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## Long-term sunspot forcing of savanna structure inferred from carbon and oxygen isotopes

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[1] We used the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  isotopes from a speleothem and  $\Delta^{14}\text{C}$  values from known age tree rings as proxies for vegetation structure, rainfall and sunspot activity over the last 10,000 years. The  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  signals are significantly correlated and wavelet coherence analysis shows that a phase locked responses is only found to occur over periods less than 150 years. The  $\delta^{13}\text{C}$  and  $\Delta^{14}\text{C}$  signals are also significantly correlated but the wavelet coherence analysis shows phase locked responses at periods in the order of 320 and 1100 years at various times in the past. We conclude that savanna vegetation structure responds to rainfall over periods of decades to about 150 years, and to solar forcing over periods greater than 150 years. We propose that elevated UV-B radiation at the earth surface during periods of low sunspot activity favours the productivity of  $\text{C}_4$  plants over  $\text{C}_3$  plants possibly because of the metabolic cost of structural adaptive responses and of producing UV-B absorbing compounds in the latter. **Citation:** Woodborne, S., J.-L. Mélice, and R. J. Scholes (2008), Long-term sunspot forcing of savanna structure inferred from carbon and oxygen isotopes, *Geophys. Res. Lett.*, *35*, L02711, doi:10.1029/2007GL032019.

### 1. Introduction

[2] Savannas are ecosystems co-dominated by trees and grasses, but what regulates the expansion of woody cover into grassland or vice versa is not fully understood [Scholes and Archer, 1997; House et al., 2003]. Woody cover in savannas has a significant impact on the ecological services offered: grazing, browsing, fuel wood, water and carbon storage [Boutton et al., 1999; Jackson et al., 2002], and the implications of changing tree:grass ratios in the savanna for the global carbon budget is large given the extent of savannas world-wide. Changes in tropospheric ozone and the redistribution of atmospheric moisture under conditions of future climate change will affect the ultraviolet (UV) (200 nm) component of incident sunlight and possibly the ecological functioning of trees and grasses in savannas. Contemporary experiments elucidating the response of selected species provide a complex picture that includes the production of chemicals (particularly UV-B protective pigments), changing plant morphology and the above to below ground attribution of resources [Musil et al., 2002;

Chimpango et al., 2003]. Although the latter is largely inferred, there are suggestions that UV induced changes in plants affect herbivorous mammals and insects, and even higher trophic levels [Selås, 2006; Selås et al., 2004]. In order to test an ecosystem response to UV-B radiation we use  $\Delta^{14}\text{C}$  measurements as a proxy for changes in UV-B radiation through time and a speleothem isotope record to infer the tree:grass ratio response over the last 10,000 years.

[3] Sunspots are the pivotal phenomenon in the relationship between UV radiation and  $\Delta^{14}\text{C}$ . Sunspots are magnetic disturbances of the sun surface that occur in 11 year, 22 year, 88 year and possibly longer period cycles [Stuiver and Braziunas, 1993]. Both dark and brighter regions are detected on the sun surface (not necessarily synchronously) during periods of high solar activity, and the overall irradiance of the sun increases by approximately 0.1% [Lean and Rind, 1998]. The brighter areas of the sun (plages and faculae) increase the intensity of ultraviolet emissions, particularly in the UV-C range (10–280 nm) but also in the UV-B (280–315 nm) range. In the upper atmosphere the UV-C radiation produces ozone which absorbs UV-B radiation leading to reduced UV-B at the earth surface during periods of elevated solar activity. Over the 11-year sunspot cycle the UV-B variation is in the range of 4–13% while longer period fluctuations may be in the order of 9–27% [Rozema et al., 2002].

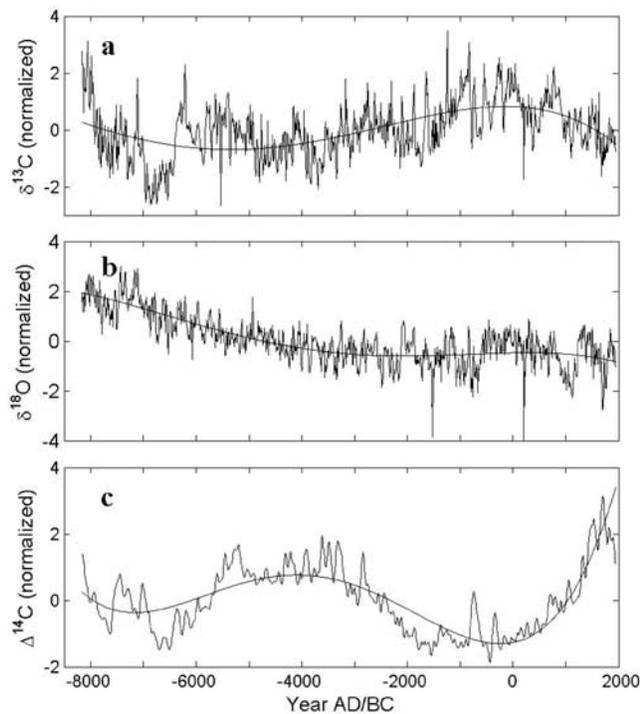
[4] Sunspots have a strong association with solar magnetic disturbances, and consequently the solar wind. Cosmogenic  $^{14}\text{C}$  production links to sunspots activity through the solar wind that deflects the  $^{14}\text{C}$ -producing cosmic flux of neutrons in the Earth's upper atmosphere. The term  $\Delta^{14}\text{C}$  denotes the deviation of atmospheric  $^{14}\text{C}$  levels from a defined standard through time [Stuiver and Polach, 1977]. Atmospheric radiocarbon ( $^{14}\text{C}$ ) concentrations (Figure 1c) reflect the equilibrium between cosmogenic production [Stuiver and Quay, 1980], radioactive decay, and dilution effects caused by changes in the distribution of carbon in other (non-atmospheric) carbon reservoirs. By comparing  $\Delta^{14}\text{C}$  with other cosmogenic isotopes such as  $^{10}\text{Be}$  [Muscheler et al., 2000], and with records of the earth's magnetic dipole [McElhinny and Senanayake, 1982; Tric et al., 1992] it is possible to isolate production from reservoir effects. Sunspot activity has been reconstructed for the last 11 400 years using the  $\Delta^{14}\text{C}$  values derived from known age tree rings [Solanki et al., 2004], and the  $\Delta^{14}\text{C}$  record has been compared with other palaeoclimatic proxy data to test for solar forcing [Bond et al., 2001; Dykoski et al., 2005].

[5] The reconstruction of past tree:grass proportions relies on the different isotopic characteristics of plants that photosynthesise by the  $\text{C}_3$  photosynthetic pathway (typically trees and shrubs) and the  $\text{C}_4$  photosynthetic pathway (savanna grasses and obligate CAM plants). The carbon

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**Figure 1.** Holocene isotope normalized datasets. (a) Carbon isotope record and (b) oxygen isotope record from the T8 Speleothem [Holmgren *et al.*, 2003] and (c) the INTCAL98 dataset for  $^{14}\text{C}$  variation [Stuiver *et al.*, 1998]. A 4<sup>th</sup> order polynomial fitted to each dataset was used to detrend the long period variability in subsequent analyses.

isotope signal of the vegetation passes to the soil atmosphere through root respiration or the decomposition of soil organic matter [Boutton *et al.*, 1999; West *et al.*, 2000]. Provided soil water retention time is long enough, atmospheric  $\text{CO}_2$  dissolved in incident rain will exchange with the soil atmosphere  $\text{CO}_2$ , and the vegetation carbon isotope signal dominates the groundwater. Speleothems precipitated in equilibrium record the carbon isotope signal of the soil  $\text{CO}_2$  and the oxygen isotope signal of the rainfall with an offset from carbonate dissolved from the bedrock [Genty *et al.*, 2003]. Oxygen isotopes in rainfall from the summer rainfall area of southern Africa reflect the relative contribution of mid-level stratiform clouds versus the upper troposphere clouds [Lee-Thorp *et al.*, 2001; Holmgren *et al.*, 2003]. The latter are associated with convective storms and the expansion of the circumpolar vortex, resulting in cooler, drier conditions, a reduction in the frequency but increase in intensity of storms and associated increased frequency of hail events [Harrison, 1986; Lee-Thorp, 2004]. The averaged  $\delta^{18}\text{O}$  of precipitation is depleted relative to periods when mid-level stratiform cloud dominates [Lee-Thorp *et al.*, 2001; Holmgren *et al.*, 2003]. Thus paired carbon and oxygen isotope determinations on the same speleothem samples provide a simultaneous indication of rainfall and ecosystem response in terms of the tree:grass ratio.

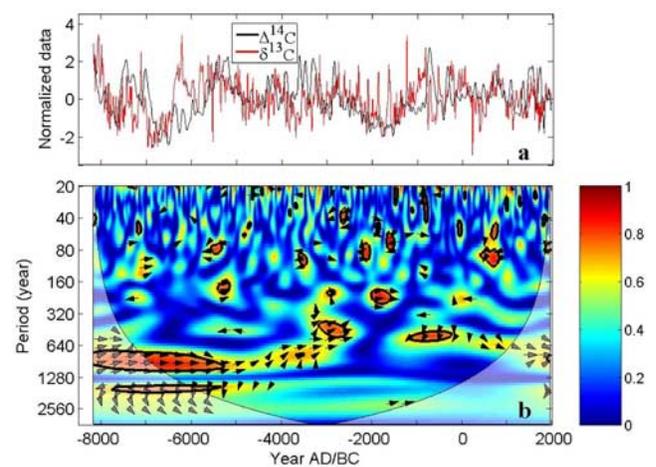
[6] We use the T8 speleothem isotope record (Figures 1a and 1b) from Cold Air Cave, Limpopo Province, South Africa [Holmgren and Lee-Thorp, 2005]. This cave is

situated in a savanna environment ( $24^\circ 1'S$ ,  $29^\circ 11'E$ ) close to the current altitudinal-controlled transition to grassland [Low and Rebello, 1996]. The savanna composition is therefore sensitive to variations in climate. The speleothem grew continuously from approximately 24,400 to 12,600 years ago, and then from 10,100 years ago to the present. Short-term  $\delta^{13}\text{C}$  variability (Figure 1a) is interpreted in terms of the relative contribution to  $\text{CO}_2$  in the soil atmosphere by trees versus grasses [Holmgren *et al.*, 2003].

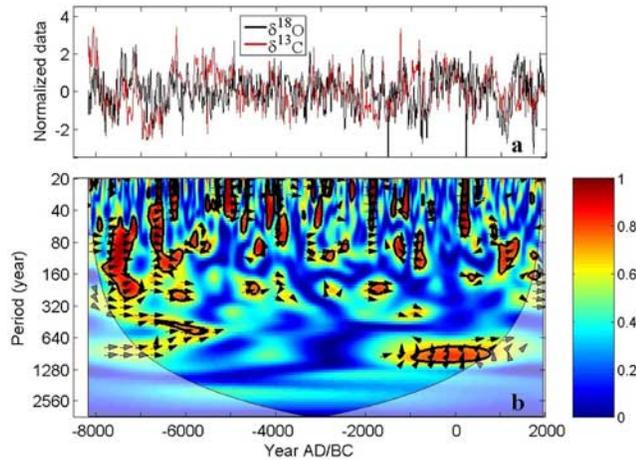
## 2. Results

[7] The relationship between  $\Delta^{14}\text{C}$  and  $\delta^{13}\text{C}$  (Figure 2a) is significant ( $n = 994$ ,  $r = 0.24$ ,  $n_{\text{eff}} = 71$ ,  $p = 0.046$ ) after taking into account the effect of serial correlation. The use of the cross-wavelet transform coherence (CWTC) analysis [Grinsted *et al.*, 2004; Maraun and Kurths, 2004] makes it possible to resolve both long and short-term co-variance in the time frequency space. The normalised  $\Delta^{14}\text{C}$  and  $\delta^{13}\text{C}$  records are subject to CWTC analysis (Figure 2b) indicating strong significant phase-locked coherence between 8000 BC and 4000 BC with a period around 1100 years. After 4000 BC the strongest coherence shifts to shorter periods with a minimum period of about 320 years. The analysis suggests that variation in solar activity over very long periods may drive changes in plant community structure, or alternatively both variables are driven by the same forcing mechanism.

[8] Synchronic studies of contemporary African savannas show that mean annual rainfall limits maximum woody cover where mean annual rainfall is  $<700$  mm, but fire regime, herbivory and soil properties typically reduce the wood cover below the rainfall-governed maximum [Sankaran *et al.*, 2005]. Accordingly a correlation between



**Figure 2.** Squared cross-wavelet transform coherence between  $\delta^{13}\text{C}$  and  $\Delta^{14}\text{C}$ . The contour designates the 5% significance level against red noise and the cone of influence where edge effects might distort the picture is shown as a lighter shade. The relative phase relationship is shown as arrows (with in-phase pointing right and anti-phase pointing left). The coherence image shows strong significant phase-locked coherence between  $\delta^{13}\text{C}$  and  $\Delta^{14}\text{C}$  with a period of approximately 1100 years prior to 4000 BC.



**Figure 3.** Squared cross-wavelet transform coherence between  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ . The significant coherence is mainly concentrated in the band with periods lower than  $\sim 150$  years but significant coherence with a period of approximately 1100 years is also observed between 1500 BC and 1000 AD.

rainfall and savanna ecosystem structure is anticipated. We found a significant relationship at the 0.001 level ( $n = 994$ ,  $r = 0.28$ ,  $n_{\text{eff}} = 169$ ,  $p = 0.0002$ ) between  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  (Figure 3a). CWTC analysis comparing  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  (Figure 3b) shows that the significant coherence is concentrated in a band with periods lower than  $\sim 150$  years although significant coherence with a period around 1100 years is observed between 1500 BC and AD 1000. This suggests that plant community structure and rainfall are closely linked on decadal to century time-scales. When the rainfall is inferred to be higher, the fraction of trees is also inferred to be higher.

[9] When the CWTC analysis was used to compare  $\delta^{18}\text{O}$  and  $\Delta^{14}\text{C}$  (i.e. rainfall and solar activity proxies) we found no significance in the comparison of the two series. Rainfall in this region is not correlated with sunspot activity over the time being studied.

### 3. Conclusions and Discussions

[10] The results show that plant community structure is strongly associated with moisture forcing over periods of decades to about 150 years, and to solar forcing over time periods greater than 150 years. This does not imply that such forcing acts or does not act over shorter time-periods; better resolved proxy data are required to test the impact of the 11-year sunspot cycle. While on such a short time scale there may be no obvious changes in plant community structure, it is still possible that tree and grass productivity is differentially influenced. The relative abundance of trees and grasses may remain unchanged on the landscape, but the amount of  $\text{CO}_2$  entering the soil atmosphere may differ as a result of different relative rates of carbon assimilation or belowground allocation.

[11] One explanation for the spectral composition of the  $\Delta^{14}\text{C}$  record invokes changes in the earth core dynamo [Kuznetsova and Tsirulnik, 2004], which would influence the Earth's magnetic field and the deflection of cosmic radiation. This mechanism is contradictory of the sunspot

number mechanism [Solanki et al., 2004] in which atmospheric fluctuations of  $^{14}\text{C}$  are largely attributed to sunspot activity modelled under a relatively predictable fluctuation in the Earth magnetic dipole. The fact that vegetation appears to respond to the same forcing suggests that there is some basis in plant physiology. Solar variability affects both sunlight intensity and wavelength, both of which have known effects on photosynthesis. We suggest that the metabolic cost of producing UV-B absorbing compounds during periods of high UV-B radiation, as well as the plant structural adaptive responses disadvantages  $\text{C}_3$  plants relative to  $\text{C}_4$  plants.

### 4. Method

[12] The average resolution of the Holocene portion of the T8 isotope dataset is 10.3 years, and the pre-Holocene record is 401.8 year resolution. The poor resolution in both the  $\Delta^{14}\text{C}$  and the stable isotope records prior to the hiatus limited the statistical approach, and we only use the Holocene part of the dataset in this analysis. The  $\Delta^{14}\text{C}$  values were derived from published tree ring samples comprising 10 growth rings (years), and occasionally 20 rings (years) for the Holocene [Stuiver et al., 1998]. We note that the resolution of the  $\Delta^{14}\text{C}$  data limits any interpretation to forcing with a period longer than 60 years. The long term sinusoidal wave (period c.6000 years) in the  $\Delta^{14}\text{C}$  record is the result of the earth's magnetic dipole and not variability in solar activity. A fourth order polynomial fitted through the detrended data (Figure 1a) is used to approximate the dipole effect and the residual (Figure 2a) is assumed to reflect the sunspot activity [Solanki et al., 2004]. Variability with long periods in the isotope records can similarly not be attributed to solar influences and fourth order polynomials were also used to filter these. All residual series are normalized (i.e. the mean is zero, and the standard deviation is one). We use the correlation coefficient to explore the relationship between the residual series. Before using the classical  $t$  test for the significance level, we take into account the effect of serial correlation in the data by estimating an "effective sample size" defined as [von Storch and Navara, 1999; von Storch and Zwiers, 1999]:

$$n_{\text{eff}} = n / \left[ 1 + 2 \sum_{k=1}^{n-1} \left( 1 - \frac{k}{n} \right) \rho_x(k) \rho_y(k) \right]$$

where  $\rho_x(k)$  and  $\rho_y(k)$  are the autocorrelation function of the series  $x$  and  $y$  of length  $n$ .

[13] While it is interesting to focus on the full signals with the correlation coefficient, it is also worthwhile to examine in which particular regions of the time frequency space the signals are related. Cross wavelet transform coherence (CWTC) examines whether regions in the time frequency space have a consistent coherence and phase relationship. CWTC can be thought of as the local correlation between the time series in the time frequency space. Moreover, the CWTC estimates the phase difference between the series in the time frequency space and thus can find locally phase locked behaviour. Monte Carlo methods are used to assess the statistical significance of the wavelet coherence against red noise background. After examination of their autocorrelation functions and power spectra, it can

be shown that the  $\Delta^{14}\text{C}$ ,  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  series have red noise characteristics that can roughly be modelled by a first order autoregressive (AR1) process. When interpreting the CWTC results with the *Grinsted et al.* [2004] tools, we have to account for the limitation of the test for significance with the red noise hypothesis. Due to multiple testing, spuriously significant peaks have to appear by definition. These problems which are investigated by *Maraun and Kurths* [2004] are not addressed here.

[14] The atmospheric record of  $\Delta^{14}\text{C}$  as manifest in trees has virtually no lag time relative to the sunspot forcing, while the date assigned to each isotope value from the speleothem must take into account the precision of the dating and must be interpreted in the context of the lag time in the eco-hydrological system connecting the plants to the cave system, including the residence time of the carbon in various plant and soil pools, and the percolation rate of the groundwater. These lags are unlikely to be constant through time. Sunspot activity is not the only variable affecting UV-B radiation at the earth surface. Volcanic aerosols and atmospheric moisture also play a role [*Lean and Rind*, 1998], and turbations caused by these variables would not be recorded in the  $\Delta^{14}\text{C}$  record. Nevertheless, the correlation between  $\Delta^{14}\text{C}$  and  $\delta^{13}\text{C}$  at high periods suggests that neither variable time lags nor short-term turbations in UV-B radiation caused by volcanoes or atmospheric moisture affect the correlation.

[15] **Acknowledgments.** We thank Karen Holmgren and Julia Lee-Thorp for access to unpublished data and Aslak Grinsted for providing the cross-wavelet transform coherence program, which can be found at [http://www.pol.ac.uk/home/research/waveletcoherence/\(2006\)](http://www.pol.ac.uk/home/research/waveletcoherence/(2006)) and the Science and Technology Consolidated Plan of Action.

## References

- Bond, G., B. Kromer, J. Beer, R. Muscheler, M. N. Evans, W. Showers, S. Hoffmann, R. Lotti-Bond, I. Hajdas, and G. Bonani (2001), Persistent solar influence on North Atlantic climate during the Holocene, *Science*, *294*, 2130–2136, doi:10.1126/science.1065680.
- Boutton, T. W., S. R. Archer, and A. J. Midwood (1999), Stable isotopes in ecosystem science: Structure, function and dynamics of a subtropical savanna, *Rapid Commun. Mass Spectrom.*, *13*(13), 1263–1277.
- Chimpango, S. B. M., C. F. Musil, and F. D. Dakora (2003), Response of purely symbiotic and  $\text{NO}_3^-$ -fed nodulated plants of *Lupinus lentus* and *Vicia atropurpurea* to ultraviolet-B radiation, *J. Exp. Bot.*, *54*(388), 1771–1784, doi:10.1093/jxb/erg190.
- Dykoski, C. A., R. L. Edwards, H. Cheng, D. X. Yuan, Y. J. Cai, M. L. Zhang, Y. S. Lin, J. M. Qing, Z. S. An, and J. Revenaugh (2005), A high-resolution, absolute-dated Holocene and deglacial Asian monsoon record from Dongge Cave, China, *Earth Planet. Sci. Lett.*, *233*(1–2), 71–86, doi:10.1016/j.epsl.2005.01.036.
- Genty, D., D. Blamart, R. Ouahdi, M. Gilmour, A. Baker, J. Jouzel, and S. Van-Exter (2003), Precise dating of Dansgaard-Oeschger climate oscillations in western Europe from stalagmite data, *Nature*, *421*, 833–837, doi:10.1038/nature01391.
- Grinsted, A., J. C. Moore, and S. Jevrejeva (2004), Application of the cross wavelet transform and wavelet coherence to geophysical time series, *Nonlinear Processes Geophys.*, *11*, 561–566.
- Harrison, M. S. J. (1986), A synoptic climatology of South African rainfall variability, Ph.D. thesis, 341 pp., Univ. of the Witwatersrand, Johannesburg, South Africa.
- Holmgren, K., and J. A. Lee-Thorp (2005), Cold Air Cave Stalagmite 25KYr Stable Isotope Data, *Contrib. Ser. 2005-034*, <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/speleothem/africa/cold-air-cave2003.txt>, World Data Cent. for Palaeoclimatol., Boulder, Colo.
- Holmgren, K., J. A. Lee-Thorp, G. R. J. Cooper, K. Lundblad, T. C. Partridge, L. Scott, R. Sithaldeen, A. S. Talma, and P. D. Tyson (2003), Persistent millennial-scale climatic variability over the past 25,000 years in southern Africa, *Quat. Sci. Rev.*, *22*, 2311–2326, doi:10.1016/s0277-3791(03)00204-x.
- House, J. I., S. Archer, D. D. Breshears, and R. J. Scholes (2003), Conundrums in mixed woody herbaceous plant systems, *J. Biogeogr.*, *30*(11), 1763–1777, doi:10.1046/j.1365-2699.2003.00873.x.
- Jackson, R. B., J. L. Banner, E. G. Jobaggy, W. T. Pockman, and D. H. Wall (2002), Ecosystem carbon loss with woody plant invasion of grassland, *Nature*, *418*, 623–626, doi:10.1038/nature00910.
- Kuznetsova, T. V., and L. B. Tsurulnik (2004), Climate change and abrupt changes in C14 data, *Adv. Space Res.*, *34*(2), 426–431, doi:10.1016/j.asr.2002.03.001.
- Lean, J., and D. Rind (1998), Climate forcing by changing solar radiation, *J. Clim.*, *11*, 3069–3094, doi:10.1175/1520-0442(1998)011<3069:CFBCSR>2.0.CO;2.
- Lee-Thorp, J. A. (2004), Longterm, high resolution records of climate variability from cave speleothems in Cold Air Cave, Makapans Valley, Limpopo Province, *Rep. 1013/1/04*, pp. 1–79, Water Res. Comm. of S. Afr., Pretoria.
- Lee-Thorp, J. A., K. Holmgren, S-E. Lauritzen, H. Linge, A. Moberg, T. C. Partridge, C. Stevenson, and P. D. Tyson (2001), Rapid climate shifts in the southern African interior throughout the mid to late Holocene, *Geophys. Res. Lett.*, *28*(23), 4507–4510.
- Low, A. B., and A. G. Rebello (Eds.) (1996), *Vegetation of South Africa, Lesotho and Swaziland, A Companion to the Vegetation Map of South Africa, Lesotho and Swaziland*, Dep. of Environ. Affairs and Tourism, Pretoria.
- McElhinny, M. W., and W. E. Senanayake (1982), Variations in the geomagnetic dipole I: The past 50,000 years, *J. Geomagn. Geoelectr.*, *34*(1), 39–51.
- Maraun, D., and J. Kurths (2004), Cross wavelet analysis: Significance testing and pit falls, *Nonlinear Processes Geophys.*, *11*, 505–514.
- Muscheler, R., J. Beer, G. Wagner, and R. C. Finkel (2000), Changes in deep-water formation during the Younger Dryas event inferred from  $^{10}\text{Be}$  and  $^{14}\text{C}$  records, *Nature*, *408*, 567–570, doi:10.1038/35046041.
- Musil, C. F., S. B. M. Chimpango, and F. D. Dakora (2002), Effects of elevated ultraviolet-B radiation on native and cultivated plants of southern Africa, *Ann. Bot.*, *90*, 127–137, doi:10.1093/aob/mcf156.
- Rozema, J., B. van Geel, L. O. Bjorn, J. Lean, and S. Madronich (2002), Towards solving the UV puzzle, *Science*, *296*, 1621–1622, doi:10.1126/science.1070024.
- Sankaran, M., et al. (2005), Determinants of woody cover in African savannas, *Nature*, *438*, 846–849, doi:10.1038/nature04070.
- Scholes, R. J., and S. R. Archer (1997), Tree-grass interactions in savannas, *Annu. Rev. Ecol. Syst.*, *28*, 517–544, doi:10.1146/annurev.ecolsys.28.1.517.
- Selås, V. (2006), UV-B-induced plant stress as a possible cause of ten-year hare cycles, *Popul. Ecol.*, *48*, 71–77, doi:10.1007/s10144-005-0235-y.
- Selås, V., O. Hogstad, S. Kobro, and T. Rafoss (2004), Can sunspot activity and ultraviolet-B radiation explain cyclic outbreaks of forest moth pest species?, *Proc. R. Soc. London, Ser. B.*, *271*, 1897–1901, doi:10.1098/rspb.2004.2811.
- Solanki, S. K., I. G. Usoskin, I. G. Kromer, M. Schussler, and J. Beer (2004), Unusual activity of the Sun during recent decades compared to the previous 11000 years, *Nature*, *431*, 1084–1087, doi:10.1038/nature02995.
- Stuiver, M., and T. F. Braziunas (1993), Sun, ocean, climate and atmosphere  $^{14}\text{CO}_2$ : An evaluation of causal and spectral relationships, *Holocene*, *3*, 289–305.
- Stuiver, M., and H. A. Polach (1977), Reporting of  $^{14}\text{C}$  data—Discussion, *Radiocarbon*, *19*(3), 355–363.
- Stuiver, M., and P. D. Quay (1980), Changes in atmospheric  $^{14}\text{C}$  attributed to a variable Sun, *Science*, *207*, 11–19, doi:10.1126/science.207.4426.11.
- Stuiver, M., P. J. Reimer, E. Bard, J. W. Beck, G. S. Burr, K. A. Hughen, B. Kromer, G. McCormac, J. van der Plicht, and M. Spurk (1998), INTCAL98 radiocarbon age calibration, 24000-0 cal BP, *Radiocarbon*, *40*(3), 1041–1083.
- Tric, E., J. P. Valet, P. Tucholka, M. Paterne, L. Labeyrie, F. Guichard, L. Tauxe, and M. Fontugne (1992), Paleointensity of the geomagnetic field during the last 80,000 years, *J. Geophys. Res.*, *97*(B6), 9337–9351.
- von Storch, H., and A. Navarra (Eds.) (1999), *Analysis of Climate Variability: Applications of Statistical Techniques*, 2nd ed., 342 pp., Springer, New York.
- von Storch, H., and F. W. Zwiers (Eds.) (1999), *Statistical Analysis in Climate Research*, 484 pp., Cambridge Univ. Press, New York.
- West, A. G., W. J. Bond, and J. J. Midgley (2000), Soil carbon isotopes reveal ancient grassland under forest in Hluhluwe, KwaZulu-Natal, *S. Afr. J. Sci.*, *96*, 252–254.

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