Forcing of Polar Motion in the Chandler Frequency Band:
An Opportunity to Evaluate Interannual Climate Variations

The Earth rotates about its axis once-per-day, but does not do so uniformly. The length of the day changes by as much as a millisecond from day to day, and the Earth wobbles as it rotates. That the Earth should wobble was predicted by the Swiss mathematician Leonhard Euler in 1765 but it was not until 1891 that the wobbling motion of the Earth was detected by the American astronomer Seth Carlo Chandler, Jr. In fact, Chandler observed that the Earth has two distinct wobbles, one with an annual period and the other with a 14-month period. The annual wobble is a forced motion of the Earth caused by seasonal variations in the atmosphere, ocean and hydrosphere.

The 14-month wobble, now known as the Chandler wobble, is a resonant, free oscillation of the rotating Earth that exists because the Earth is not rotating about its figure axis. Dissipation processes associated mainly with the wobble-induced deformation of the solid Earth cause the Chandler wobble to freely decay on a timescale of about 30 to 100 years. Over the last century, the amplitude of the Chandler wobble has been observed to occasionally increase, therefore, one or more mechanisms must be acting to excite it. Since its discovery, the excitation of the Chandler wobble has been an intriguing scientific problem that has stimulated research in various geophysical and geodetic fields. Nevertheless, the actual mechanism in the Earth system that is most responsible for sustaining the Chandler wobble is still under investigation.

In principle, the Chandler wobble can be excited by changes in the moment of inertia of the solid Earth (e.g. through earthquakes, see *Mansinha and Smylie*, 1970, *Chao and Gross*, 1987, or through surface loading, see *Chao et al*., 1987, *Kuehne and Wilson*, 1991) or by angular momentum exchange with the atmosphere, oceans, and core (see *Gross*, 2005, and *Liao*, 2005, for reviews). Recently, air pressure (*Plag*, 1997), tropospheric winds (*Aoyama and Naito*, 2001) and ocean-bottom pressure variations (*Gross*, 2000) have been independently proposed as major contributions to the excitation of the Chandler wobble. A fourteen to sixteen month oscillation (FSO) in the atmosphere-ocean system has also been proposed as a candidate mechanism that could force a wobble having a frequency close to that of the Chandler resonance (*Plag*, 1997, *Aoyama et al*., 2003).

Outstanding problems concerning the excitation of the Chandler wobble were recently discussed at a workshop held in Luxembourg in April 2004. The workshop discussions concentrated on several key issues:

- the quality and interpretation of observations of the Earth's rotation with particular emphasis on determining the observed Chandler excitation from wobble observations;
- the consistency and completeness of estimates of atmospheric and oceanic angular momentum and the models from which they are derived;
- the theoretical approaches being used to model the dynamics of the Earth's rotation with particular focus on the period and damping of the Chandler wobble.

While the theory of the Earth's rotation is well developed, certain long-period approximations have typically been made in its derivation, such as assuming that the oceans wobble with the solid Earth and exhibit an equilibrium pole tide. Thus, while the theory can be accurately used to study the annual and Chandler wobbles, it may need revision when applied to wobbles having periods of a few days or less. In addition, the model of the Earth itself in terms of its structure, rheology and coupling at internal boundaries is rather simplistic, and the theory as numerically implemented is linearized. Nevertheless, uncertainties due to model deficiencies and simplifications of the theory are expected to be small, especially at the Chandler period (*Wahr*, 2005), except for a potentially larger effect due to unaccounted core-mantle coupling (*Dickman*, 2003) . Likewise, present-day Earth rotation observations are of high quality and discrepancies between predictions and observations cannot be attributed to uncertainties in the observations. However, it is noted here that the separation of the Chandler Wobble is still an issue under discussion (*Vondrák and Ron*, 2005).

The strong seasonal variations in atmospheric, oceanic, and hydrospheric processes excite a large annual wobble made even larger by its close proximity in frequency to the 14-month Chandler resonance. While not in perfect agreement, predictions of the annual wobble based on models of the forcing are in reasonably good agreement with the observations.

Although much smaller than at seasonal frequencies, variations in atmospheric, oceanic, and hydrospheric processes also occur in the Chandler frequency band, and thus can excite the Chandler wobble. While there is considerable evidence that the combination of such processes fully accounts for the Chandler excitation, there is uncertainty about the relative contribution of wind and ocean circulation on the one hand and pressure forcing due to atmospheric, hydrospheric and oceanic loading on the other hand (*Brzezinski*, 2005). This uncertainty is due to inadequate observations and models of relevant atmospheric, oceanic and hydrospheric parameters such as the wind field. For example, different atmospheric models, and different methods of computing the angular momentum from the modeled wind fields, yield different estimates for the contribution of atmospheric winds to the Chandler wobble excitation (*Aoyama*, 2005). Moreover, estimates of oceanic and hydrospheric excitation of the Chandler wobble derived from models that are forced with atmospheric fields will be inaccurate because, at a minimum, the forcing fields are inaccurate. Nevertheless, including the modeled oceanic excitation improves the agreement between predictions and observations (*Gross et al.*, 2003).

Consequently, a key to improved understanding of the excitation of the Chandler wobble lies in the improvement of the forcing models, which will also imply improved knowledge of the Chandler period and damping, and hence of the dissipation mechanisms causing the damping (*Wilson and Chen*, 2005). Studies of the Earth's wobbles will continue to contribute to the validation of observational data sets as well as atmospheric, oceanic and hydrospheric models. Earth rotation studies have a rich history and we look forward to their future contributions to our knowledge of the Earth and its interacting systems.

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