Semi-decadal and decadal signals in atmospheric excitation of length-of-day

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Abstract At timescales shorter than about 2–yr, non-tidal length-of-day (LOD) variations are mainly excited by angular momentum exchanges between the atmospheric, oceanic and continental hydrological fluid envelopes and the underlying solid Earth. On decadal timescales, the dominant excitation sources of LOD variations are from core and mantle coupling. But the excitations of semi-decadal (specifically 2–8 yr here) signals in length-of-day is less clear, and have been characterized by signals with a wide range of periods and varying amplitudes, including a peak at about 5–6 yr. Here sliding window average filtering is applied to isolate semi-decadal signals from both geodetic technique observed LOD excitation (shorter to geodetic excitation for convenience) and atmospheric LOD excitations. Based on careful comparison between these two excitation series, we find that (1) the 5–6 yr oscillation in geodetic excitations is not periodically consistent; (2) there is a 5–yr oscillation in atmospheric excitation series, and atmosphere can explain all the semi-decadal oscillation shorter than about 5–yr in geodetic LOD excitations; (3) contributions from atmosphere to 5–6 yr oscillation in LOD variations is small and cannot be clearly determined; (4) it appears that there are some modest long-period (longer than 10 yr periods) signals in the atmospheric excitations, but these could be artifacts of the models. Then we compare those peaks/troughs epochs in the residual series between geodetic and atmospheric excitations (ROBS_ATM series for short) with the observed geomagnetic jerks, and find that all of the geomagnetic jerks can match one peaks/troughs in the ROBS_ATM series, and they occurred at the same time or within one year before these peaks/troughs. It implies that there is a common origin for the processes giving rise to geomagnetic jerks and the remaining 5–6 yr oscillation in the ROBS_ATM series.

1. Introduction

Changes in the excess length-of-day (LOD), compared to 86 400 SI s, reflect variations of the speed of the Earth’s axial rotation. The non-tidal LOD variations, over timescales shorter than about 2 yr, are mainly caused by the dynamic interaction of the solid Earth with its fluid envelopes (atmosphere, oceans and continental hydrology; e.g. Barnes et al., 1983; Höpfner, 1998; Brzeziński et al., 2002; Gross, 2015; Yu et al., 2018). LOD changes are ultimately largest on decadal and longer time scales and involve angular momentum exchanges between the solid mantle and fluid outer core (e.g. Bloxham, 1998; Davies et al., 2014; Jault, 2004; Kuang & Chao, 2003; Roberts & Aurnou, 2012). There is also a quite stable and continuous 5–6 yr oscillation in the residuals of the differences between geodetic and atmospheric LOD excitations (ROBS_ATM series for short), with an amplitude about 0.2–0.3 ms. Many studies focus on this 5–6 yr oscillation and already obtained many useful conclusions (e.g. del Rio et al., 2000; Duan et al., 2018; Hao & Chao, 2018; Holme & De Viron, 2013; Liao & Greiner-Mai, 1999; Silva et al., 2012). These studies only examined the filtered ROBS_ATM series (e.g. Holme & De Viron, 2013; Liao & Greiner-Mai, 1999) and discussed possible excitation mechanisms in the deep earth for this 5–6 yr oscillation (e.g. Duan et al., 2018; Hao & Chao, 2018; Silva et al., 2012), but paid less attention to whether there is also a 5–6 yr oscillation in the original atmospheric excitation series.

We focus on the semi-decadal (2–8 yr) signals in atmosphere and LOD observation series individually. By working in the time domain rather than the frequency domain, we compare semi-decadal LOD signals in geodetic excitations from IERS 14C04 and atmospheric excitations from NCEP (National Centers for Environmental Prediction) (e.g. Kalnay et al., 1996, and revised by Zhou & Salstein, 2006) and ESMGFZ (Earth System Modelling group at GFZ) (e.g. Dobslaw & Dill, 2018) model AAM (Atmospheric Effective
Angular Momentum) series. Sliding window average filtering is applied to both original IERS 14C04 geodetic and NCEP/ESMFGFZ atmospheric excitation series to remove their trends longer than decadal and those signals shorter than about 2 yr. By using sliding window average filtering, we get semi-decadal signals from IERS 14C04 and NCEP/ESMFGFZ.

Rapid variation impulses sourcing from the earth core to suddenly change the surface field is called as a “geomagnetic jerk”. A large geomagnetic jerk not only changes Earth’s magnetic field it also changes LOD (Mandea et al., 2000; P. De Michilis et al., 2005; Olsen & Mandea, 2007). Geomagnetic jerks were firstly noted by Courtillot et al., 1978. The clearest ones, observed all over the world, happened in 1969, 1978, 1991, and 1999 (Brown et al., 2013; Pinheiro et al., 2011). Other events in 1932, 1949, 1958, 1986, and 2003 were detected only in some parts of the world (Chulliat et al., 2010; Silva & Hulot, 2012; Wardinski et al., 2008). The most recent geomagnetic jerks occurred near epochs 2007, 2011 and 2014 (Chulliat et al., 2010; Chulliat et al., 2015; Chulliat & Maus, 2014; Torta et al., 2015). These events are believed to originate in rising blobs of metal that form deep inside Earth (Aubert & Finlay, 2019). Here we compare the peaks/troughs epochs in the residuals of IERS 14C04 and NCEP excitation series (RIERS_NCEP series for short) with the above observed geomagnetic jerks, and demonstrate that geomagnetic jerks can excite the remaining 5~6 yr oscillation in the RIERE_NCEP series.

2. Data

The EOP 14C04 (IAU2000A version) series from the International Earth Rotation and Reference Systems Service (IERS) provides internationally recognized EOP, recently updated to be consistent with the new ITRF2014 terrestrial reference frame (see hpiers.obspm.fr/eoppc for details; data used in this paper were downloaded on August 1st, 2019). Past versions of this series, which is based on a non-rigorous combination of raw measurements made by independent space geodetic observing systems, have been most widely used for excitation studies (e.g. Altamimi et al., 2016; Bizouard et al., 2017). The tidal effects are removed with the model recommended by the IERS 2010 Conventions (e.g. Petit & Luzum, 2010). The Fortran routine RGZONT2.F provided by R. Gross (JPL) through the IERS website is applied here to derive this correction, which includes variations due to the elastic body tide (Yoder et al., 1981), the inelastic body tide (Wahr & Bergen, 1986) and the ocean tide (Kantha et al., 1998), see http://tai.bipm.org/iers/convupdt/convupdt_c8.html.

NCEP re-analysis products (e.g. Kalnay et al., 1996) span the period from 1948 to the present and were obtained from the IERS Special Bureau for the Atmosphere. The data set contains 6-hr values of AAM driven by changes in atmospheric pressure and atmospheric winds. The angular momentum due to winds has been computed as described in Zhou and Salstein (2006), who reprocessed AAM series by integrating zonal and meridional winds from the Earth’s surface to 10 hPa, the top of the atmospheric model. The surface topography is taken into account when calculating the atmospheric motion term (e.g. Aoyama & Naito, 2000). The Earth System Modelling group at ESMGFZ routinely also provides EAMF (Effective Angular Momentum Functions) describing the non-tidal geophysical excitations of Earth orientation changes due to mass redistribution and relative motion in atmosphere (e.g. Dobslaw & Dill, 2018). ESMGFZ AAM is based on re-analysis and operational analysis outputs from ECMWF (European Centre for Medium-Range Weather Forecasts). The ESMGFZ AAM temporal resolution is 3 hr (given at 0.5° equiangular grid points). Tidal variations for 12 most relevant frequencies are fitted and removed by ESMGFZ from the data to retain the non-tidal signals only. Further information on the products is provided via the webpage www.gfz-potsdam.de/en/esmdata. Detailed information of the data sets used in this paper is listed in the table below.

Though NCEP AAM series are available from 1948, only results from January 1st, 1962 to December 31st, 2018 (57 years in total) are used due to the later start of IERS 14C04 series. This time span is sufficient for study of both semi-decadal and decadal signals. The geodetic LOD excitations from IERS 14C04 are sampled every day, NCEP and ESMGFZ AAM are sampled every 6 hr and 3 hr. To match the sampling of IERS 14C04, NCEP and ESMGFZ data are averaged from 6 hr and 3 hr to daily, respectively.

3. Method

For geodetic excitations from IERS 14C04, decadal and longer oscillations are dominant. 8-yr sliding window average filtering is applied first to remove the secular (decadal) trends from IERS 14C04 to
emphasize the semi-decadal and seasonal variability. Then 2-yr sliding window average filtering is applied again to remove the signals shorter than about 2 yr, after that we get semi-decadal signals. The original and filtered semi-decadal signals of IERS 14C04 geodetic excitations are shown in the Figure 1.

As we know, all smoothing methods are unreliable near the ends. The advantage of the sliding window is that the unreliable part is limited strictly to the last bin on each end, not in any of the middle segments. So, in the two lower panels, only data values from 1967 to 2013 (47 yr in total) are available.

From the bottom panel of Figure 1 we can see that the amplitude of semi-decadal signals in IERS 14C04 are around ±0.2 ms, and the periodicity has apparent abnormally, that is, characterized by signals with a wide range of periods and varying amplitudes, but a single peak around 5~6 yr is not obvious or continuous.

Similarly, for NCEP and ESMGFZ excitation series, 8-yr sliding window average filtering is applied first to remove the decadal trends, and then 2 yr sliding window average filtering is applied again to remove the signals shorter than about 2 yr, to obtain the semi-decadal signals. The original and filtered results of NCEP and ESMGFZ are compared in the Figure 2.

**Figure 1.** (top panel) Geodetic LOD excitations from IERS 14C04 over the recent period from January 1st, 1962 till December 31st, 2018. The blue color is the original geodetic LOD excitation series and the red color is the decadal trends determined by 8-yr sliding window average filtering. (middle panel) Geodetic LOD excitations after decadal trends removed. (bottom panel) Semi-decadal signals after removing both decadal trends and signals shorter than 2 yr. The unit of geodetic LOD excitations is ms.

| LOD Excitations Provided by EOP Series and Two Geophysical Models |
|---------------------------------------------------------------|
| IERS 14C04 | NCEP (AAMs) | ESMGFZ (AAMs) |
| availability | since 1962 | since 1948 | since 1976 |
| resolution | 1 d | 6 hr | 3 hr |
From the middle panel of Figure 2 we can see an obvious difference between decadal signals in NCEP and ESMGFZ excitation series. Those variations at periods longer than 1 yr in the AAMs have been considered as longer-term instabilities in the atmosphere modeling, which are known to happen for various reasons, such as caused by the signal processing procedures or to some extent due to small variations in the model developments or in their imperfect source data sets. So both of the small decadal variations in Figure 2 could be artifacts of the atmosphere models. In the bottom panel of Figure 2, there are also semi-decadal signals in both NCEP and ESMGFZ excitations, and they correspond quite well. So we believe that the semi-decadal signals in NCEP and ESMGFZ excitation series in the bottom panel of Figure 2 are likely reliable, and the NCEP series will be used to compare with semi-decadal signals in IERS 14C04 geodetic excitations in the next section due to its longer time spans. Comparing with the bottom panel in Figure 1, the amplitude of NCEP/ESMGFZ semi-decadal signals is only slightly smaller, around 0.15 ~ 0.2 ms.

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4. Results

First, NCEP excitations are subtracted from IERS 14C04 geodetic excitations, and their residual series, $R_{\text{IERS-NC}}$ is obtained. Then 7-yr sliding window average filtering is applied to remove the decadal trends from the $R_{\text{IERS-NC}}$ series. We know that NCEP correction accounts for most of the LOD variations at yearly and shorter periods. The remaining short-period signals in $R_{\text{IERS-NC}}$ is dominantly semi-annual, but here we still use a 2 yr sliding window average filtering both to eliminate this signal and also to remove shorter-period noise, which corresponds to differencing the semi-decadal signals in IERS 14C04 (bottom panel in
This filtered residual series we name as $R_{\text{IERS-NCEP}}$ (see bottom panel of Figure 3).

From the middle panel of Figure 3 we can see that the high-frequency noise before 1985 is obviously stronger than the noises in later data. The reason is that the post-VLBI observing era only began in 1984 and was not so reliable for the first several years (Carter et al., 1984; Robertson et al., August 1985). From the bottom panel, the dominant semi-decadal signals in $R_{\text{IERS-NCEP}}$ series is 5–6 yr period, and the amplitude of this oscillation varies with time. This argues against the results of Holme, R. & De Viron, O., 2013, while in favor of del Rio et al., 2003, that such variations in amplitudes or periods in 5–6 yr oscillations maybe originate from solar processes. Figure 4 gathers together the semi-decadal signals in IERS 14C04 (bottom panel in Figure 1), NCEP (bottom panel in Figure 2) and $R_{\text{IERS-NCEP}}$ series (bottom panel in Figure 3).

From the first panel in Figure 4, there is a 5 yr oscillation in NCEP excitation series, and 5–6 yr oscillation in residual series $R_{\text{IERS-NCEP}}$, but no obvious or continuous signals around 5–6 yr in original IERS 14C04 geodetic excitation series. For the second panel in Figure 4, the light blue curve is $R_{\text{IERS-NCEP}}$ series, from the third panel in Figure 3, which is the filtering series after decadal signals and shorter than 2 yr signals removed from $R_{\text{IERS-NCEP}}$. The pink curve is $R_{\text{IERS-NCEP}}$ series, which is the residuals between semi-decadal IERS 14C04 and semi-decadal NCEP. We found that $R_{\text{IERS-NCEP}}$ and $R_{\text{IERS-NCEP}}$ series are the same (so we can see only one curve here), indicating that the 5–6 yr oscillation in $R_{\text{IERS-NCEP}}$ and $R_{\text{IERS-NCEP}}$ are both from the difference of semi-decadal IERS 14C04 geodetic and semi-decadal NCEP atmospheric excitation series. Comparing semi-decadal IERS 14C04 with $R_{\text{IERS-NCEP}}$ series, NCEP excitations remove all the semi-decadal signals shorter than about 5 yr in IERS 14C04. After subtracting NCEP excitations from IERS 14C04, 5–6 yr oscillation is the dominant semi-decadal signals left in $R_{\text{IERS-NCEP}}$. $R_{\text{IERS-NCEP}}$ corresponds with IERS 14C04 quite well in both amplitudes and phases, and their
The correlation coefficient is 0.8940, while the correlation between R_{IERS-NCEP_2} and NCEP excitations is not obvious, indicating that atmosphere cannot excite clearly determined 5~6 yr oscillation in LOD geodetic excitations. Excitations from deep earth may excite nearly all of the 5~6 yr oscillation in LOD variations. Before 2000, NCEP series matches nearly every peak/trough in IERS 14C04, and they have similar phases variations. The correlation coefficient between IERS 14C04 and NCEP before 2000 is 0.4095. After 2000, the amplitudes and phases of IERS 14C04 and NCEP excitation series differ greatly. Above all, atmosphere can account for all of the semi-decadal oscillation shorter than about 5 yr in geodetic LOD excitations.

Rapid variation impulses sourcing from the earth core to suddenly change the surface field is known as a "geomagnetic jerk". A large geomagnetic jerk not only changes Earth's magnetic field it also changes the LOD. The clearest ones, observed all over the world, happened in 1969, 1978, 1991, and 1999. Other events in 1932, 1949, 1958, 1986, and 2003 were detected only in some parts of the world. The most recent

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**Figure 4.** (first panel) Comparisons between the semi-decadal signals of IERS 14C04 (from bottom panel of Figure 1), NCEP (from bottom panel of Figure 2) and the residuals of these two series (semi-decadal IERS 14C04 – semi-decadal NCEP), R_{IERS-NCEP_2} for short. (second panel) Comparison between two residual series, R_{IERS-NCEP_1} (from bottom panel of Figure 3) and R_{IERS-NCEP_2} (from first panel of Figure 4). Parts of peaks/troughs epochs information of R_{IERS-NCEP_2} residual series are also indicated.

**Table 2**

| epochs                  | 1969 | 1978 | 1986 | 1991 | 1999 | 2003 | 2007 | 2011 | 2014 |
|-------------------------|------|------|------|------|------|------|------|------|------|
| geomagnetic jerks       |      |      |      |      |      |      |      |      |      |
| peaks/troughs in R_{IERS-NCEP_2} series | 1969 | 1978 | 1986.5 | 1991 | 2000 | 2003.5 | 2007 | 2012 | -    |

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geomagnetic jerks occurred near epochs 2007, 2011 and 2014. Table 2 gathers together parts of peaks/troughs information of \( R_{\text{IERS-NCEP}_2} \) series (from the bottom panel of Figure 4) and observed geomagnetic jerk epochs.

For all of the observed 9 geomagnetic jerks except 2014 (which is too recent for the available LOD data set to test), no matter global or regional, can match one 5–6 yr oscillation peak or trough in the \( R_{\text{IERS-NCEP}_2} \) series. Comparing \( R_{\text{IERS-NCEP}_2} \) series with geomagnetic jerks, on the epochs of 1969, 1978, 1991 and 2007, there are no apparent lags between the peaks/troughs of \( R_{\text{IERS-NCEP}_2} \) series and geomagnetic jerks. For epochs of 1999 and 2011, geomagnetic jerks occurred one year before the peaks/troughs in \( R_{\text{IERS-NCEP}_2} \) series, and for the epochs of 1986 and 2003, geomagnetic jerks occurred just half year before the peaks/troughs in \( R_{\text{IERS-NCEP}_2} \) series. The fact that the 5–6 yr oscillation in \( R_{\text{IERS-NCEP}_2} \) series are correlated with the known geomagnetic jerks within the past 47 years implies that their driving source and its associated mechanism are identical.

5. Conclusions

In this study, we compared atmospheric excitations from NCEP and ESMGFZ AAM series and found that there are semi-decadal and decadal oscillations in both NCEP and ESMGFZ excitation series. The semi-decadal oscillations in NCEP and ESMGFZ excitation series correspond quite well with each other and their amplitude magnitudes are similar to semi-decadal signals in geodetic LOD excitation series. There is no obvious 5–6 yr oscillation in original IERS 14C04 geodetic excitation series (or this signals is not continuous, and hidden by the other semi-decadal signals), but an oscillation is apparent around 5 yr period in NCEP/ESMGFZ atmospheric excitation series. Based on the comparisons between two panels in Figure 4, the line in second panel becomes much smoother than the lines in the first panel, which indicates that, for the semi-decadal signals between 2 yr and 8 yr, atmospheric excitation can explain all of the signals shorter than 5 yr in LOD variations. There are no obvious phases or amplitudes differences between IERS 14C04 excitation series and the \( R_{\text{IERS-NCEP}_2} \), indicating that excitations from deep earth excite nearly all of the 5–6 yr oscillation in LOD variations. Decadal signals in atmosphere are weak, with the largest peak-to-peak amplitude of only about 0.1 ms, and there is an obvious difference between the decadal signals in NCEP and ESMGFZ excitation series. Such differences may be caused by the signal processing procedures or to some extent due to small variations in the model developments or in their input data sets. But filtered atmosphere decadal signals results in this paper can offer a reference for the level of decadal stability that one can expect for such AAM models. All of the geomagnetic jerks can match one peak/trough in the \( R_{\text{IERS-NCEP}_2} \) series, and they occurred at the same time or within one year before the peaks/troughs. It implies that there is a common origin for the processes giving rise to geomagnetic jerks and the remaining 5–6 yr oscillation in the \( R_{\text{IERS-NCEP}_2} \) series.

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