# NOTES AND CORRESPONDENCE

## Air Temperature and Anthropogenic Forcing: Insights from the Solid Earth

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ABSTRACT

Earth's rotation rate [i.e., length of day (LOD)], the angular momentum of the core (CAM), and surface air temperature (SAT) all have decadal variability. Previous investigators have found that the LOD fluctuations are largely attributed to core–mantle interactions and that the SAT is strongly anticorrelated with the decadal LOD. It is shown here that 1) the correlation among these three quantities exists until 1930, at which time anthropogenic forcing becomes highly significant; 2) correcting for anthropogenic effects, the correlation is present for the full span with a broadband variability centered at 78 yr; and 3) this result underscores the reality of anthropogenic temperature change, its size, and its temporal growth. The cause of this common variability needs to be further investigated and studied. Since temperature cannot affect the CAM or LOD to a sufficient extent, the results favor either a direct effect of Earth's core-generated magnetic field (e.g., through the modulation of charged-particle fluxes, which may impact cloud formation) or a more indirect effect of some other core process on the climate—or yet another process that affects both. In all three cases, their signals would be much smaller than the anthropogenic greenhouse gas effect on Earth's radiation budget during the coming century.

### 1. Introduction

The length of day (i.e., the time needed by Earth to make one full rotation) fluctuates around its mean 24-h value, over a broad range of periods. Earth rotation is observed with a very high accuracy from precise geodetic techniques such as very-long-baseline interferometry, which allows for the determination of the length of day (LOD) at the 0.02-ms level (less than 1 cm at the equator). Earth rotation data collected before 1975 are the results of traditional optical observations; uncertainties during this period are significantly larger than for current determinations. Here we use a combined solution using early optical data with the modern space geodetic measurements (Gross 2004). The observed fluctuation of the LOD can be interpreted, at seasonal time scales, in terms of angular momentum exchange between the solid Earth and the superficial fluid layers (the atmosphere and the ocean), without the need to invoke influences from the core (Dickey et al. 2010). For the atmosphere, variations in global angular momentum are dominated by the effect of the winds (the wind term), with the moment-of-inertia changes (the pressure term) being an order of magnitude smaller (Hide and Dickey 1991; Rosen 1993). The ocean contributions, being yet smaller than the pressure term, are significant in the closure of the angular momentum balance (Marcus et al. 1998). In the frame of Newtonian physics, the angular momentum of an isolated system is known to be conserved. The effect of the atmosphere and of the ocean on LOD can thus be computed from changes of the atmospheric and oceanic angular momentum.

At decadal and longer time scales, the main source of rotational variation is the interaction between the mantle and core, as substantiated by the significant correlation between the low-degree zonal components of the magnetic field and the LOD (Jault and Le Mouel 1991; Hide et al. 2000). The decadal LOD variations (e.g., ~4 ms

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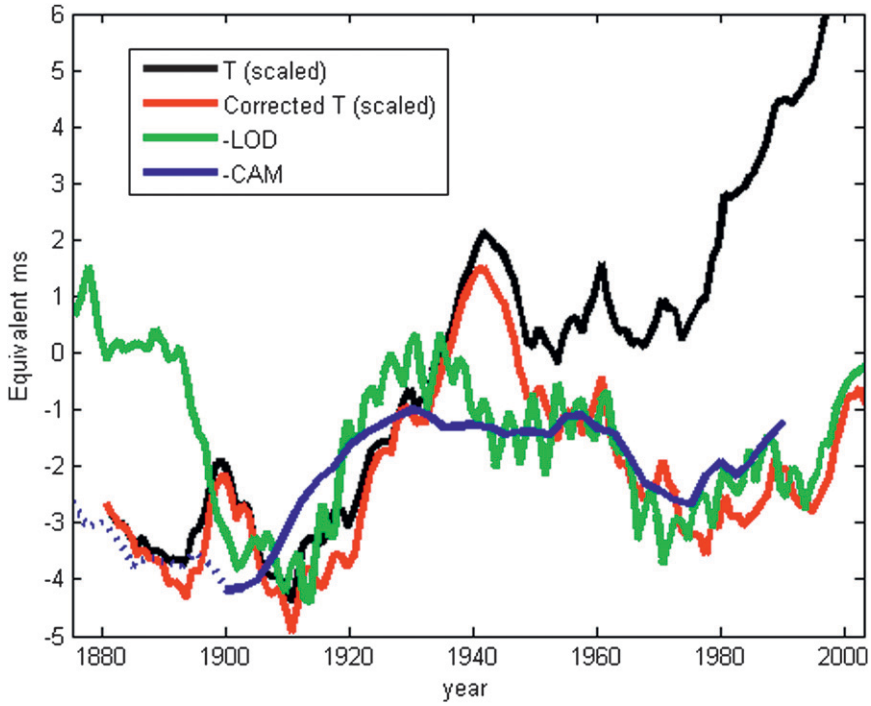


FIG. 1. Time series of the surface air temperature (black line; Hansen et al. 2007) and that corrected for anthropogenic effect according to GISS ModelE (red; Hansen et al. 2007), the LOD (green; International Earth Rotation and Reference Systems Service), and the CAM (blue; Hide et al. 2000). The unit of temperature is 0.1 degrees Celsius, LOD is in milliseconds, and CAM is in equivalent milliseconds, corresponding to $6 \times 10^{25}$ N m s; the sign of CAM and LOD has been reversed. Note that GISS temperature starts at ~1880.

around 1900; Hide et al. 2000) are too large in amplitude to be explained by the atmosphere; the largest atmospheric contributions observed are from the seasonal cycle and El Niño events (~1 ms in amplitude). The ocean is not the prime mover in these processes since its effect on LOD is found to be substantially smaller than that of the atmosphere, on time scales ranging from subseasonal (e.g., Marcus et al. 1999; Dickey et al. 2010) to decadal (Gross et al. 2005); together, in fact, the atmosphere and ocean account for only 14% of the observed decadal LOD changes during 1949–2002 (Gross et al. 2005). Nevertheless, the long-term global mean Earth surface air temperature (SAT) is significantly anticorrelated with decadal and longer LOD (e.g., Lambeck and Cazenave 1976). Variability at periods of 60–80 yr has been well established in LOD (e.g., Jault and Le Mouel 1991; Hide et al. 2000; Roberts et al. 2007) and in the core angular momentum (CAM), using both observational data (Zatman and Bloxham 1997; Dickey and de Viron 2009) and theoretical studies (Mound and Buffett 2007).

There are no direct observations of the fluid core motions. However, geomagnetic fields generated by the dynamo inside the fluid core can be used to infer the motion field and its velocity by utilizing several assumptions and the induction equation. One of the major assumptions is that the flow inside the core is adequately represented by the "Taylor column" model (Hide et al. 2000), which implies that the velocity field is equivalent to a rigid rotation of coaxial cylinders around Earth's rotation axis and that this velocity is the mean velocity of the fluid at the intersection of each cylinder by the core–mantle boundary. If the solid Earth-core system is assumed to be isolated, the changes of the solid-Earth angular momentum, and thus its rotation speed and the associated LOD, can be deduced from changes of the CAM. Conversely, since the Earth rotation observations are better constrained than the inferred core flow velocities, the Earth rotation data can be used to check the quality of the core-flow modeling.

## 2. Data used

In this study, we used the CAM associated with the flow reconstructed by Hide et al. (2000) from Jackson et al.'s (1995) data. This CAM is given separately for the 20 cylinders used in the reconstruction of the flow. It was

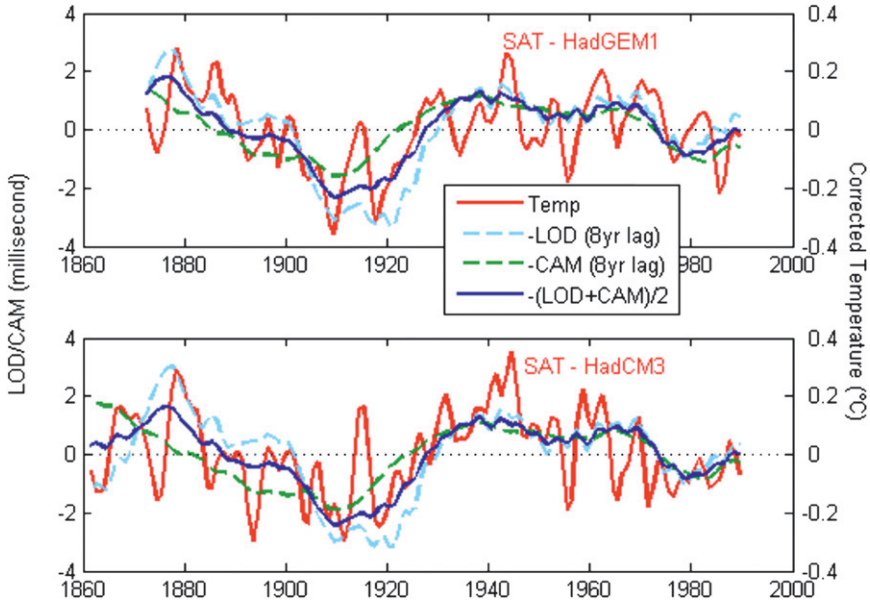


FIG. 2. Comparison of corrected HadCRUT3 annual mean surface temperature (solid red lines) with LOD and CAM (dashed cyan and green lines, respectively) and with the average of the LOD and CAM series (solid blue lines), using anthropogenic climate change computed from experiments with the (top) HadGEM1 and (bottom) HadCM3 models. All series have been smoothed with a 3-yr running mean and detrended over the intervals shown.

shown by Hide et al. (2000) that the LOD variation inferred from the total CAM fits convincingly the observed decadal variation of the LOD. Yearly LOD observations were taken from the "LUNAR97" dataset (Gross 2001), augmented after 1997 by average yearly values from the Jet Propulsion Laboratory "COMB2003" series (Gross 2004). Climate variations for the purpose of this study are represented by yearly mean values of the global average surface temperature, available from the Goddard Institute for Space Studies (GISS) temperature series since 1880 (GISTEMP; Hansen and Lebedeff 1987) and from the Met Office Hadley Centre–University of East Anglia Climatic Research Unit temperature series since 1850 (HadCRUT3; Brohan et al. 2006). Because anthropogenic effects have significantly altered Earth's climate since the start of the industrial revolution (Solomon et al. 2007), we correct for these by removing estimated anthropogenic temperature change as specified by appropriately forced runs of coupled atmosphere–ocean general circulation models from the observed temperature series. The GISTEMP data were corrected using the anthropogenic temperature changes since 1880 computed from the GISS "ModelE" runs described by Hansen et al. (2007), and the HadCRUT3 data were corrected using the average of the A1FI, A2, B1, and B2 experiments with the Hadley Centre Coupled Model, version 3, (HadCM3) conducted by Johns et al. (2003) beginning in 1860, and also using the "ANTHRO" experiment described by Stott et al. (2006), beginning in 1871.

## 3. Results

Figure 1 shows the GISS observed and corrected temperature series (black and red lines, respectively) beginning in 1880 (cf. Hansen and Lebedeff 1987). The LOD and CAM are given in units of equivalent milliseconds, with sign reversed so that positive anomalies correspond to increased rotational speed of the solid Earth, and the temperature series are given in units of 0.1°C; note that all series show decadal–centennial changes in the indicated quantity, with arbitrary choice of reference values. The correlation among the three data types is strong until 1930 and worsens thereafter, as the observed SAT continues to increase while the LOD and CAM do not; in the last few decades, in particular, a robust global warming has been observed and is attributed to increasing anthropogenic greenhouse gases (Hansen et al. 1999). The corrected temperature, however, is seen to maintain its strong correlation with LOD and CAM for the whole series; the disagreement around 1940–50 may partially reflect natural variability (cf. Marcus et al. 1999) or difficulties in calibrating sea surface temperatures due to a shift in ocean sampling from bucket to engine intake (Thompson et al. 2008). The continued correlation of the corrected

TABLE 1. Correlation coefficient and significance using the Student's $t$ test for all three corrected temperature $T$ series with LOD and CAM.

| | Correlation coef: $T$ vs LOD | Significance (Student's $t$ test) | Correlation coef: $T$ vs CAM | Significance (Student's $t$ test) |
|---|---|---|---|---|
| GISS | 0.38 | 90% | 0.56 | 96% |
| HadCM3 | 0.43 | 98% | 0.41 | 97% |
| HadGEM1 | 0.45 | 97% | 0.51 | 95% |

temperatures with Earth rotation variations after this time underscores the significance and size of the anthropogenic effect on SAT and implies that the observed temperature cannot be the cause of the correlated variation in Earth rotation but rather that both are instead influenced by an external cause (Lambeck and Cazenave 1976). Note an approximately 8-yr lag between the (negative) LOD and the corrected temperature; this lag agrees with the 8-yr lag between changes in Earth's rotational speed and surface geomagnetic field perturbations found by Roberts et al. (2007).

Figure 2a shows a comparison among CAM, LOD, and the Hadley Centre Global Environmental Model, version 1 (HadGEM1)-corrected version of the HadCRUT3 observed global mean temperature, beginning in 1871. Here the CAM and LOD (with sign reversed) have both been lagged by 8 yr, and all series have been detrended over the interval shown. The CAM and LOD series disagree somewhat because of difficulties in translating sparse geomagnetic observations into a full determination of core flow and because of fluctuations in LOD related to atmospheric forcing, for which reliable data are not available for the full span of the record studied here. The corrected global mean temperature shows substantial decadal fluctuations possibly related to natural forcing, which has not been removed from the data studied here. All three data types, however, show strong evidence of multidecadal variability, with a period in the 60–80-yr range. The arithmetic average of the CAM and LOD data (solid blue line), in particular, tracks the global mean temperature residual very well over the interval shown, confirming and extending earlier reports of an apparent link between Earth rotation and climate anomalies on decadal–century time scales. Figure 2b shows similar results using the HadCM3-corrected version of the HadCRUT3 global temperature series, beginning in 1860. Again, variations in all data

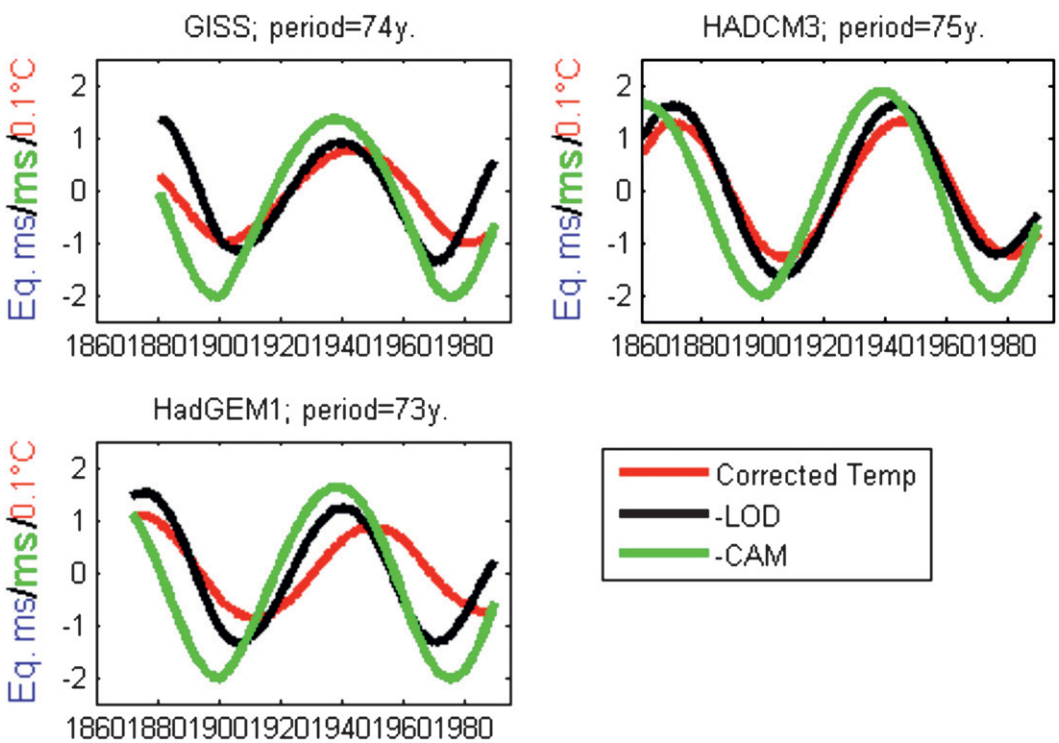


FIG. 3. Time series of the first mode of corrected temperature (red lines), −LOD (black), and −CAM (green) reconstructed using MSSA with all quantities done jointly. Three corrected temperature series have been considered: (top left) GISS ModelE (Hansen et al. 2007); (top right) HadCM3 (Johns et al. 2003); (bottom) HadGEM1 (Stott et al. 2006). The unit of temperature is 0.1 degrees Celsius, LOD is in milliseconds, and CAM is in equivalent milliseconds, corresponding to $6 \times 10^{25}$ N m s; the sign of CAM and LOD has been reversed.

types with periods in the 60–80-yr range are evident, with the mean of the CAM and LOD series tracking the low-frequency portion of the temperature changes very well over the time period shown.

Quantitative comparisons of the three corrected temperature series with the Earth rotation and CAM data are given in Table 1. The agreement between the temperature and LOD is significant for all three series; the confidence levels are 90%, 98%, and 97% for GISS, HadCM3, and HadGEM1 temperatures, respectively. The agreement between the temperature and CAM is also significant for the three series, with confidence levels of 96%, 97%, and 95% for GISS, HadCM3, and HadGEM1, respectively. Note that the degrees of freedom for the significance tests of the correlation coefficients were estimated by dividing the length of each series by its $1/e$ autodecorrelation time.

To better characterize the time-domain behavior of both the Earth rotation and temperature series, we use singular spectrum analysis (SSA) and its multichannel generalization (Vautard and Ghil 1989). SSA and multichannel SSA (MSSA) have been applied separately and jointly to the three data types (LOD, CAM, and corrected temperature). MSSA emphasizes common variability among time series, whereas SSA isolates modes of regular variation in the individual series. Applying these techniques to all three series results in the detection of a broadband variability centered at 78 yr (see Table 2). MSSA variability ranges from 77 to 80 yr; the SSA produces a broader span (67–86 yr). The first mode explains a major percentage of the variance in the individual and combined series. Using SSA, the percentage variances explained are 83%, 72%, and 74% for temperature (GISS), LOD, and CAM, respectively. With MSSA, the corresponding percentages are 86%, 73%, and 70%.

TABLE 2. Periods (years) of the first mode of variability in GISS-corrected surface air temperature, LOD, and CAM.

| | Temperature | LOD | CAM |
|---|---|---|---|
| Period for SSA (yr) | 66.5 | 75.0 | 85.6 |
| % variance explained for SSA | 83% | 72% | 74% |
| Period for MSSA (yr) | 77.5 | 76.8 | 79.6 |
| % variance explained for MSSA | 86% | 73% | 70% |

## 4. Conclusions

Oscillations in global temperatures with periods in the 65–70-yr range were originally reported by Schlesinger and Ramankutty (1994). Subsequent observational studies and simulations with coupled atmosphere–ocean models have found similar multidecadal climatic modes, typically originating in the North Atlantic Ocean; however, the excitation source or sources of these oscillations have not been unambiguously identified (Knight 2009). Our work suggests that the same core processes that are known to affect Earth's rotation and magnetic field (Roberts et al. 2007) may also contribute to the excitation of such modes, possibly through geomagnetic modulation of near-Earth charged-particle fluxes that may influence cloud nucleation processes, and hence the planetary albedo, on regional as well as global scales (Usoskin et al. 2008). A reverse process (e.g., excitation of the observed multidecadal LOD variability by oceanic oscillations) seems unlikely in view of observational data constraints (see the appendix). Further work remains to be done, especially in linking common modes of variability between Earth's subsystems and better describing the physical connections between them.

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## APPENDIX

### Oceanic Effects on LOD

Oceanic contributions to LOD variability arise from changes in its axial angular momentum due to circulation (motion) and mass distribution (moment of inertia) effects. The Antarctic Circumpolar Current (ACC), for example, which makes a complete circuit of Earth at the latitude of the Drake Passage (−55°), contributes approximately 1.4 $\mu$s to the LOD per sverdrup ($10^6$ m$^3$ s$^{-1}$) of eastward transport (Dickey et al. 1993). The total transport of the ACC is about 120 Sv; therefore, if it were stopped or doubled in magnitude the resulting change in LOD would be on the order of 0.2 ms, which is far too small to explain the multidecadal LOD variability of several milliseconds analyzed in this paper. Similar considerations apply to the Kuroshio and Gulf Stream systems, for which the longer lever arm resulting from their lower latitude is counterbalanced by the partial misalignment of their

vectorial angular momentum with Earth's rotation axis.

LOD variations caused by mass redistribution associated with basinwide thermohaline oscillations are also found to be small. Some idea of the potential effect of multidecadal variations in the Atlantic meridional overturning circulation on Earth rotation, for example, can be gained from the work of Wang et al. (2010). Using available temperature and salinity data, they show that density changes for the upper 700 m tend to oscillate out of phase between the subpolar and subtropical basins of the North Atlantic, with an amplitude of about 0.05 kg $m^{-3}$. For the regions used (see their Fig. 13) this translates to a redistribution of approximately $5 \times 10^{14}$ kg of mass through 25° of latitude (neglecting possible compensating changes in sea level), which is readily shown to affect LOD at about the 0.01-ms level, indicating that oceanic oscillations of the type postulated by Schlesinger and Ramankutty (1994) cannot be the source of the several-millisecond LOD variations found in the observational data record.

## REFERENCES


Brohan, P., J. J. Kennedy, I. Harris, S. F. B. Tett, and P. D. Jones, 2006: Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. *J. Geophys. Res.,* **111,** D12106, doi:10.1029/2005JD006548.

Dickey, J. O., and O. de Viron, 2009: Leading modes of torsional oscillation within the earth's core. *Geophys. Res. Lett.,* **36,** L15302, doi:10.1029/2009GL038386.

——, S. L. Marcus, C. M. Johns, R. Hide, and S. R. Thompson, 1993: The oceanic contribution to the earth's seasonal angular momentum budget. *Geophys. Res. Lett.,* **20,** 2953–2956.

——, ——, and O. de Viron, 2010: Closure in the earth's angular momentum budget observed from subseasonal periods down to four days: No core effects needed. *Geophys. Res. Lett.,* **37,** L03307, doi:10.1029/2009GL041118.

Gross, R. S., 2001: A combined length-of-day series spanning 1832–1997: LUNAR97. *Phys. Earth Planet. Inter.,* **123,** 65–76.

——, 2004: Combinations of Earth orientation measurements: SPACE2003, COMB2003, and POLE2003. Jet Propulsion Laboratory Publ. 04-012, 28 pp.

——, I. Fukumori, and D. Menemenlis, 2005: Atmospheric and oceanic excitation of decadal-scale Earth orientation variations. *J. Geophys. Res.,* **110,** B09405, doi:10.1029/2004JB003565.

Hansen, J., and S. Lebedeff, 1987: Global trends of measured surface air temperature. *J. Geophys. Res.,* **92,** 13 345–13 372.

——, R. Ruedy, J. Glascoe, and M. Sato, 1999: GISS analysis of surface temperature change. *J. Geophys. Res.,* **104,** 30 997–31 022.

——, and Coauthors, 2007: Climate simulations for 1880–2003 with GISS modelE. *Climate Dyn.,* **29,** 661–696.

Hide, R., and J. O. Dickey, 1991: Earth's variable rotation. *Science,* **253,** 629–637.

——, D. H. Boggs, and J. O. Dickey, 2000: Angular momentum fluctuations within the earth's liquid core and torsional oscillations of the core–mantle system. *Geophys. J. Int.,* **143,** 777–786.

Jackson, A., J. Bloxham, and D. Gubbins, 1995: Time-dependent flow at the core surface and conservation of angular momentum of the coupled core–mantle system. *Rev. Geophys.,* **33,** 97–107.

Jault, D., and J. L. Le Mouel, 1991: Exchange of angular momentum between the core and the mantle. *J. Geomag. Geoelectr.,* **43,** 111–119.

Johns, T. C., and Coauthors, 2003: Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios. *Climate Dyn.,* **20,** 583–612, doi:10.1007/s00382-002-0296-y.

Knight, J. R., 2009: The Atlantic multidecadal oscillation inferred from the forced climate response in coupled general circulation models. *J. Climate,* **22,** 1610–1625.

Lambeck, K., and A. Cazenave, 1976: Long-term variations in the length of day and climatic change. *Geophys. J. Roy. Astron. Soc.,* **46,** 555–573.

Marcus, S. L., Y. Chao, J. O. Dickey, and P. Gegout, 1998: Detection and modeling of nontidal oceanic effects on Earth's rotation rate. *Science,* **281,** 1656–1659.

——, M. Ghil, and K. Ide, 1999: Models of solar irradiance variability and the instrumental temperature record. *Geophys. Res. Lett.,* **26,** 1449–1452.

Mound, J., and B. Buffett, 2007: Viscosity of the earth's fluid core and torsional oscillations. *J. Geophys. Res.,* **112,** B05402, doi:10.1029/2006JB004426.

Roberts, P. H., Z. J. Yu, and C. T. Russell, 2007: On the 60-year signal from the core. *Geophys. Astrophys. Fluid Dyn.,* **101,** 11–35.

Rosen, R. D., 1993: The axial momentum balance of Earth and its fluid envelope. *Surv. Geophys.,* **14,** 1–29.

Schlesinger, M. E., and N. Ramankutty, 1994: An oscillation in the global climate system of period 65–70 years. *Nature,* **367,** 723–726.

Solomon, S., D. Qin, M. Manning, M. Marquis, K. Averyt, M. M. B. Tignor, H. L. Miller Jr., and Z. Chen, Eds., 2007: *Climate Change 2007: The Physical Science Basis*. Cambridge University Press, 996 pp.

Stott, P. A., G. S. Jones, J. A. Lowe, P. Thorne, C. Durman, T. C. Johns, and J.-C. Thelen, 2006: Transient climate simulations with the HadGEM1 climate model: Causes of past warming and future climate change. *J. Climate,* **19,** 2763–2782.

Thompson, D. W. J., J. J. Kennedy, J. M. Wallace, and P. D. Jones, 2008: A large discontinuity in the mid-twentieth century in observed global-mean surface temperature. *Nature,* **453,** 646–649.

Usoskin, I. G., M. Korte, and G. A. Kovaltsov, 2008: Role of centennial geomagnetic changes in local atmospheric ionization. *Geophys. Res. Lett.,* **35,** L05811, doi:10.1029/2007GL033040.

Vautard, R., and M. Ghil, 1989: Singular spectrum analysis in nonlinear dynamics, with applications to paleoclimatic time series. *Physica D,* **35,** 395–424.

Wang, C., S. Dong, and E. Munoz, 2010: Seawater density variations in the North Atlantic and the Atlantic meridional overturning circulation. *Climate Dyn.,* **34,** 953–968.

Zatman, S., and J. Bloxham, 1997: Torsional oscillations and the magnetic field within the earth's core. *Nature,* **388,** 760–763.