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A review of Holocene solar-linked climatic variation on centennial to millennial timescales: Physical processes, interpretative frameworks and a new multiple cross-wavelet transform algorithm

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ABSTRACT

We report on the existence and nature of Holocene solar and climatic variations on centennial to millennial timescales. We introduce a new solar activity proxy, based on nitrate (NO_3^-) concentration from the Talos Dome ice core, East Antarctica. We also use a new algorithm for computing multiple-cross wavelet spectra in time–frequency space that is generalized for multiple time series (beyond two). Our results provide a new interpretive framework for relating Holocene solar activity variations on centennial to millennial timescales to co-varying climate proxies drawn from a widespread area around the globe. Climatic proxies used represent variation in the North Atlantic Ocean, Western Pacific Warm Pool, Southern Ocean and the East Asian monsoon regions. Our wavelet analysis identifies fundamental solar modes at 2300-yr (Hallstattzeit), 1000-yr (Eddy), and 500-yr (unnamed) periodicities, leaves open the possibility that the 1500–1800-yr cycle may either be fundamental or derived, and identifies intermediary derived cycles at 700-yr and 300-yr that may mark rectified responses of the Atlantic thermohaline circulation to external solar modulation and pacing. Dating uncertainties suggest that the 1500-yr and 1800-yr cycles described in the literature may represent either the same or two separate cycles, but in either case, and irrespective too of whether it is a fundamental or derived mode in the sense of Dima and Lohmann (2009), the 1500–1800-yr periodicity is widely represented in a large number of paleoclimate proxy records. It is obviously premature to reject possible links between changing solar activity at these multiple scales and the variations that are commonly observed in paleoclimatic records.

Contents

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1. Introduction

In 1973, Denton and Karlen published a pioneering study of glacier expansion and contraction activity and associated tree-line fluctuations during the Holocene. Since then, numerous other paleoclimatic proxy studies have documented a rich pattern of Holocene climate variation and oscillation on multiple timescales. Our use of the terminology "centennial to millennial"[1] in description of such variability follows the order-of-magnitude tradition in geological literature, whereby the terms encompass several hundreds to several thousands of years.

Climatic rhythmicities[2] previously identified in proxy studies include the solar 50–100 year Gleissberg–Yoshimura cycle, a distinct 120-year cycle, the 200 year solar deVries–Suess cycle, the millennial Eddy cycle (see Kanda, 1933 for an earlier speculation of this scale identified based on ancient records of sunspots and auroras) and the bi-millennial Hallstattzeit rhythm. We recognize the Hallstattzeit signature in this paper at a periodicity of 2200–2400 years, which is consistent with its former identification at timescales of "~2000 year" by Obrochta et al. (2012), and of "~2400 year" by Vasiliev and Dergachev (2002) and "2500 year" by Debret et al. (2009) and Dima and Lohmann (2009). We also study other apparently derived climate modes on multi-centennial and millennial timescales include the well known 1500-year cycle as those proposed recently in Dima and Lohmann (2009).

Mayewski et al. (2004), Wanner et al. (2008) and Debret et al. (2009) have shown that the amplitudes of these centennial to millennial climate variations are quite large, generally accounting for between 10 and 30% of the total variance of a given paleo-time series. Mayewski et al. (1997) report that 40% of the variance of both the residual ^{14}C and the polar circulation index derived from the Greenland Ice Sheet Project 2 (GISP2) Holocene glacio-chemical time series can be explained by just the three bandpass-combined components of 2300 + 1450 + 512 year variability (see Fig. 9 of their paper).

Throughout this paper, we refer to 1500-yr or 1800-yr rhythms interchangeably because the underlying solar and climatic proxy records so far described do not have sufficient resolution to discriminate accurately between them. But we do consider the 1500-yr or 1800-yr solar-climatic rhythm to be statistically different from those of 1000-yr and Hallstattzeit period of 2200–2300-yr and hence a distinction useful for physical interpretation.

An important reason for studying millennial scale variation (or more generally any other repeating rhythmic timescale) is the possible use of the signals for diagnosing and contrasting between the competing physical processes that may have caused them. This was highlighted in the recent study by Konecky et al. (2013). Those authors showed evidence for the persistence of a millennial-scale intensification of the rainfall in southwestern Indonesia, through their precipitation proxy, δD_{wax}, from Lake Lading, East Java, and suggested that periods of higher rainfall were connected to the strengthening of the tropical Pacific Walker circulation. In contrast, if the precipitation signals were to be controlled by the migrations of Intertropical Convergence Zone (ITCZ) on multidecadal timescales, the authors suggested that they should have seen a drying tendency rather than seeing the rainfall increase persisting into the 20th century.

In seeking to better understand centennial to millennial solar and climatic cyclicities, we have deliberately restricted our study to Holocene time-series. In this way, we avoid the complexity of the ocean-atmosphere interactions with large ice-sheets that are known to be represented by the abrupt, warming–cooling Dansgaard–Oeschger events and their associated Heinrich events of iceberg discharges during the Late Pleistocene and earlier glacial periods. It is probable that the broadband 1600-year pacing of the large and abrupt 8–16 °C warming, and the roughly equivalent 45 m of sea level rise that occurred during Dansgaard–Oeschger events (Schulz et al., 1999; Schulz, 2002; Pisias et al., 2010; Petersen et al., 2013), involve a different set of physical processes[3] than those that were operating during the Holocene. In addition, MacKay et al. (2013) have recently shown that millennial-scale variability during the Last Interglacial was more muted than Holocene variability, perhaps because of a diminished influence of freshwater discharge on the Atlantic Meridional Overturning Circulation (AMOC) during times of higher global temperature.

Our study of climate variability on intermediate, sub-orbital timescales utilized the following techniques:

(1) The introduction of a new solar activity proxy based on nitrate concentration, using ice core data from Talos Dome, East Antarctica (Traversi et al., 2012). The physical reasoning is that nitrate concentration in polar regions, beside having tropospheric sources mainly located in low latitude areas, has a direct connection to the stratospheric production sources that result from the effects of solar irradiation and/or persistent modulation by extra-terrestrial fluxes of energetic particles (see for instance, Savarino et al., 2007).
(2) The development of a new multiple-cross-wavelet transform algorithm that is capable of incorporating multiple time series, a method that is akin to standard statistical multi-regression analysis.
(3) The deployment of this algorithm to study a range of hydro-climatic proxies from the North Atlantic Ocean, Western Pacific

[1] This term refers to orders of magnitude, i.e. to century-scale or millennial-scale, following an established usage in parts of the literature.

[2] We note that we have adopted and used phrases like "periodicities", "cyclicities", "oscillations", "timescales" and "rhythmicities" throughout the paper in the loose limit and constraint of our wavelet time–frequency analysis. Such use of course contrasts with the strict periodicity as often used and interpreted in the traditional Fourier transform sense. But we find that our usages stick more closely to the current state of our understanding of climate variations over the Holocene, rather than pretending any precise knowledge or definition of climate and its variations. We refer those readers interested in the rather poor state of development of climate theory in this regard to Essex (2011) and Essex (2013).

[3] One analysis and interpretation by Ditlevsen et al. (2005, 2007) concluded that Dansgaard–Oeschger events during glacial intervals are probably climate shifts that "are purely noise driven with no underlying periodicity". We assume no position nor view on this possibility because our study of millennial-scale variations during the Holocene strives to understand physical processes and mechanisms involved without the use of any particular favorite statistical models.