ESD Ideas: A 6-year oscillation in the whole Earth system?

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Abstract. An oscillation of about 6 years has been reported in Earth's fluid core motions, magnetic field, Earth's rotation, and crustal deformations. Recently, a 6-year cycle has also been detected in several climatic parameters (e.g., sea level, surface temperature, precipitation, land hydrology, land ice, and atmospheric angular momentum). Here we suggest that the 6-year oscillations detected in the Earth's deep interior, rotation, and climate are linked together, and that the core processes previously proposed as drivers of the 6-year cycle in the Earth's rotation, cause in addition the atmosphere to oscillate together with the mantle, inducing fluctuations in the climate system with similar periodicities.

Numerous studies have reported a ~6-year cycle in the rotation of the Earth's mantle (or equivalently in the length of day -LOD-) (e.g., Abarca de Rio et al., 2000, and many subsequent publications). While LOD oscillations related to seasonal changes and the El Niño-Southern Oscillation (ENSO) are well explained by the exchange of angular momentum from the atmosphere (and to a lesser degree, from the oceans and hydrosphere) to the mantle, the 6-year signal in LOD has been attributed to deep Earth processes, namely exchange of angular momentum between the core and the mantle (see Rekier et al., 2022 and references herein) (Fig.1). However, the exact nature of the torques at work is still debated. One mechanism invokes electromagnetic coupling. Relying on geomagnetic data (that display a clear 6-year cycle, in particular in the secular acceleration) and inferred core flow modelling, Gillet et al. (2010) showed that the 6-year signal in LOD can be predicted by the geostrophic wave-like pattern induced by torsional Alfven waves travelling from the inner core to the outer core equator, with a fundamental mode of 6 years. Another proposed mechanism is a gravitational coupling between the mantle and the inner core (e.g., Chao, 2017).

A recent study by Chen et al. (2019) also reported a strong 6-year signal in the motion of the Earth's axis of rotation. Mass redistributions in the surface fluid envelopes (atmosphere, oceans, land hydrosphere) appear unable to explain this observation, suggesting rather deep Earth sources as for LOD. Using satellite laser ranging and GRACE space gravimetry data, Chao and Yu (2020) reported a 6-year variation in the degree 2, order 2 spherical harmonics of the gravity field (or equivalently in the ellipticity of the Earth's equator). They attributed it to a gravitational coupling between the solid inner core and the Earth's mantle. Other studies (Watkins et al., 2018, Ding and Chao, 2018) based on GPS (Global Positioning System) data also reported a 6-year cycle in crustal deformations. According to these authors, loading from the surface fluid envelopes (atmosphere, ocean and land hydrosphere) cannot explain this 6-year signal. They rather suggest core-mantle coupling as the source of the surface deformations.

More recently, a series of observations have incidentally reported a 6-year oscillation in the Earth's climate. Moreira et al. (2021) discovered that the rate of change of the global mean sea level displays a clear 6-year signal, also seen in the main contributors to the global mean sea level variations, in particular the mass balance of glaciers, Greenland and Antarctica ice sheets. A cycle of ~6-7 years has also been reported in the European surface temperature (Meyer and Kantz, 2019). Further analysis of combined land and sea surface temperature indicates that this 6-year cycle is a global phenomenon. Recently, Pfeffer et al. (2023) reported novel observations of a 6-year cycle in land water storage based on data analysis of the GRACE and GRACE-FO missions. This 6-year cycle in GRACE-based land water storage appears highly correlated with observed precipitation and hydrological model-based water storage. This signal is clearly visible in specific river basins or above large aquifers in all continental areas. It is particularly significant over the Amazon and Orinoco river basins in South America, the Congo basin and great lakes region in Africa, the Mississippi basin and Central Valley in North America, as well as over several areas of the Eurasian continent (Pfeffer et al., 2023). Besides, several climate modes (reflecting natural variability of the Earth climate) also display significant energy around 6 years (Moreira et al., 2021). This is the case of MEI (Multivariate ENSO index), PDO (Pacific Decadal Oscillation) and AMO (Atlantic Multidecadal Oscillation). As the definition of these climate indices is based on the combination of a variety of atmospheric and oceanic variables (e.g., atmospheric pressure, sea surface temperature, surface winds, etc.), this suggests that the 6-year cycle affects the climate system as a whole.

Conservation of angular momentum is a fundamental property of rotating systems as long as they are not subject to external torques. Angular momentum change in any part of the system is compensated by equal and opposite changes in the rest of the system. This is exactly what happens in the Earth system at the seasonal frequency, where changes in the rotation of the solid Earth (i.e., the mantle) result from opposite changes in the atmospheric angular momentum (AAM) caused by seasonal changes of the tropospheric wind circulation (Chen et al., 2019 and references herein). It has been further established that transfer of angular momentum from the atmosphere (with marginal contribution from the ocean and land hydrosphere) to the solid Earth also occurs at ENSO frequencies (around 2-3 years). For the seasonal and ENSO frequencies, AAM and LOD variations are in phase, indicating a transfer of angular momentum from the surface fluid envelopes to the mantle (note that LOD and mantle rotation variations are of opposite sign). For the 6-year cycle, the situation is totally different. First, the AAM also presents a clear 6-year oscillation, but most importantly, LOD and AAM variations are almost perfectly in opposition of phase (Pfeffer et al., 2023). This was previously noticed by Chen et al. (2019) and Rekier et al. (2022) who found that correcting LOD for the angular momentum contribution of the surface fluid envelopes (mostly atmosphere because ocean and hydrosphere contribute little) does not cancel the LOD 6-year variations (unlike at the seasonal and ENSO frequencies) but rather enhances them. Such an unexpected observation has profound consequences on the dynamics of the Earth' system. The phase opposition of LOD and AAM means that at the 6-year frequency, the Earth's mantle and the atmosphere oscillate in phase together as a coupled system (Pfeffer et al., 2023). As LOD changes are likely explained by deep Earth processes, core dynamics may be the driver of the AAM 6-year oscillation and other surface changes, hence of the reported 6-year cycle in the Earth's climate. Several other global observables oscillate almost synchronously with LOD and AAM at the 6-year frequency, in particular the magnetic and gravity fields (Mandea et al., 2012), as well as mean Earth' surface temperature (Pfeffer et al., 2023). However, the exact nature of the coupling mechanism between mantle and surface fluid envelopes at the 6-year frequency remains to be elucidated.

A periodic oscillation in the Earth magnetic field dipole of approximately ~60-65 years has been known for some time (Roberts et al., 2007), as well as in the LOD, mean Earth's temperature and global mean sea level (e.g., Zotov et al., 2016). Using seismic observations, Yang and Song (2023) have recently reported a ~65-year oscillation of the inner core, nearly in phase opposition with LOD, and noted that climate, LOD and magnetic field fluctuations at 60-65 years are almost synchronous (as observed here for the 6-year cycle). They conclude that the multidecadal climate variations are linked to core-mantle oscillations, suggesting strong coupling interactions between the main layers of the Earth system, from the deep interior to the surface fluid envelopes. In our view, a similar scenario may apply to the 6-year cycle that affects the Earth system as a whole. However, in both cases, exact coupling mechanisms between the different layers of the planet, able to reproduce the observations, are still to be discovered.

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Figure 1: Schematic representation of the different layers of the Earth system, from the solid inner core to the atmosphere, and of the coupling mechanisms at the outer core-mantle boundary. The black thin curves around the Earth represent the magnetic field lines.