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Evidence of solar and tropical-ocean forcing of hydroclimate cycles in southeastern Australia for the past 6500 years

Hamish A. McGowan
The University of Queensland

Samuel K. Marx
University of Wollongong, smarx@uow.edu.au

Joshua Soderholm
University of Queensland

John Denholm
Snowy Hydro Limited, Cooma, NSW

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Abstract

Evidence of solar and tropical-ocean forcing of climate cycles has been found in numerous palaeoclimate records. Numerical modelling studies show physical mechanisms by which direct and indirect solar forcing may affect climate, while there is mounting evidence of solar forcing of tropical ocean-atmosphere teleconnections. This study has developed a 6500 year record of dust deposition, a proxy for regional hydroclimate variability for the Snowy Mountains region of Australia. Spectral analysis of the record provides evidence of statistically significant cycles in dust deposition of 35–43 years, 62–73 years, 161 years and 2200 years. These correlate with variability in solar irradiance and the Pacific Decadal Oscillation (PDO). We present evidence to support physical links between variability in solar irradiance and change in the hydroclimate of southeast Australia and suggest that the effects of global warming and solar maxima on atmospheric circulation over extra-tropical regions may exacerbate these impacts.

Keywords

6500, past, australia, southeastern, cycles, hydroclimate, forcing, years, ocean, evidence, tropical, solar, GeoQUEST

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

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Evidence of solar and tropical-ocean forcing of hydroclimate cycles in southeastern Australia for the past 6500 years

Hamish A. McGowan,[1] Samuel K. Marx,[1] Joshua Soderholm,[1] and John Denholm[2]

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[1] Evidence of solar and tropical-ocean forcing of climate cycles has been found in numerous palaeoclimate records. Numerical modelling studies show physical mechanisms by which direct and indirect solar forcing may affect climate, while there is mounting evidence of solar forcing of tropical ocean-atmosphere teleconnections. This study has developed a 6500 year record of dust deposition, a proxy for regional hydroclimate variability for the Snowy Mountains region of Australia. Spectral analysis of the record provides evidence of statistically significant cycles in dust deposition of 35–43 years, 62–73 years, 161 years and 2200 years. These correlate with variability in solar irradiance and the Pacific Decadal Oscillation (PDO). We present evidence to support physical links between variability in solar irradiance and change in the hydroclimate of southeast Australia and suggest that the effects of global warming and solar maxima on atmospheric circulation over extra-tropical regions may exacerbate these impacts.

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1. Introduction

[2] The vulnerability of regions to adverse affects of water scarcity due to climate change has raised awareness of the urgent need to better understand causes of variability in the hydrological cycle [*Intergovernmental Panel on Climate Change*, 2007]. In Australia, water allocation decisions made during favourable climate conditions have resulted in the development of significant irrigated agriculture, particularly into semi-arid areas including the 1.06 million km^2 Murray-Darling Basin (MDB). Prolonged drought over the past decade combined with the consequences of historical over allocation of water resources now threaten the long-term productivity and sustainability of this region.

[3] *Ummenhofer et al.* [2009] presented evidence that the recent prolonged drought was in-part caused by the Indian Ocean Dipole (IOD), while *Kiem and Franks* [2004] found positive phases of the Pacific Decadal Oscillation (PDO) to be linked with increased drought risk over southern Australia. A positive trend in the Southern Annular Mode (SAM) over the past ≈25 years has also been linked to the decline of rainfall over southern Australia with precipitation bearing extra-tropical cyclones and associated fronts tracking further south, particularly through winter [*Hendon et al.*, 2007]. An increased tropical to mid-latitude tropospheric temperature gradient due to global warming and stratospheric ozone depletion have been postulated as causing the positive trend in SAM [*Murphy and Timbal*, 2008].

[4] While the effects of ENSO, IOD, SAM and to a lesser degree the PDO are well represented in observational records, longer period centennial to sub-Milankovitch millennial scale climate cycles are not. The mechanisms responsible for these cycles and their impacts on climate must be resolved to improve accuracy of longer term climate predictions, and to confirm causes of environmental change evident in many palaeoclimate records.

[5] Analysis of ^{10}Be and ^{14}C cosmogenic isotope records constructed from ice core and tree rings records suggest variability in radiation emitted from the Sun as a potential driver of longer period climate cycles [*Horiuchi et al.*, 2008; *Knudsen et al.*, 2009]. Distinct peaks in these isotope records at ≈88 and 208–212 years correspond to the Gleissberg and Suess solar cycles [*Knudsen et al.*, 2009]. The c. 2400 year Hallstattzeit solar cycle is also evident in some palaeo-environmental records [*Vasiliev et al.*, 1999].

[6] Direct solar forcing has been suggested as a possible mechanism to explain evidence of these cycles in palaeoclimate records, although the change in solar irradiance of ~0.1% is often considered too little to affect climate [*Rind et al.*, 2008]. Proposed amplification mechanisms such as stratosphere UV-ozone interactions and solar modulated terrestrial cosmic ray flux have been suggested as mechanisms by which subtle change in irradiance can affect climate. *Ram and Stolz* [1999] found dust concentrations spanning 100,000 years of the GISP2 ice core displayed regular periods close to the Hale, Gleissberg and Suess solar cycles. They proposed that increased solar activity resulted in decreased cosmic ray flux leading to decreased cloud contact nucleation, decreased precipitation and therefore increased atmospheric dust [*Ram et al.*, 2009]. *Franks* [2002] and *Jackson et al.* [2008] suggested that PDO variability was linked to solar forcing with positive phases corresponding to periods of reduced solar irradiance [*Mann et al.*, 2005]. Here we present a 6500 year record of dust deposition from southeastern Australian. This record shows statistically significant cycles in dust deposition that appear to indicate solar and tropical-ocean forcing of multi-decadal to millennial cycles in the regions climate.

2. Method

[7] In April 2007 a 1 m peat core was collected from an ombrotrophic mire in the Snowy Mountains, Australia [lat.

[1]Climate Research Group, School of Geography, Planning and Environmental Management, University of Queensland, Brisbane, Queensland, Australia.

[2]Snowy Precipitation Enhancement Research Project, Snowy Hydro Limited, Cooma, New South Wales, Australia.

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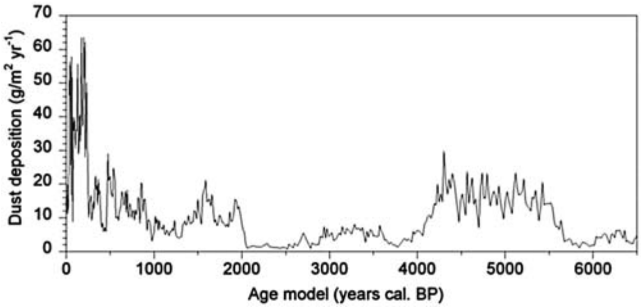

Figure 1. Dust deposition record for the past 6,500 years for our sampling site in the Upper Snowy River, Australian Alps.

36.463 °S, long. 148.299 °E]. The site is located in the centre of the Australian southeast dust transport pathway (auxiliary material), through which dust is transported by westerly quarter winds [*McGowan et al.*, 2005].[1] Dust storm frequency over this region increases in response to decreasing rainfall, thereby reflecting broad scale change in atmospheric circulation [*McTainsh et al.*, 1989; *Lamb et al.*, 2009]. Accordingly, dust deposition at this site is proxy for variability in regional hydroclimate.

[8] The core was sliced into 2 mm segments with a subsample of each segment combusted in chemically inert ceramic crucibles at 450 °C for 12 h to destroy organic material and allow recovery of the dust. Potential contamination of the core by local sediments was accounted for using trace element fingerprinting to determine their source. This was achieved by comparing the chemistry of the core samples to those of all potential dust source area sediments in eastern Australia and local sediments by normalizing all potential source area chemistries with the sediment sample in question. The degree of match can be quantified by the sum of deviates (Σ_D), which is defined as the sum of the differences between the number of trace elements used, in this case thirty in the core sediment samples with those in a potential source sediment [see *Marx et al.*, 2009, 2010]. Using this method, contributions from various sources were differentiated and the aeolian dust deposition record constructed for the core. Age control for the core was established by seven ^{210}Pb and six ^{14}C dates (auxiliary material). This gave a temporal resolution for each core sediment sample of ≈3 to 40 years.

[9] Spectral analysis of the dust deposition record was conducted using the REDFIT program of *Schulz and Mudelsee* [2002]. This estimates red-noise spectra directly from unevenly spaced time series, without requiring interpolation. The frequency spectrum of unevenly spaced time steps is calculated using the Lomb-Scargle Fourier transform in combination with a first order auto-regressive process to estimate red noise.

[10] To analyse the spectral content of the non-stationary dust deposition time series record we applied Morlet wavelet power spectrum in which the wavelet basis is normalised by the global wavelet spectrum. The cone-of-influence boundary is calculated to isolate useful periods, i.e., where there is insufficient time span for analysing larger periods. The MHAT basis for filtration following the method of *Ogurtsov et al.* [2002] was then applied in order to identify epochs when the cycles found by the spectral analysis of the dust deposition time series were most dominant.

3. Results

[11] Dust deposition in the Snowy Mountains for the past 6500 years is presented in Figure 1. From ca. 6500 to ca. 5700 years BP dust deposition rates averaged approximately 4 g m^2 yr^{-1} increasing to about 16 g m^2 yr^{-1} after 5600 years BP. They decreased to approximately 4 g m^2 yr^{-1} from about 4100 years BP through until 2100 years BP when they increased again to a mean of near 14 g m^2 yr^{-1}. The pronounced increase in dust deposition toward the present that peaked at 55 g m^2 yr^{-1} we believe corresponds to the introduction of European farming practices and associated land clearing throughout southeastern Australia. Dust deposition rates decreased late in the 20th century returning to pre-1800 AD levels due most likely to introduction of soil conservation practices rather than climate variability.

[12] Spectral analysis of the dust deposition record identified statistically significant cycles centered on 35, 43, 62, 73 and 161 years which all exceed the 95% confidence interval, and a 2200 year cycle which exceeded the 90% confidence interval (not shown) using the Chi^2 test (Figure 2). Results of the Morlet wavelet analysis are presented in Figure 3 for all cycles except the 2200 year cycle, which if shown would dominate half of the respective plot. These show that the ≈35 year cycle was most pronounced during the past 300 years with a trend toward a slightly longer period of ≈43 years around 250 years BP. This cycle also appears dominant around 550 and 850 years BP, while the ≈63–73 year cycle was dominant around 550, 1000 and 1500 years BP, and then again between 4000–4500 years BP (Figure 3a). The longer ≈ 161 year cycle was most pronounced during the past 1000 years (Figure 3b) and around 4200 years BP.

4. Discussion

[13] Fourier and wavelet analyses of our 6500 year record have identified highly significant cycles in dust deposition. These reflect variability in the hydroclimate of the dust source area, the MDB, with higher rates of dust deposition corresponding to periods of increased aridity which are associated with drought.

[14] The ≈35–43 years cycle in dust deposition appears to correlate with the PDO which has been shown to be a principal forcing of hydroclimate variability around the Pacific Basin including southeast Australia [*Mantua and Hare*, 2002; *McGowan et al.*, 2009]. Positive phases of the PDO are associated with weather patterns, particularly during autumn, that are less conducive to rainfall over southeast Australia [*Verdon-Kidd and Kiem*, 2009] and likely to increase dust transport [*Lamb et al.*, 2009]. Our record indicates that the ≈ 35–43 years cycle in dust deposition has been most prevalent over the past 1000 years. The reason for this is uncertain however the observation corresponds to a period when cosmogenic isotope records indicate that the Sun was in a relatively calm phase [*Bard and Frank*, 2006]. The associated change in insolation may have allowed the PDO to more strongly imprint on

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL042918.

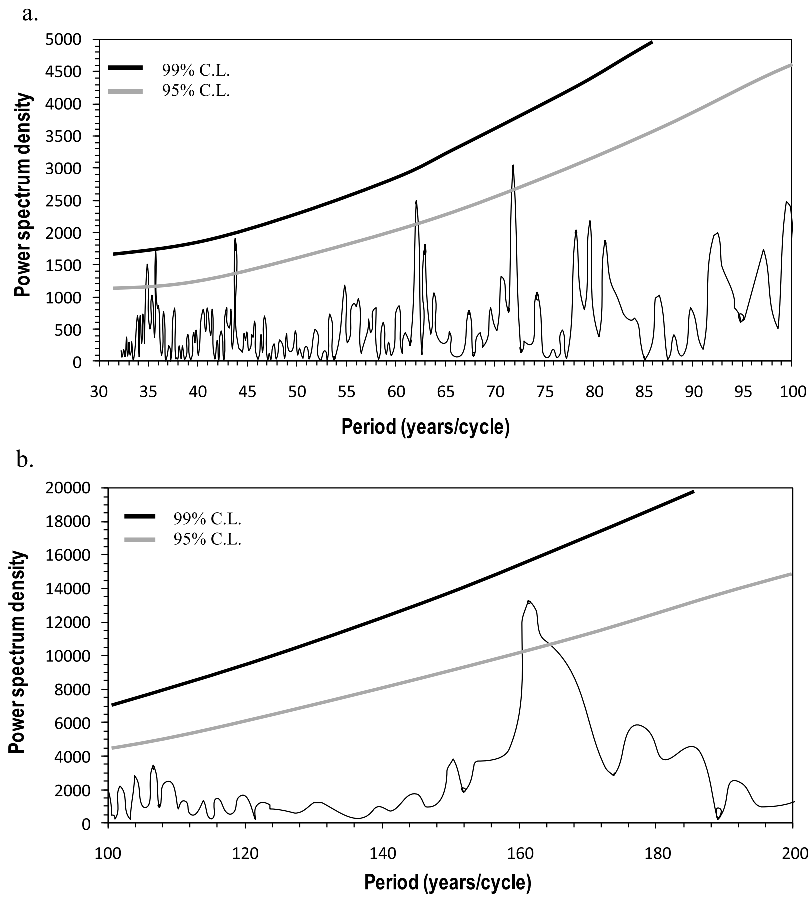

Figure 2. Plots of spectral power density against period between (a) 30 to 100 year and (b) 100 to 200 year cycles with 95% and 99% confidence levels determined using Chi^2 test shown.

the hydroclimate of southeast Australia during this period although further research is clearly required to answer this issue.

[15] The ≈62–73 years cycle in the dust record may relate to the pentadecadal PDO cycle and/or the ≈88 year Gleissberg solar cycle. It is most pronounced around 550, 1000 and 1500 years BP and then again between 4000–4500 years BP. Differentiation of the exact mechanism responsible for this cycle is not possible by this study as variability in the PDO on multi-decadal and longer timescales may in-part be a response to variations in solar output [*Kirov and Georgieva*, 2002]. *Cook et al.* [2006] also identified a 62–76 years cycle in a 3600 year tree ring record from Tasmania Australia. Unlocking the cause(s) of this cycle has potential for multi-decadal forecasting of hydroclimate trends in southeast Australia and should be considered a research priority.

[16] The highly significant ≈161 year dust deposition cycle (most pronounced during the past 1000 years and around 4200 years BP) correlates closely to a ≈150 solar cycle reported by *Knudsen et al.* [2009] in their analyses of the ^{14}C and ^{10}Be data from the IntCal04 and GRIP ice core records respectively. This solar cycle was also observed by *Peristykh and Damon* [2003] following their analysis of the $\Delta^{14}C$ INTCAL98 record. This cycle is much shorter than the 208–212 years Suess cycle which we find no evidence of in our dust deposition record. Our results are the first evidence of the impact of the ≈150–160 years solar cycle on the hydroclimate of mainland Australia, with the wavelet analysis confirming the greatest effect centered on 500 years BP encompassing the Maunder, Spörer and Wolf solar minima.

[17] The ≈2200 year cycle in our dust deposition record correlates with the c. 2200 year Hallstattzeit solar cycle which has been reported in many ^{14}C and ^{10}Be records, confirming a solar origin [*Vasiliev and Dergachev*, 2002; *Nederbragt and Thurow*, 2005]. While a longer dust deposition record would confirm the robustness of this cycle and its affects on southeast Australia, our record shows it to be a significant forcing of the mid to late Holocene climate, possibly through changes in ocean circulation and/or ice cap extent as suggested by *Nederbragt and Thurow* [2005]. Importantly, this cycle would appear to control the longer term millennial scale climate (wet – dry phases) in southeast Australia on which the centennial to multi-decade climate cycles are superimposed.

[18] A mechanism for the manifestation of solar cycles in wind erosion and dustiness, and by association, the hydroclimatology of southeast Australia has not been offered. The dust deposition record from the Snowy Mountains clearly shows evidence of cycles aligned with well documented solar (and tropical ocean SST) cycles. *Rind et al.* [2008] using the Goddard Institute for Space Studies Global Climate Middle Atmosphere Model 3 to investigate the influence of solar cycles on troposphere/stratosphere processes,

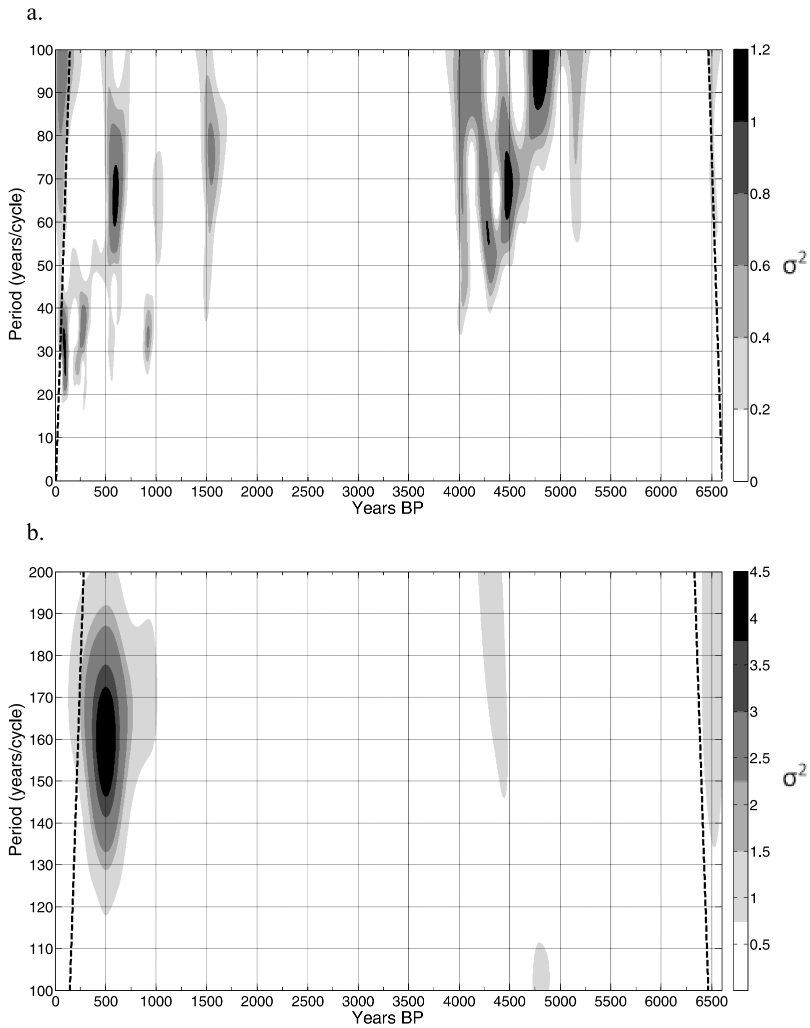

Figure 3. Local wavelet (Morlet basis) spectrum of dust deposition for (a) 0 to 100 year and (b) 100 to 200 year cycles. Also shown is the cone of influence.

found the solar UV effect during solar maximums produced stronger westerly wind stratospheric circulation. This was able to propagate to the troposphere, particularly in the Southern Hemisphere producing a more positive SAM [*Rind et al.*, 2008, p. 23]. The subtropical jet was also found to weaken and move southward with the Hadley Cell. *Haigh et al.* [2005] found a similar poleward shift of the subtropical jets and expansion of the Hadley Circulation with a more active sun which *Ram et al.* [2009] linked to reduced precipitation as a result of decreased cosmic ray flux and cloud contact nucleation. As a result, there is now strong evidence to support physical links between variability in solar irradiance and change in the hydroclimate of southeast Australia. The potential impact of solar variability on weather and climate in this region, and elsewhere, must therefore be accounted in prediction of future climate change. This is critical, particularly in regions such as southeast Australia where a positive trend in SAM and southward expansion of the Hadley Cell over the past two decades has been linked by some researchers to anthropogenic global warming and stratospheric ozone depletion only, and proposed as the principal cause of recent prolonged drought over southern Australia [*Murphy and Timbal*, 2008; *Previdi and Liepert*, 2007; *Son et al.*, 2009]. This has occurred during solar minima from which it appears we are emerging to the next maxima. *Haigh et al.* [2005] and *Ram et al.* [2009] have suggested this will produce changes similar in atmospheric circulation to those postulated due to anthropogenic global warming. As a result, the effects of possible synergies occurring between global warming and solar maxima on atmospheric circulation over extratropical regions could result in severe drought becoming the typical climate state in regions such as southeast Australia.

5. Conclusion

[19] Our results imply that the hydroclimate of southeast Australia over the past 6500 years has displayed significant cyclic variability on timescales from ≈35–2200 years. Higher rates of dust accumulation between 5700 years BP to 4100 years BP and from 2100 years BP to present suggest greater variability in the climate of southeast Australia during these periods, including drought severity and dust transport. These cycles appear to be driven by multi-decadal change in Pacific Ocean SSTs through the PDO and variability in solar irradiance. Predictions of future climate

must consider these forcings so that in water-scarce regions such as southeast Australia the affect on the hydroclimate is incorporated into the design of water allocation policy and infrastructure, and the management of environmental systems.

[20] The adverse impact that may arise as a result of the synergies between global warming and solar maxima on atmospheric circulation over extra-tropical regions is cause for significant concern. The effect on the hydroclimate of regions could be catastrophic as a consequence of prolonged severe drought not previously experienced or planned for.

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J. Denholm, Snowy Precipitation Enhancement Research Project, Snowy Hydro Limited, Monaro Highway, Cooma, NSW 2630, Australia.

S. K. Marx, H. A. McGowan, and J. Soderholm, Climate Research Group, School of Geography, Planning and Environmental Management, University of Queensland, Brisbane, Qld 4072, Australia. (h.mcgowan@uq.edu.au)