time-variable amplitude of both AW and CW and more rapid polar motion, we can simply model the polar motion like:

$$M(t) = A \exp(2\pi \mathrm{it}/365.25) + B \exp(-2\pi \mathrm{it}/365.25) + C \exp(2\pi \mathrm{it}/P) + Dt^2 + Et + F\#(1)$$

where P is the Chandler period. By contrast, the model without CW is

$$M(t) = A \exp(2\pi \mathrm{it}/365.25) + B \exp(-2\pi \mathrm{it}/365.25) + Ct^2 + Dt + E\#(2)$$

Firstly, we fit the polar motion data with the "standard" model, Equation (1), and estimate the three components: CW, AW (prograde and retrograde), and the long-term secular motion. The total period of the data used to fit with the standard model is between 1 January 1971 and 31 December 2006. Here, we fix the Chandler period with 435 days. We call the modeled polar motion M_3^{EST}. The second model is a no-CW model, Equation (2), used to test the hypothesis that CW becomes negligible after 2015. The data used for fitting is between 1 January 2015 and 28 December 2021. We call the modeled polar motion M_2^{EST}. Then we compare the model M_3^{EST}, M_2^{EST} and the observed polar motion data M^{OBS}, extending the temporal coverage of M_3^{EST} and M_2^{EST} to the entire period with the estimated coefficients in Equations. (1) and (2).

We also use EOP C01 IAU 1980 provided by IERS, covering from 18 January 1890 to 31 December 2021, to compare the recent CW anomaly with those in the 1920s.

Moreover, to check if the available AAM and OAM can explain the recent CW anomaly, we first examined whether the power level of non-seasonal AAM and OAM function has changed over time, particularly before and after 2005. The

AAM and OAM are based on the NCEP reanalysis data and the output from the ECCO model, respectively (Salstein et al., 1993; Zhou et al., 2006; Fukumori et al., 2017). The AAM and OAM data start from 5 January 1962 to 30 December 2021 with a daily interval. Furthermore, we also performed an integration approach (Furuya et al., 1997; Bizouard et al., 2011) to examine whether the AAM and OAM could reproduce the recent CW anomaly. First, we split the entire AAM and OAM data into five groups of decade-long data, starting from 1 January in 1965, 1975, 1985, 1995, and 2005. Second, we remove the seasonal signals and long-term trend using the least-squares method. Then, the residuals are numerically integrated with zero initial values, assuming that the P and Q were fixed as 435 days 100, respectively.

1. Results

(a) Excitation domain analysis

The result of the "apparent" time-variable P is shown in Figure 1. In the case of 12 years' clipped data, we notice the 6-years periodic fluctuation in the estimated Chandler period with an amplitude of up to 18 days; we consider the 6-years fluctuation as an apparent change caused by the well-known 6-years beat that happens to be identical to a half of the clipped length of data. After January 2003, however, the estimated Chandler period became shorter and shorter and finally reached 365 days, which is inconsistent with the theory of the time-invariable Chandler period. Although we searched for the minimizing period around 0.8 cpy, this result suggests that only the AW is present in the recent decade. Also shown in Figure 1 are the results derived from different clipped polar motion data lengths. Although we no longer observe the 6-years periodic fluctuation, we can confirm the significant shortening of the Chandler period in the case of 15 years' clipped data; 18 years was too long to resolve the recent changes of the "apparent" CW period.

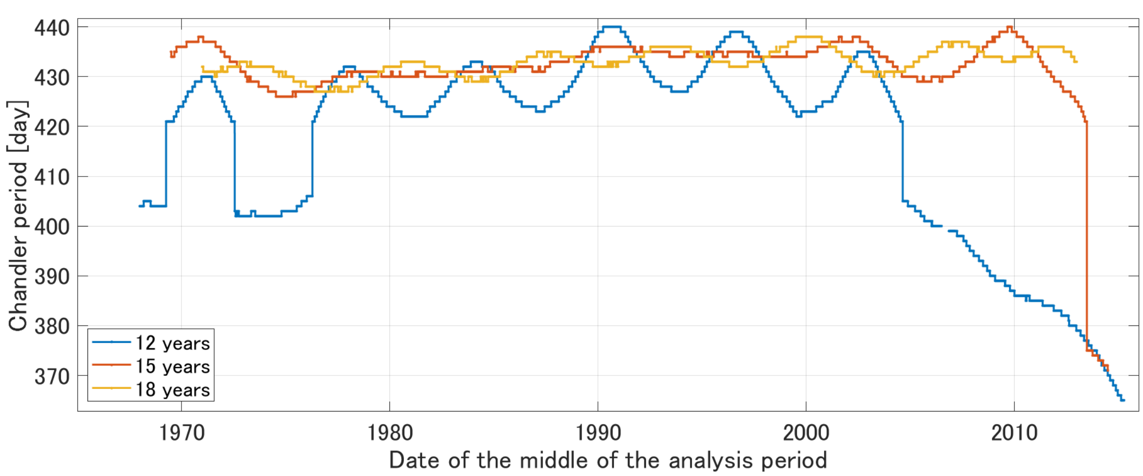

Figure 1. The "apparent" Chandler period changes with time. The horizontal axis indicates the date at the center of the analysis period. Blue, Red, and Yellow curves depict the estimated Chandler period from the clipped data of 12, 15, and 18 years, respectively.

1. Wobble domain analysis

The results of the polar motion modeling by $M_3^{\mathrm{EST}}$and $M_2^{\mathrm{EST}}$are shown in Figures 2 and 3 with the observed polar motion data. We realize that the amplitude of the 6-year beating in the observed data has been obviously smaller in recent years than previously (Figures 2a and 3a). We derive the M_3^{EST} in Figure 2 by fitting the model with the observed data from 1971 to 2007. The misfit residual between the model and the observation after 2005 becomes apparently larger than before. In Figure 3, we show the observed data with the model M_2^{EST} estimated only after 1 January 2015 (Figure 3a) and their misfit (Figure 3b).

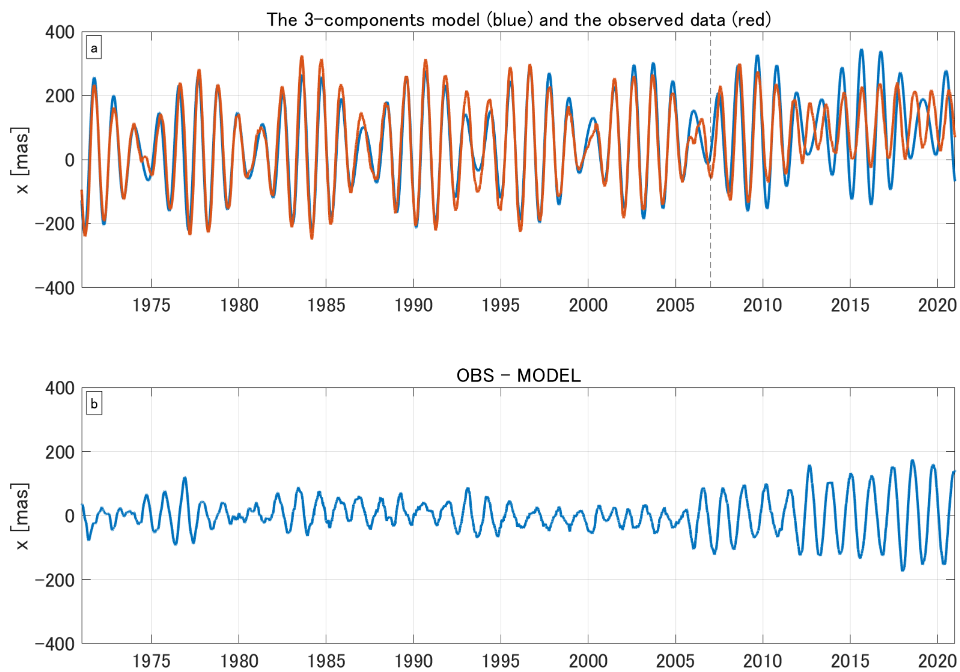

Figure 2. (a). The red and blue lines depict the observed polar motion $\mathbf{M}^{\mathrm{OBS}}$ and model $\mathbf{M}_3^{\mathrm{est}}$, respectively. The black dashed line indicates 31 December 2006, until when the data fitting for $\mathbf{M}_3^{\mathrm{est}}$ was done. (b). The residual between the observed and model data. The unit of the vertical axis is milli-arcseconds (mas). A similar time series was derived for the Y-component as well.

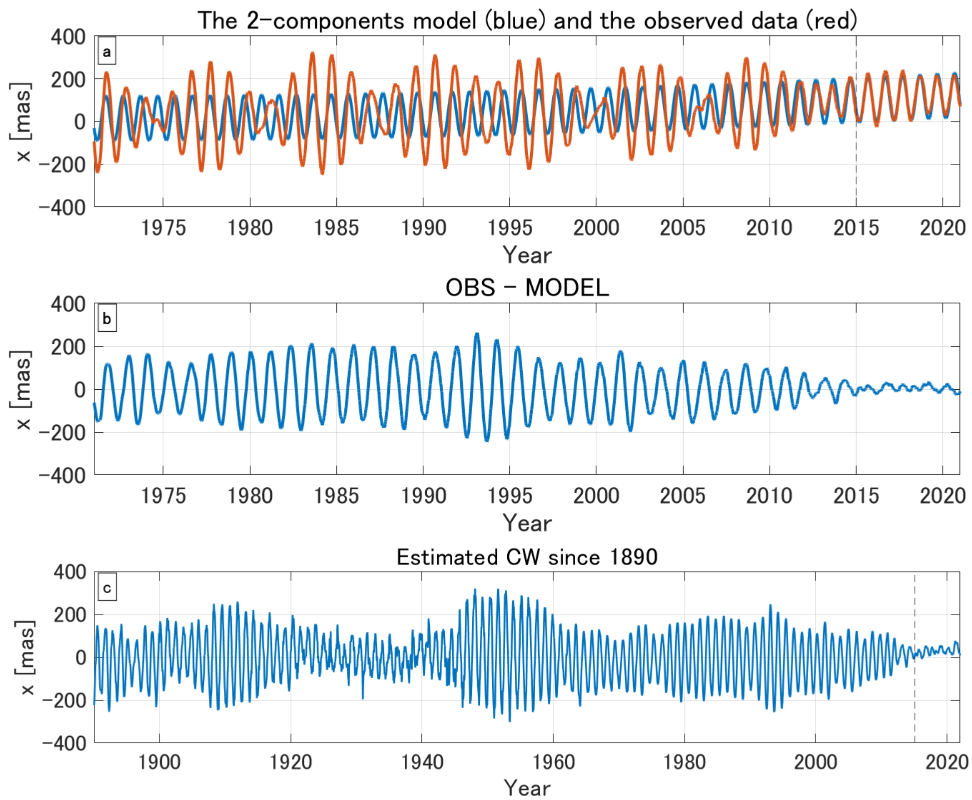

Figure 3. (a). The red and blue lines depict the observed polar motion M^{OBS} and the model M_2^{est}. The black dotted line indicates 1 January 2015, when the data fitting to derive M_2^{est} starts. (b). The residual between the observed and model data. (c) The residual between the observed and the model using the data EOP C01 IAU 1980. It can be regarded as CW since 1890. A similar time series was derived for the Y-component as well.

Because the AW does not change its phase by definition and its amplitude variation has been insignificant, we can trace the CW amplitude back to the 1900s by removing the AW derived by fitting the post-2015 polar motion data, given the absence of CW after 2015.

Figure 3c shows the difference, indicating the X-component of CW component and misfit residuals. Although we can confirm the small CW in the 1920s (e.g., Vondrák & Ron, 2005), the "post-2015 CW" is much smaller and almost zero. In this regard, we can claim that the post-2015 disappearance of CW is the first time in observation history.

1. Analysis results of the AAM and OAM data

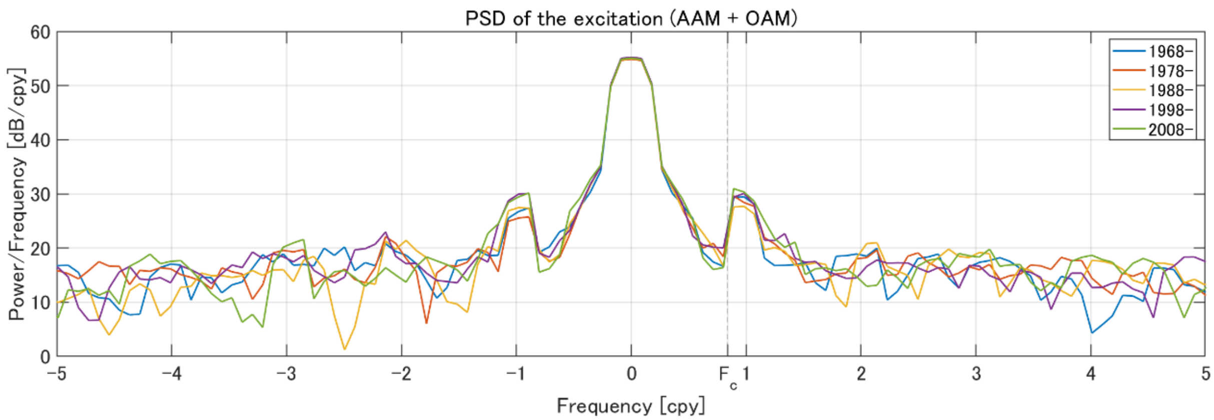

Figure 4. The Power Spectrum Density (PSD) of the non-seasonal AAM + OAM excitation function with 10 years' clipped data. The black dashed line indicates the Chandler frequency, 0.84 cpy.

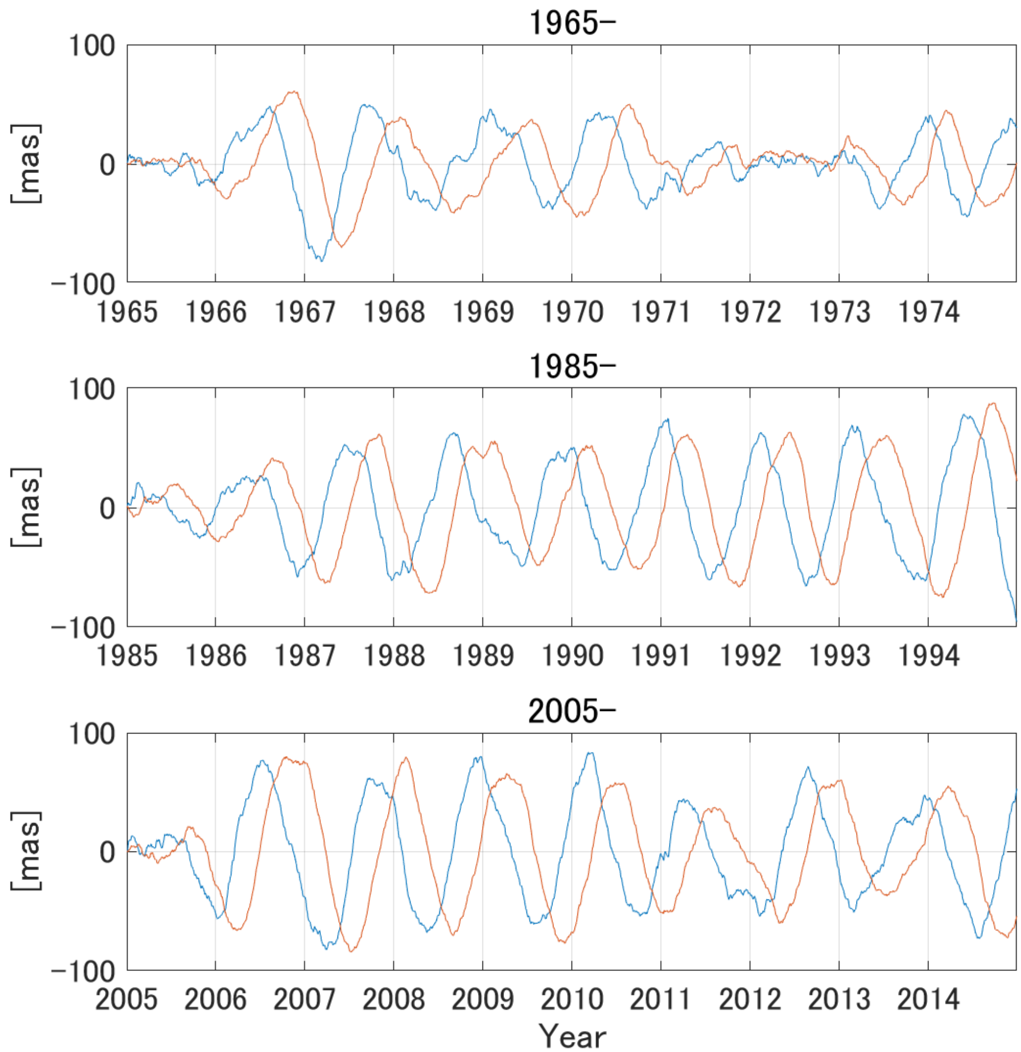

Figure 5. The simulated polar motion from the integration of the AAM + OAM function. The blue and red lines present X and Y components, respectively.

Figure 4 shows the PSD of the "clipped" AAM + OAM excitation series with different 10-years of coverage. Although the spectral resolution is limited in the lower frequencies, there is no noticeable reduction in the power level around the Chandler frequency in the post-2008 data, during which the CW amplitude became much smaller than before.

Figure 5 shows the integration of the AAM + OAM function initiated in 1965, 1985, and 2005. Although the recent absence of CW has been persistent for over 5 years (Figure 3), no integrated CW time series since 1965 shows such a long-term absence (Figure 5), consistent with our inference from Figure 4. Namely, the currently available AAM + OAM excitation functions do not reproduce the observed CW's anomaly.

1. Discussion and Conclusion

The analysis results in both the excitation and wobble domains show that the CW started to behave abnormally around 2005 and almost disappeared in 2015 (Figure 3). The absence of CW seems to have been persistent as of writing this manuscript.

Suppose that the CW started to be unexcited in 2005. Then, the disappearance of CW after 2015 indicates that the e-folding damping time is less than 10 years, from which we can readily infer a very small Q-value below 25. To our knowledge, this is not only the smallest estimate for the Q-value of CW in the previous estimates (e.g., Furuya & Chao, 1996) but also the most simply derived estimate. Moreover, the low Q-value has implications for the power and excitation process, as argued below.

It is widely accepted that the atmosphere and ocean are the primary excitation sources of CW (e.g., Gross, 2000; Brzezinski & Nastula, 2002, Bizouard et al., 2011). However, the PSD results around the Chandler frequency (Figure 4) and the integration of the AAM plus OAM (Figure 5) cannot explain the absence of CW in the recent decade. Figures 4 and 5 suggest that the present AAM and OAM are still not accurate enough to reproduce the recent CW anomaly and that some other signals could be missing either in the AAM or OAM or possibly in both. Otherwise, another contribution from hydrological and cryospheric angular momentum. (HAM/CAM) changes might be canceling out the power of AAM and OAM, whereas the impact of HAM/CAM needs to be further examined in detail (e.g., Śliwińska et al., 2021).

As another anomaly in polar motion since around 2005, Chen et al. (2013) reported that the long-term motion began drifting to the east, which was attributed to the rapid ice melting in Greenland. To explain the absence of CW, on the other hand, we should expect a reduction in the spectral power of the excitation around the Chandler frequency. However, the effect of abrupt ice melting is more significant in the lower frequency than around the Chandler frequency and thus is unlikely to account for the missing CW. Nonetheless, we speculate that the absence of CW and the direction shift of polar drift in 2005 would be more or less associated with the recent global warming trend. However, by analogy with the classical thermal-noise model, global warming should increase the noise level and amplify the CW, which conflicts with the observation, suggesting that the simple analogy is wrong. Therefore, we must carefully examine the impact of global warming upon AAM/OAM and HAM/CAM.

Previous studies have reported that the CW amplitude used to be much smaller in the 1920s to 1940s and that the CW phase also underwent dramatic changes (e.g., Vondrák & Ron, 2005). Based on the integration approach by a series of Gaussian random noise, Chao and Chung (2012) concluded that the minimal amplitude of CW in the 1920s "was simply fortuitous by chance". As long as the excitations for CW are assumed to be random white noise processes, we may also consider the post-2015 anomaly as caused by chances.

Meanwhile, regarding the CW excitation processes, it is still an open question whether they are random or resonant. Although numerous previous studies on CW excitations have explicitly or implicitly assumed the Gaussian random process (e.g., Okubo, 1982; Chao & Chung, 2012), we can recall several earlier studies that instead conform to the resonant excitation model (e.g., Furuya et al., 1996, 1997; Plag, 1997; Aoyama & Naito, 2001; Aoyama et al., 2003). In the wake of the post-2015 CW anomaly, it would be hard for the random excitation model to point out any specific phenomena in either atmosphere or the ocean. On the other hand, the resonant excitation model will correspond to an abrupt termination of the continual excitation process with a characteristic period of ~14 months, which is what earlier studies suggested in the atmosphere (e.g., Furuya et al., 1996, 1997; Plag, 1997; Aoyama & Naito, 2001; Aoyama et al., 2003). Moreover, any resonant excitation sources, if any, would more easily excite the CW even with very low Q.

Unfortunately, the follow-up studies on atmospheric resonant excitation have been lacking because the precision and accuracy of meridional wind velocities were imperfect at least until the early 2000s. In light of the recent advances in modeling the atmosphere (e.g., Alexander et al., 2010), it needs to re-examine the effect of atmospheric wind term using the state-of-the-art analysis data and model. One intriguing global-scale atmospheric phenomenon in the recent decade is the disruption of the equatorial quasi-biennial oscillation (QBO) in the 2015/2016 winter (Osprey et al., 2016; Newman et al., 2016) and 2019/2020 winter (Anstey et al., 2021). As QBO is essentially zonally symmetric wind oscillation in the tropics with its mean period of 28 months, it can affect the length-of-day change (e.g., Chao, 1989) but should not directly impact the polar motion excitation. However, since even QBO would be neither strictly symmetric around the equator nor uniform along the entire longitude, it deserves to examine if and how the QBO could affect the equatorial angular momentum budgets and possibly link to the CW excitation.

Open Research

The polar motion data EOP C04 IAU1980 and EOP C01 IAU1980 used in this study are freely available from IERS https://www.iers.org/IERS/EN/DataProducts/EarthOrientationData/eop.html. The AAM and OAM data are archived at the Paris Observatory https://hpiers.obspm.fr/eop-pc/index.php?index=excitactive.

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