GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L15307, doi:10.1029/2010GL043185, 2010

Solar forcing of the semi-annual variation of length-of-day

Jean-Louis Le Mouël,[1] Elena Blanter,[1,2] Mikhail Shnirman,[1,2] and Vincent Courtillot[1]

Received 11 March 2010; revised 23 April 2010; accepted 4 May 2010; published 13 August 2010.

[1] We study the evolution of the amplitude **A** of the semi-annual variation of the length-of-day (lod) from 1962 to 2009. We show that **A** is strongly modulated (up to 30%) by the 11-yr cycle monitored by the sunspot number *WN*. **A** and *WN* are anticorrelated, *WN* leading **A** by 1-yr. **A** is therefore directly correlated with galactic cosmic ray intensity. The main part of the semi-annual variation in lod is due to the variation in mean zonal winds. We conclude that variations in mean zonal winds are modulated by the solar activity cycle through variations in irradiance, solar wind or cosmic ray intensity. **Citation:** Le Mouël, J.-L., E. Blanter, M. Shnirman, and V. Courtillot (2010), Solar forcing of the semi-annual variation of length-of-day, *Geophys. Res. Lett.*, *37*, L15307, doi:10.1029/2010GL043185.

1. Introduction

[2] The length-of-day (lod) undergoes a wide spectrum of fluctuations. The decadal fluctuations (10 to 30 years) are mainly attributed to exchanges of angular momentum between the core and mantle of the planet [e.g., *Lambeck*, 1980; *Jault and Le Mouël*, 1991; *Gross*, 2007]. Seasonal changes, which include semi-annual, annual and biennial components, are almost entirely due to variations in atmospheric zonal wind circulation (apart from an important tidal component). The amplitudes of seasonal variations are not constant from year to year, and different hypotheses have been proposed to account for this variability. *Okazaki* [1975] suggested changes in star catalogue or station longitudes. *Lambeck and Hopgood* [1981] listed possible contributions from redistribution of groundwater, variations in global sea-level or seasonal changes in the strength of oceanic currents. However, *Rosen and Salstein* [1985] have shown convincingly that non-atmospheric contributions to nontidal changes in lod on seasonal timescales were unimportant.

[3] Correlation between solar activity and lod has first been suggested by *Bourget et al.* [1992]. *Höppner and Bittner* [2007] made a similar suggestion, but without reaching firm conclusions. Our attention has been drawn after submission of this paper to *Winkelnkemper*'s [2008] thesis, in which he points out that semiannual amplitudes in lod and atmospheric angular momentum are anti-correlated with the semiannual means of the solar constant [see also *Abarca del Rio et al.*, 2003]. In the present paper, we analyze the semi-annual frequency in lod and determine its decadal and longer term variations, in the spirit of other recent studies [*Blanter et al.*, 2006; *Le Mouël et al.*, 2007, 2008; *Shnirman et al.*, 2009].

2. LOD Analysis

[4] Length-of-day data, measured in seconds, are provided by the International Earth Rotation and Reference System Service (IERS), Earth Orientation Center at the Paris Observatory (http://hpiers.obspm.fr/iers/eop/eopc04_05/eopc04.62-now). We use a 48-yr long time series of daily values without gap from Jan 1 1962 to Sep 2 2009. We restrict our analysis to the semi-annual variation, which has a sharp spectral peak. In order to eliminate the strong irregular longer-term variation, we first compute, for each day k, the slope of the straight line regression (in a least squares sense) through the daily values *lod*(*j*) over a one month-long interval centered on day k. This slope provides an estimate of the first derivative *lod*′(*k*) and is measured in seconds per day. We then calculate the amplitude and phase of the Fourier coefficient *C*(*k*) of the 6-month spectral line of *lod*′. This is computed for each day *k* in a sliding window of 4-yr length centered on day *k*. As we wish to study the evolution of *C*(k) over the period from 1962 to 2009, we need a large enough window to estimate it accurately. We have:

$$C(k) = A(k) + iB(k) = \frac{\Delta t}{2\tau + 1} \sum_{\rho=k-\tau}^{\rho=k+\tau} lod'(k)(\cos(\omega\rho) + i\sin(\omega\rho)) \tag{1}$$

with ω = 360°/T (in degrees per day), T = 6 months = 182.62 days and τ = 2 years = 730 days (we express time in days; the sampling interval Δt is one day). The amplitude and phase of the spectral line are:

$$\mathbf{A}(k) = \left(A^2(k) + B^2(k)\right)^{1/2} \tag{2}$$

$$\phi(k) = \tan^{-1}(B(k)/\mathrm{A}\ (k)) \tag{3}$$

In the 4-year interval centered on day k, the semi-annual variation (upper index ^{T} for T = 6 months = 182.62 days) of *lod*′ has the expression:

$$lod'^{T}(t) = \mathbf{A}(k)\cos(\omega t - \phi(k)) \tag{4}$$

where t is in days numbered from January 1st, 1960 (starting year arbitrary, starting day used to evaluate the phase), ω in degrees per day, and ωt and ϕ are in degrees. For the sake of comparison with previous studies, we compute the amplitude $\alpha(k)$ and phase $\gamma(k)$ of the six-month variation of lod itself:

$$\alpha(k) \cong (182.62/2\pi)\ .\ \mathbf{A}(k) \tag{5}$$

$$\gamma(k) = \phi(k) + 90^\circ \tag{6}$$

$$lod^{T}(t) = \alpha(k)\cos(\omega t - \gamma(k)) \tag{7}$$

---

[1] Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Paris, France.

[2] International Institute of Earthquake Prediction Theory and Mathematical Geophysics, Moscow, Russia.

0094-8276/10/2010GL043185

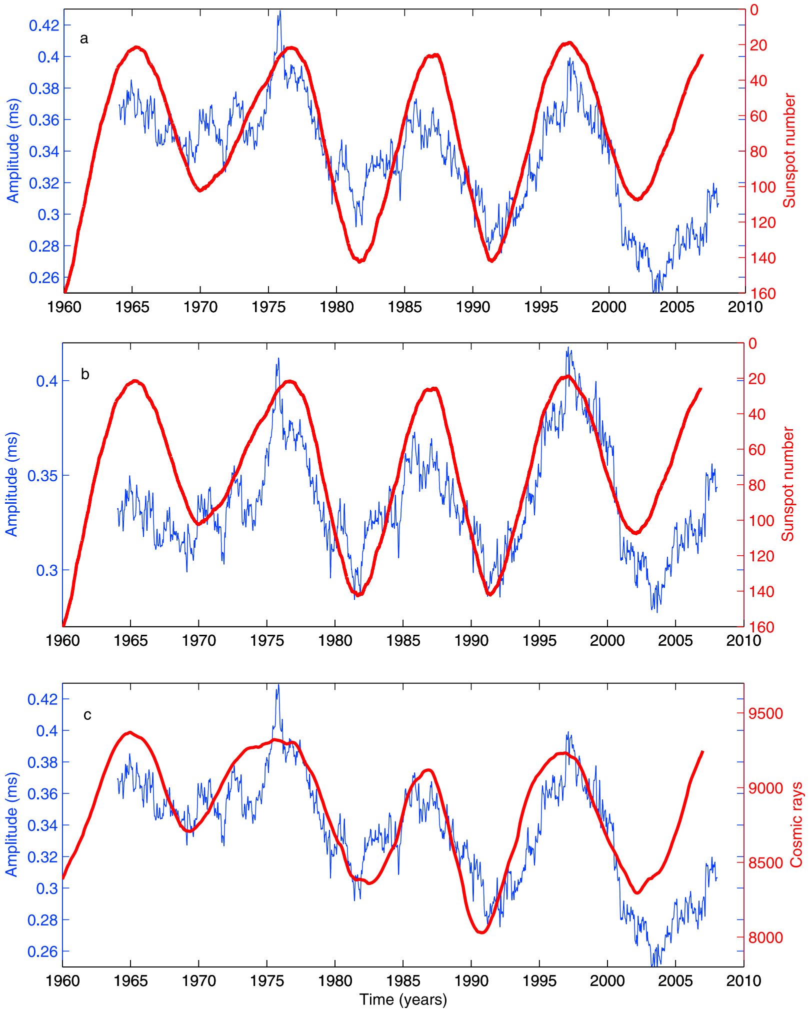

Figure 1. Long-term variations in the amplitude α of the semiannual oscillation in lod (in blue). A 4-yr centered sliding window is used. (a) Comparison of the semiannual amplitude of lod with the sunspot number WN (red); WN is both reversed in sign and offset by one year (see text). (b) Comparison of the detrended semiannual amplitude of lod (blue) with the sunspot number WN (red); WN is reversed in sign and offset by one year. (c) Comparison of the semiannual amplitude of lod (blue) with galactic cosmic ray flux GCR (red); GCR is neither reversed in sign nor offset (see text).

[5] Note that α is in seconds (whereas $(182.62/2\pi)$ is expressed in days) and ωt and γ in degrees. Figure 1a shows the evolution of $\alpha(k)$ over the 1964–2007 time span (two years are lost on either side due to the 4-yr window). The mean values of α and γ over the time span under study (44 years) are approximately 0.320 ms and 215°. Estimates of the dimensionless parameter:

$$m_3^T = -lod^T/\overline{lod} \tag{8}$$

(where $\overline{lod}$ = 86164s is the length of the mean sidereal day) are given by *Lambeck* [1980, Table 7.6] (from *Lambeck and Cazenave* [1973] for the 1957–1963 period):

$$m_3^T = 0.346.10^{-8} \ \cos\left(\omega t - 24^\circ\right)$$

[6] *Lambeck* [1980] gives other estimates of the phase and amplitude of m_3^T. *Höpfner* [1997] reviews estimates published between 1985 and 1996: m_3^T ranges from 0.240 to $0.431.10^{-8}$ in amplitude and 52° to 78° in phase (with data ranging from 1976 to 1992). *Gross et al.* [2004] find, for the period 1980–2000, $m_3^T = 0.320.10^{-8}$ cos $(\omega t - 63°)$. This is one of the most recent determinations to which our values, which provide an average over the longer 1964–2007 period, can be compared:

$$m_3^T = 0.370.10^{-8} \ \cos\left(\omega t - 35^\circ\right) \tag{9}$$

[7] Our amplitude is somewhat larger and phase smaller than the values of *Gross et al.* [2004]. Considering the variability of both phase and amplitude in the 1964–2007 time span, the differences may not be very significant. Discrepancies between phase estimates should probably be partly attributed to the filtering processes. Our estimates do not change when windows of 1 or 2 years rather than 4 years are used, although of course short period noise becomes larger.

[8] The important result outlined by Figure 1a is that the amplitude of the 6-month line in lod displays a strong 11-yr cycle (about 30% of the absolute values); the phase (not

shown) on the other hand has no obvious periodicity, but fluctuates with a range of about 15°.

3. Zonal Winds

[9] Let ϕ (latitude), λ (longitude) and h (altitude) be the coordinates of a current point in the atmosphere, $u_\lambda(\phi,\lambda,h,t)$ the (eastward) zonal component of the wind at this point, at time t, and $[u_\lambda]$ the longitudinal average of u_λ:

$$[u_\lambda](\phi,h,t) = (1/2\pi)\int_0^{2\pi} u_\lambda(\phi,\lambda,h,t)d\lambda \qquad (10)$$

The distribution of the zonal mean-wind $[u_\lambda]$ is one of the best known characteristics of global atmospheric circulation [e.g., *Hartmann*, 1994, Figure 6.4]. $[u_\lambda]$ is westerly through much of the volume of the troposphere and lower stratosphere.

[10] Let us consider the component along the Earth's rotation axis of the (relative) angular momentum of the wind velocity field $[u_\lambda](\phi,h,t)$ at time t:

$$h_3(t) = \left(2\pi a^3\right)\int_{-\pi/2}^{\pi/2}\int_0^H \rho_a(h)\cos^2\phi[u_\lambda](\phi,h,t)d\phi dh \qquad (11)$$

ρ_a is the air density, supposed to depend only on altitude h, a the mean Earth's radius, and H an altitude high enough for most of the atmosphere's angular momentum to be captured. *Lambeck and Cazenave* [1973] take H to be 60 km.

[11] We are interested in the periodic component of h_3(t) with period T. In order to compute it, one uses a compilation of zonal wind measurements $u_\lambda(\phi,\lambda,h,t)$, then calculates their zonal average $[u_\lambda](\phi,h,t)$, then the seasonal component of period T, $u_\lambda^T(h,\phi).\cos(\omega t-\beta(h,\phi))$, and finally the periodic component of the relative angular momentum h_3:

$$h_3^T(t) = H_3^T\cos(\omega t-\delta) \qquad (12)$$

[*Belmont and Dartt*, 1970; *Newell et al.*, 1973; *Lambeck and Cazenave*, 1973; *Lambeck*, 1980; *de Viron et al.*, 1999; *Gross et al.*, 2004].

[12] The semi-annual oscillation extends to all latitudes and down to low altitudes, as does the annual term. But, unlike the annual term, the main part of the oscillation is symmetrical about the equator; the partial cancellation of the angular momentum of the two hemispheres, which occurs for the annual oscillation, does not happen there [*Lambeck*, 1980]. Thus, we have here a measure of the seasonal variation of the total angular momentum of the atmosphere of the two hemispheres at the semi-annual frequency. The semi-annual wind pattern displays small maxima of about 5 ms^{-1} near the tropopause at equatorial latitudes [*Lambeck*, 1980], whereas in the stratosphere the amplitude of the semi-annual term achieves its maximum value in the tropics [*Rosen and Salstein*, 1985].

4. Excitation of LOD

[13] Let ω_3^T(t) be the semi-annual variation of mantle rotation corresponding to the variation of the length-of-day given by equation (7):

$$\omega_3^T/\Omega = -lod^T/\overline{lod} = m_3^T \qquad (13)$$

Ω is the mean angular velocity of the Earth, 7.29 10^{-5} rad/s. The conservation of angular momentum of the solid Earth plus ocean plus atmosphere system leads to (assuming there is no other source of excitation):

$$C\,\omega_3^T = -C\,\Omega\left(lod^T/\overline{lod}\right) = -h_3^T \qquad (14)$$

where C is the polar moment of inertia of the solid Earth. *Gross et al.* [2004, Table 1] find that "the effects of semi-annual atmospheric surface pressure and oceanic current and bottom pressure changes on the length-of-day are each less than 3% of that observed". With $\Psi_3^{Twind} = -h_3^T/C\Omega$, we have:

$$m_3^T = \Psi_3^{Twind} \qquad (15)$$

Ψ_3 is the excitation function. *Gross et al.* [2004] find:

$$\Psi_3^{Twind} = 0.277.\ 10^{-8}.\ \cos(\omega t - 70^\circ) \qquad (16)$$

to be compared to our estimate of m_3^T (0.37 10^{-8} given in section 2).

[14] There is a tidal contribution to the excitation of m_3^T, Ψ_3^{Ttide}, smaller than Ψ_3^{Twind} but of the same order of magnitude, and out of phase with respect to it. When stratospheric winds are taken into consideration, $\Psi_3^{Twind} + \Psi_3^{Ttide}$ accounts well for m_3^T (for the time span 1980–1981 [*Rosen and Salstein*, 1985]). Since Ψ_3^{Ttide} is stable in amplitude and phase, the large observed variation in the phase $\gamma(k)$ and amplitude $\alpha(k)$ of lod^T (equation (7) and Figure 1) should be assigned to the meteorological excitation Ψ_3^{Twind}. Note that, due to the presence of the excitation Ψ_3^{Ttide}, the variations in the phase and amplitude of m_3^T are not independent.

5. Discussion

[15] It is natural to attribute the eleven-year modulation of the semi-annual lod variation observed in Figure 1a to the solar Schwabe cycle, through a modulation of the excitation function Ψ_3^{Twind} of the zonal wind. The average period of the modulation taken over the 1964–2007 time span is ~10.5 years. The sign of the modulation is opposite to that of the sunspot number: in Figure 1a, we superimpose the sunspot number (*WN*) curve over the same time interval, reversed in sign and phase shifted by 1 year to the right, on the semi-annual lod variation: we see that *WN*(*k*) and $\alpha(k)$ are closely anti-correlated, with sunspot number leading by approximately one year (correlation coefficient ~0.7). The affinity ratio between the two curves is not constant: whereas the last solar cycle is smaller than the preceding ones, the corresponding cycle in α is larger. If the lod $\alpha(k)$ series is detrended, the correlation is improved (Figure 1b; correlation coefficient 0.76). The multi-decadal variation could be due to a different cause, such as the exchange of angular momentum between the mantle and core [*Jault and Le Mouël*, 1991; *Jackson*, 1997]. Figure 1c compares the evolution of $\alpha(k)$ with the flux of galactic cosmic rays *GCR* [e.g., *Usoskin et al.*, 1998; *Svensmark*, 2000] (data from ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/COSMIC_RAYS/STATION_DATA/MOSCOW/docs/moscow.tab). Note that *GCR* is neither reversed in sign nor offset in phase with respect to α, demonstrating the excellent correlation between the two time series.

[16] But how can variations in the rotation of the solid Earth be related to galactic cosmic rays? The zonal winds

contributing to lod seasonal variations are dominantly low altitude winds. High altitude winds contribute less to angular momentum [e.g., *Höpfner*, 1997]. Winds above 30 km contribute less than 20% of angular momentum change [*Belmont and Dartt*, 1970; *Rosen and Salstein*, 1985; *Gross et al.*, 2004]. Most of the contribution from the layer below 30 km is tropospheric in origin. How then can variations in solar activity or galactic cosmic rays affect tropospheric winds?

[17] Taken in average over a year, the difference between radiation received from the Sun and outgoing long wavelength radiation is positive equatorward and negative poleward of 40° latitude. The latitudinal gradient in annual mean net radiation must be balanced by a poleward flux of energy in the climate system [e.g., *Hartmann*, 1994]. This transport from tropics to poles is effected by the longitude averaged meridional motion and eddies. The mean zonal wind $[u_\lambda]$ is a consequence of this meridional flow due to the conservation of total angular momentum about the Earth's rotation axis. When considering separately monthly averages rather than annual ones, differences in the net radiative flux distribution appear, due to the seasonal variation in insulation which is asymmetric with respect to the equator. Seasonal variations of insulation result in seasonal variations of poleward meridional transport, hence of averaged zonal wind. Annual and semi-annual variations are present in $h_3(t)$, i.e., in the excitation function Ψ_3.

[18] The argument above serves to show that the semi-annual variation in lod is linked to a fundamental feature of climate: the latitudinal distribution and transport of energy and momentum. *Höppner and Bittner* [2007] argued for a correlation between variations in lod from 1980 to 2005, the general Hale cycle of the solar magnetic field and planetary wave activity. They attributed this coupling to modulation of the internal Earth's field by the Hale cycle – which is problematic. But only one 22yr cycle was available and the analysis by *Höppner and Bittner* [2007] did not reveal the Schwabe cycle.

[19] It is generally argued that, because relative changes in total solar irradiance (TSI) are less that 10^{-3}, variations in solar activity cannot have a significant influence on climate in the troposphere [e.g., *Foukal et al.*, 2006; *Ram et al.*, 2009]. This argument does not hold in the present case: solar activity can affect the radiative equilibrium of the troposphere in an indirect way, which cannot be simply deduced from the magnitude of TSI variations. *Winkelnkemper* [2008] proposes that lod oscillations could be driven by intensified seasonality in meteorological parameters due to strengthened irradiation; he notes however that this fails to describe the anticorrelation for the semiannual oscillations.

[20] *Ney* [1959] was among the first to suggest a link between cosmic radiation and weather. The correlation that we find between h_3^T and cosmic ray intensity (Figure 1c) supports galactic cosmic rays as a viable mechanism. There is a well-established anticorrelation, also with a ~1yr lag, between solar activity and cosmic rays reaching the Earth's surface [*Nymmik and Suslov*, 1995; *Usoskin et al.*, 1998]. The "instantaneous" lag is actually variable, as shown by *Usoskin et al.* [1998], which may adversely affect the correlation in Figure 1c. GCRs ionize molecules in the atmosphere; the intensity of this ionization affects the behavior of aerosols and, as a result, of condensation and ice formation nuclei. As a whole, GCRs can therefore affect cloud microphysics, cloud cover and the amount of sunlight reflected by and transmitted to the rest of the atmosphere.

[21] A significant correlation between cosmic rays and low cloud cover has been suggested by *Svensmark and Friis-Christensen* [1997] [see also *Svensmark*, 2000; *Svensmark et al.*, 2009]. Therefore, the troposphere radiative equilibrium could be affected by cosmic ray intensity. Seasonal variations of the latitudinal energy distribution and poleward energy and momentum transfer, hence also of h_3^T would be modulated accordingly.

[22] Other mechanisms involving solar action on tropospheric layers have been proposed. For instance, the UV part of TSI, which has a very large variation up to 100% during a solar cycle, could be a significant solar forcing agent of climate [e.g., *Haigh*, 1996; *Dudok de Wit*, 2008]. Coupling between the different atmospheric layers which link the base of the ionosphere and the troposphere may occur through the global electric circuit [e.g., *Tinsley et al.*, 2007; *Tinsley*, 2008]: changes in cloud cover, atmospheric pressure and intensity of winter cyclones show correlations with changes in the electrical current J_z [*Tinsley et al.*, 2007; *Tinsley*, 2008]. In a recent paper, *Ram et al.* [2009] propose a chain of events that link variations in solar activity to variations in dust accumulation observed in ice cores, with a plausible amplifying mechanism. Whatever the actual amplitude of variations in total solar irradiance, cosmic ray flux (Figure 1c), ionospheric currents and J_z fluctuate by 10% and more over a solar cycle and at longer periods. Since relative variations of $\alpha(k)$ exceed 30%, some further amplification mechanism must operate. This mechanism remains to be fully understood and modeled.

6. Conclusion

[23] The solid Earth behaves as a natural spatial integrator and time filter, which makes it possible to study the evolution of the amplitude of the semi-annual variation in zonal winds over a fifty-year time span. We evidence strong modulation of the amplitude of this lod spectral line by the Schwabe cycle (Figure 1a). This shows that the Sun can (directly or undirectly) influence tropospheric zonal mean-winds over decadal to multi-decadal time scales. Zonal mean-winds constitute an important element of global atmospheric circulation. If the solar cycle can influence zonal mean-winds, then it may affect other features of global climate as well, including oscillations such as the NAO and MJO, of which zonal winds are an ingredient [*Wheeler and Hendon*, 2004]. The cause for this forcing likely involves some combination of solar wind, galactic cosmic rays, ionosphere-Earth currents and cloud microphysics.

[24] **Acknowledgments.** We thank H. Schuh and two anonymous reviewers for their useful and constructive comments. We thank an anonymous reviewer for pointing out *Bourget et al.*'s [1992] abstract and *Rosen and Salstein* [1985]. *Winkelnkemper*'s [2008] thesis was brought to our attention after submission of the paper but before revision, allowing to take it into account in the final version. After revision, D. Gambis and B. Legras pointed out *Abarca del Rio et al.*'s [2003] paper which we add as a further useful reference for the reader. This is IPGP contribution NS 3002.

References

Abarca del Rio, R., D. Gambis, D. Salstein, P. Nelson, and A. Dai (2003), Solar activity and earth rotation variability, *J. Geodyn. Res.*, *36*, 423–443, doi:10.1016/S0264-3707(03)00060-7.

Belmont, A. D., and D. G. Dartt (1970), The variability of tropical stratospheric winds, *J. Geophys. Res.*, *75*, 3133–3145, doi:10.1029/JC075i015p03133.

Blanter, E. M., J. L. Le Mouël, F. Perrier, and M. G. Shnirman (2006), Short term correlation of solar activity and sunspot evidence of lifetime increase, *Sol. Phys.*, *237*, 329–350, doi:10.1007/s11207-006-0162-x.

Bourget, P., D. Gambis, and D. Salstein (1992), Mise en évidence d'une relation entre l'activité solaire, la rotation de l'atmosphère et de la Terre, in *Journées 1992: Systèmes de Référence Spatio-Temporels*, pp. 172–176, Obs. de Paris, Paris.

de Viron, O., C. Bizouard, D. Salstein, and V. Dehant (1999), Atmospheric torque on the Earth and comparison with atmospheric angular momentum variations, *J. Geophys. Res.*, *104*, 4861–4875, doi:10.1029/1998JB900063.

Dudok de Wit, T. (2008), L'atmosphère sous ultraviolets, *La Recherche*, *1425*, 38–40.

Foukal, P., C. Fröhlich, H. Spruit, and T. M. L. Wigley (2006), Variations in solar luminosity and their effect on the Earth's climate, *Nature*, *443*, 161–166, doi:10.1038/nature05072.

Gross, R. S. (2007), Earth rotation variations—Long period, in *Treatise of Geophysics*, vol. 3, *Geodesy*, edited by G. Schubert and T. Herring, pp. 239–294, Elsevier, Amsterdam.

Gross, R. S., I. Fukumori, and D. Menemenlis (2004), Atmospheric and oceanic excitation of length-of-day variations during 1980–2000, *J. Geophys. Res.*, *109*, B01406, doi:10.1029/2003JB002432.

Haigh, J. D. (1996), The impact of solar variability on climate, *Science*, *272*, 981–984, doi:10.1126/science.272.5264.981.

Hartmann, D. L. (1994), *Global Physical Climatology*, 411 pp., Academic, New York.

Höpfner, J. (1997), Seasonal variations in length-of-day and atmospheric angular momentum, *Sci. Tech. Rep. STR97/08*, Eur. Geophys. Soc., Vienna.

Höppner, K., and M. Bittner (2007), Evidence for solar signals in the mesopause temperature variability?, *J. Atmos. Sol. Terr. Phys.*, *69*, 431–448, doi:10.1016/j.jastp.2006.10.007.

Jackson, A. (1997), Time-dependency of tangentially geostrophic core surface motions, *Phys. Earth Planet. Inter.*, *103*, 293–311, doi:10.1016/S0031-9201(97)00039-3.

Jault, D., and J. L. Le Mouël (1991), Exchange of angular momentum between the core and mantle, *J. Geomagn. Geoelectr.*, *43*, 111–129.

Lambeck, K. (1980), *The Earth's Variable Rotation: Geophysical Causes and Consequences*, 449 pp., doi:10.1017/CBO9780511569579, Cambridge Univ. Press, New York.

Lambeck, K., and A. Cazenave (1973), The Earth's rotation and atmospheric circulation—I. Seasonal variations, *Geophys. J. R. Astron. Soc.*, *32*, 79–93.

Lambeck, K., and P. Hopgood (1981), The Earth's rotation and atmospheric circulation from 1963 to 1973, *Geophys. J. R. Astron. Soc.*, *64*, 67–89.

Le Mouël, J. L., M. Shnirman, and E. Blanter (2007), The 27 day signal in sunspot number series and the solar dynamo, *Sol. Phys.*, *246*, 295–307, doi:10.1007/s11207-007-9065-8.

Le Mouël, J. L., V. Courtillot, E. Blanter, and M. Shnirman (2008), Evidence for a solar signature in 20th century temperature data from the USA and Europe, *C. R. Geosci.*, *340*, 421–430, doi:10.1016/j.crte.2008.06.001.

Newell, R. E., J. W. Kidson, D. G. Vincent, and G. J. Boer (1973), *The General Circulation of the Tropical Atmosphere and Interactions With Extratropical Latitudes*, vol. 1, 320 pp., MIT Press, Cambridge, Mass.

Ney, E. P. (1959), Cosmic radiation and the weather, *Nature*, *183*, 451–452, doi:10.1038/183451a0.

Nymmik, R. A., and A. A. Suslov (1995), Characteristics of galactic cosmic ray flux lag times in the course of solar modulation, *Adv. Space Res.*, *16*(9), 217–220, doi:10.1016/0273-1177(95)00338-F.

Okazaki, S. (1975), On the amplitude changes of seasonal components in the rate of rotation of the Earth, *Publ. Astron. Soc. Jpn.*, *27*, 367–378.

Ram, M., M. R. Stolz, and B. A. Tinsley (2009), The terrestrial cosmic ray flux: Its importance for climate, *Eos Trans. AGU*, *90*(44), doi:10.1029/2009EO440001.

Rosen, R. D., and D. A. Salstein (1985), Contribution of stratospheric winds to annual and semiannual fluctuations in atmospheric angular momentum and the length-of-day, *J. Geophys. Res.*, *90*, 8033–8041, doi:10.1029/JD090iD05p08033.

Shnirman, M., J. L. Le Mouël, and E. Blanter (2009), The 27 day and 22 year cycles in solar and geomagnetic activity, *Sol. Phys.*, *258*, 167–179, doi:10.1007/s11207-009-9395-9.

Svensmark, H. (2000), Cosmic rays and Earth's climate, *Space Sci. Rev.*, *93*, 175–185, doi:10.1023/A:1026592411634.

Svensmark, H., and E. Friis-Christensen (1997), Variation of cosmic ray flux and global cloud coverage—A missing link in solar-climate relationships, *J. Atmos. Sol. Terr. Phys.*, *59*, 1225–1232, doi:10.1016/S1364-6826(97)00001-1.

Svensmark, H., T. Bondo, and J. Svensmark (2009), Cosmic ray decreases affect atmospheric aerosols and clouds, *Geophys. Res. Lett.*, *36*, L15101, doi:10.1029/2009GL038429.

Tinsley, B. A. (2008), The global atmospheric electric circuit and its effects on cloud microphysics, *Rep. Prog. Phys.*, *71*, 066801, doi:10.1088/0034-4885/71/6/066801.

Tinsley, B. A., G. B. Burns, and L. Zhou (2007), The role of the global electric circuit in solar and internal forcing of clouds and climate, *Adv. Space Res.*, *40*, 1126–1139, doi:10.1016/j.asr.2007.01.071.

Usoskin, I. G., H. Kananen, K. Mursula, P. Tanskanen, and G. A. Kovaltsov (1998), Correlative study of solar activity and cosmic ray intensity, *J. Geophys. Res.*, *103*, 9567–9574, doi:10.1029/97JA03782.

Wheeler, M. C., and H. H. Hendon (2004), An all season real time multivariate MJO index: Development of an index for monitoring and prediction, *Mon. Weather Rev.*, *132*, 1917–1932, doi:10.1175/1520-0493(2004)132<1917:AARMMI>2.0.CO;2.

Winkelnkemper, T. (2008), Ensemble simulations of atmospheric angular momentum and its influence on the Earth's rotation, thesis dissertation, 146 pp., Rheinischen Friedrioch-Wilhelms-Univ., Bonn, Germany.

E. Blanter and M. Shnirman, International Institute of Earthquake Prediction Theory and Mathematical Geophysics, Warshavskoye sh. 79 kor. 2, Moscow 113556, Russia.

V. Courtillot and J.-L. Le Mouël, Institut de Physique du Globe de Paris, 4, place Jussieu, F-75252 Paris CEDEX 05, France. (courtil@ipgp.fr)