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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, 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 ice, land hydrology, and atmospheric angular momentum). Here we suggest that the 6-year oscillations detected in the Earth's deep interior, mantle rotation, and atmosphere 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 the hydrosphere) to the mantle (e.g., Gross, 2015), the 6-year signal in LOD has been attributed to deep Earth processes, namely exchange of angular momentum between the core and the mantle (Gillet et al., 2010, Rekier et al., 2022) (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 the secular acceleration) and inferred core flow modelling, Gillet et al. (2010) showed that the 6-year signal in LOD can be well predicted by the geostrophic wave-like pattern induced by torsional Alfven waves travelling from the inner core

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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) has 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, 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 of the ellipticity of the Earth's equator). They attributed it to a gravitational coupling between the solid inner core and the Earth's mantle. A recent study by Watkins et al. (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 (atmospheric, oceanic and hydrological loading) cannot explain this 6-year signal. They rather suggest a core-mantle pressure 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 in 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 land and sea surface temperature indicates that this 6-year cycle in temperature is a global phenomenon. Recently, Pfeffer et al. (2023) reported novel observations of a 6-year cycle in continental water storage based on data analysis of the GRACE and GRACE-FO gravity missions. This 6-year cycle in GRACE-based land water storage appears highly correlated with observed precipitation and water storage estimated from global hydrological models. 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, and 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), NAO (North Atlantic oscillation) and AMO (Atlantic Multidecadal Oscillation). As the definition of these climate indices are based on the combination of a variety of atmospheric and oceanic variables (e.g.,

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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 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 (e.g., Gross, 2015). It has been further established that transfer of angular momentum from the atmosphere to the solid Earth also occurs at ENSO frequencies (around 2-3 years). Ocean and hydrosphere angular momenta also contribute to this transfer but only by a small amount. For the seasonal and ENSO frequencies, AAM and LOD variations are in phase, indicating a transfer of angular momentum from the atmosphere 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 of all, the AAM also presents a clear 6-year oscillation, but most importantly, LOD variations are almost perfectly out of phase with AAM (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 (atmosphere, ocean and hydrosphere) did not lead to cancelling the LOD 6-year variations (as for the seasonal and ENSO frequencies) but rather to enhancing them. Such an unexpected observation has a profound consequence 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 the same sense as a coupled system (it is worth noting that the ocean and the hydrosphere contribute little; Pfeffer et al., 2023). As LOD changes are well explained by deep Earth processes, we conclude that core dynamics is very likely the driver of the AAM 6-year oscillation and other surface changes, hence of the reported cycle in the Earth's climate. It is worth noting that several global observables oscillate almost synchronously at the 6-year frequency, in particular the magnetic and gravity fields (Mandea et al., 2012). However, the exact nature of the coupling mechanism between mantle and surface fluid envelopes at the 6-year frequency is still 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 (e.g., Gross, 2015), the latter being attributed to angular momentum exchange between the core and the mantle (e.g., Jault et al., 1988). Besides, a 60-65 year signal has also been discovered in the climate system as discussed in Yang and Song (2023), who report an oscillation of the inner core in the same

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frequency band, based on seismic observations. Interestingly, these authors find that the 65-year inner core oscillation is nearly opposite to that of the LOD and note that climate, LOD and magnetic field fluctuations at 60-65 years are almost in phase (as noted for the 6-year cycle). They conclude that such multidecadal climate variations result from core-mantle oscillations, suggesting strong coupling interactions within 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.