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Earth rotation changes since −500 CE driven by ice mass variations

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ABSTRACT

We predict the perturbation to the Earth's length-of-day (LOD) over the Common Era using a recently derived estimate of global sea-level change for this time period. We use this estimate to derive a time series of "clock error", defined as the difference in timing of two clocks, one based on a theoretically invariant time scale (terrestrial time) and one fixed to Earth rotation (universal time), and compare this time series to millennial scale variability in clock error inferred from ancient eclipse records. Under the assumption that global sea-level change over the Common Era is driven by ice mass flux alone, we find that this flux can reconcile a significant fraction of the discrepancies between clock error computed assuming constant slowing of Earth's rotation and that inferred from eclipse records since 700 CE. In contrast, ice mass flux cannot reconcile the temporal variability prior to 700 CE.

1. Introduction

Ancient eclipse observations compiled from Babylonian, Chinese, European, and Arab sources provide the primary constraint on changes in the Earth's rotation rate over the past 3000 yr of Earth history (Stephenson and Morrison, 1984, 1995; Stephenson, 1997, 2003). Analyses of these records have yielded a relatively continuous time series since ∼−700 CE of the clock error (ΔT; Fig. 1A), defined as the difference in the timing of an eclipse as measured using timescales that are theoretically-invariant (terrestrial time, TT) or fixed to Earth rotation (universal time, UT). A cubic spline fit through the time series (Stephenson and Morrison, 1995; Stephenson, 1997, 2003) indicates that the clock error accumulates to ∼18000 s, or 5 hr, by −500 CE (Fig. 1A, black line). The first derivative of this spline fit yields the change in the rotation period, or length-of-day (LOD; Fig. 1B, black line). Note that the fit to ΔT in Fig. 1A is constrained to reach a minimum at 1820 CE, when LOD in the TT timescale is precisely 86400 s, and thus changes in the LOD are estimated relative to this date (the black line in Fig. 1B is zero at 1820 CE). All numerical calculations described below will be referenced to the same date.

The clock error monotonically increases as one moves back in time from ∼1820 CE, reflecting a shorter rotation period, or LOD, relative to the value over the past few centuries (Fig. 1B). Stephenson and Morrison (1995) and Stephenson (1997, 2003) characterized the clock error as the combination of a quadratic background trend (Fig. 1A, green line) and a millennial timescale oscillation of ∼1000 s around this trend (green line in Fig. 2A). In this case, the change in the LOD comprises a linear background trend of ∼1.7 ms/century (cy) (∼40 ms since −500 CE; green line, Fig. 1B) and a millennial timescale oscillation with peak-to-peak amplitude of 10 ms (green line in Fig. 2B).

Tidal dissipation produces a significant slowing of the Earth's rotation over time (Lambeck, 2005). Modern satellite geodetic and lunar laser-ranging measurements imply a rate of change of LOD due to this dissipation mechanism of 2.3 ms/cy (Christodoulidis et al., 1988; Williams and Dickey, 2003). If one assumes that the dissipation rate has remained constant since −500 CE, then the red lines in Figs. 1A–B show the clock error and the change in LOD associated with tidal dissipation over this period, respectively. This quadratic signal in Fig. 1A (red line) is often termed the "tidal parabola".

The differences between the time series of the clock error and LOD estimated from the ancient eclipse record and the associated signals due to tidal dissipation are shown in Fig. 2 (red lines). The secular trends in these curves (or the black minus red lines in Figs. 1A, B) are characterized by a clock error

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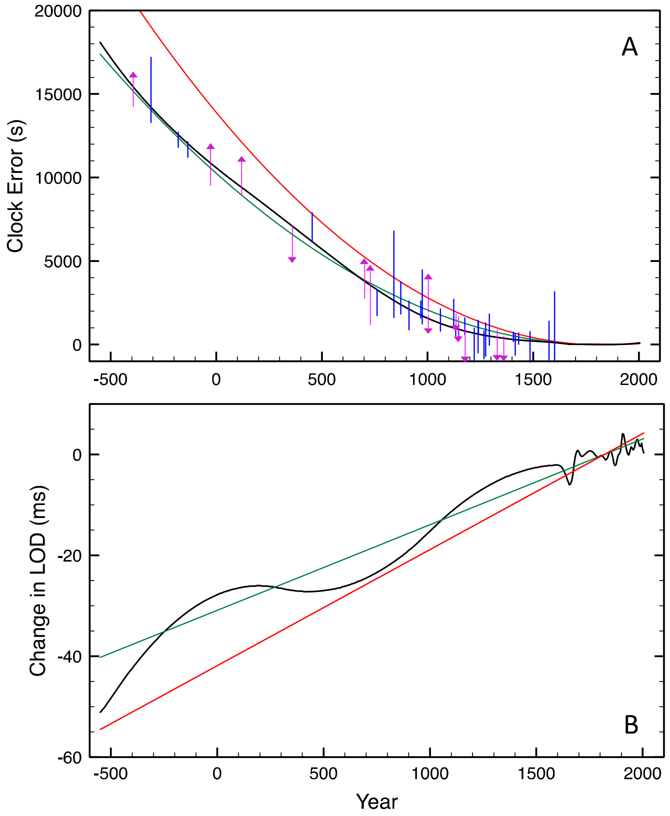

Fig. 1. Changes in Earth rotation over the last 2500 yr inferred from ancient eclipse records. (A) Constraints on clock error from untimed total and annular solar eclipses (blue lines) and untimed partial solar eclipses (magenta, with arrows, showing the start and direction of the allowable bounds) tabulated in Appendix B of Stephenson (1997) (see also Stephenson and Morrison, 1995). Black line – cubic spline fit to the eclipse record, as estimated in Stephenson (1997). Green line – best fitting quadratic form through the same time series, as estimated in Stephenson (1997) ($\Delta T = 31t^2 - 20$ s, where t is measured in centuries from 1820 CE). Red line – clock error associated with the slowing of Earth rotation due to tidal dissipation computed by assuming the dissipation rate is constant and equal to the present rate ($\Delta T = 44t^2 - 20$ s). (B) Black line – change in LOD estimated by (Morrison and Stephenson, 2001) from the associated spline fit in frame (A) and, for the period after ~1600 CE, astronomical observations. Green, red lines – change in LOD associated with the quadratic fit and the tidal parabola, respectively, in frame (A). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

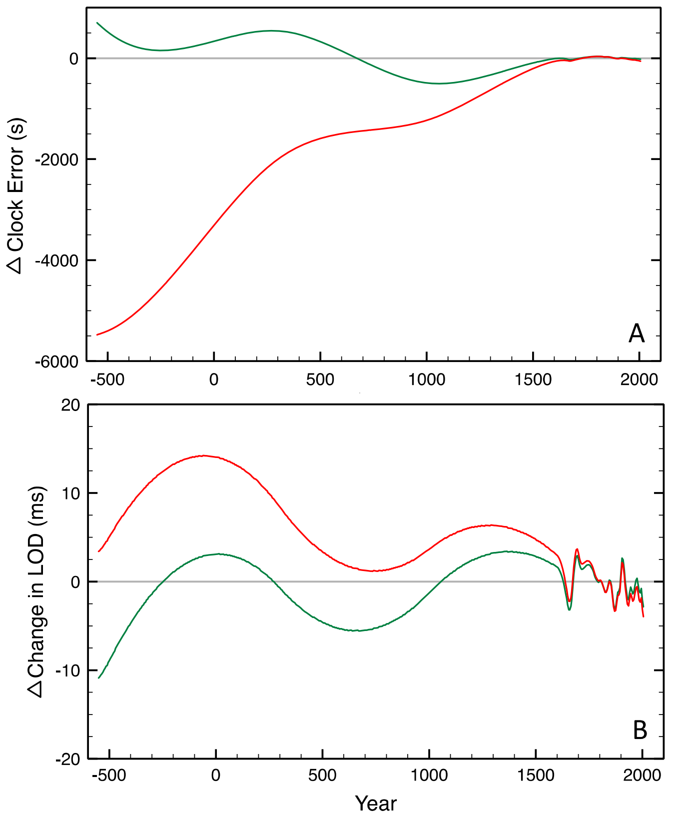

Fig. 2. Discrepancy in Earth rotation over the last 2500 yr relative to a best-fit quadratic curve through the ancient eclipse record. (A) Green line – difference between the cubic spline and quadratic fit to the eclipse-inferred clock error, ΔT, shown in Fig. 1A. Red line – difference between the cubic spline fit to the total clock error, ΔT, and the tidal parabola in Fig. 1A. (B) Green line – difference between the LOD change computed from the spline and quadratic fits in Fig. 1A. Red line – difference between the LOD change computed from the spline fit and the tidal parabola in Fig. 1A. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

that grows to ~5400 s, or ~1.5 hr, at −500 CE and a change in LOD of ~0.6 ms/cy. These reflect a non-tidal acceleration of the Earth's rate of rotation, and they have been widely associated with a poleward shift of mass from ongoing glacial isostatic adjustment (GIA) in consequence of the last deglaciation phase of the ice age, which ended ~5 ka (Stephenson and Morrison, 1984, 1995; Stephenson, 1997, 2003; Sabadini et al., 1982; Wu and Peltier, 1984; Vermeersen et al., 1997; Mitrovica et al., 2006), or a combination of GIA and angular momentum exchange between flows in the Earth's outer core and rocky mantle (i.e., core–mantle coupling) (Mitrovica et al., 2015).

The origin of the millennial time scale oscillations in the time series (Fig. 2, green lines), remains enigmatic, and serves as the sole focus of the present study. There have been arguments that these oscillations arise either from core–mantle coupling (Stephenson, 2003; Dumberry and Bloxham, 2006) and/or ice volume changes affecting global sea level (Stephenson, 2003). However, the inferred departure of the clock error from a simple quadratic form is driven by a relatively small set of untimed solar eclipse observations (Stephenson, 1997) (Fig. 3), each of which is subject to a suite of error sources (Stephenson, 1997; Steele and Ptolemy, 2005). (The term "untimed" refers to eclipse observations in which the occurrence of an eclipse was recorded but not the duration; in such cases, timing of the event may be bounded by knowledge of the location of the observation and the nature of the solar eclipse, i.e., total, annular, or partial (Stephenson, 1997).)

Fig. 3 shows the constraint on clock error implied by these observations relative to the best fitting quadratic form. The eleven records have dates of −708 CE, −180 CE, −135 CE, 454 CE, 761 CE, 1133 CE, 1147 CE, 1178 CE, 1221 CE, 1267 CE, and 1361 CE, and the individual constraints imply a minimum departure from the best-fit quadratic of +439 s, 0 s, 0 s, +365 s, −167 s, −293 s, −194 s, −118 s, −112 s, −108 s, and −133 s, respectively (Stephenson, 1997). The consistency in the seven observations spanning the period 761–1361 CE in Fig. 3 suggests that a departure of the clock error from the best-fit quadratic over this period is relatively robust. However, it is clear that the spline fit adopted in Stephenson and Morrison (1995); Stephenson (1997, 2003) (Figs. 1A and 3) may be overestimating the maximum discrepancy of the clock error from a quadratic form within this time interval. The departure from the quadratic form of the observations at both −708 CE and 454 CE is of opposite sign, and it drives the trends in the spline fit for the periods prior to −250 CE and from 0–500 CE, respectively (Fig. 3). In this case, the spline fit may be overestimating the peak amplitude of the millennial scale oscillation prior to 500 CE. For these reasons, we focus in the analysis below on the individual constraints shown in Fig. 3 rather than the