SOLAR ARCTIC-MEDIATED CLIMATE VARIATION ON MULTIDECADAL TO CENTENNIAL TIMESCALES: EMPIRICAL EVIDENCE, MECHANISTIC EXPLANATION, AND TESTABLE CONSEQUENCES

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Abstract: Soon (2005) showed that the variable total solar irradiance (TSI) could explain, rather surprisingly, well over 75% of the variance for the decadally smoothed Arctic-wide surface air temperature over the past 130 years. The present paper provides additional empirical evidence for this physical connection, both through several newly published high-resolution paleo-proxy records and through robust climate-process modeling outputs. This paper proposes a mechanistic explanation, involving: (1) the variable strength of the Atlantic meridional overturning circulation (MOC) or thermohaline circulation (THC); (2) the shift and modulation of the Inter-Tropical Convergence Zone (ITCZ) rainbelt and tropical Atlantic ocean conditions; and (3) the intensity of the wind-driven subtropical and subpolar gyre circulation, across both the North Atlantic and North Pacific. A unique test of this proposed solar TSI–Arctic thermal–salinity–cryospheric coupling mechanism is the 5- to 20-year delay effect on the peak Atlantic MOC flow rate centered near 30–35°N, and on sea surface temperature (SST) for the tropical Atlantic. The solar Arctic–mediated climate mechanism on multidecadal to centennial timescales presented here can be compared with and differentiated from both the related solar TSI and UV irradiance forcing on decadal timescales. The ultimate goal of this research is to gain sufficient mechanistic details so that the proposed solar–Arctic climate connection on multidecadal to centennial timescales can be confirmed or falsified. A further incentive is to expand this physical connection to longer, millennial-scale variability as motivated by the multiscale climate interactions shown by Braun et al. (2005), Weng (2005), and Dima and Lohmann (2009). [Key words: solar–Arctic climate connection, total solar irradiance, Atlantic meridional overturning circulation, climate variability.]

THE SOLAR ARCTIC-MEDIATED CLIMATE VARIATION ON MULTIDECADAL TO CENTENNIAL TIMESCALES

Paleoclimatic proxies show ubiquitous, multidecadal to centennial-scale variabilities that may ultimately be associated with the persistent forcing by solar irradiance variability as properly projected and amplified through the annual progression of the Earth around the Sun (Table A1, Appendix). The present study indirectly assumes the optimal climatic response filter of the Earth ocean-atmosphere-ice system to peak around such multidecadal to centennial scales, which can be taken to be roughly 50 to 500 years (i.e., much less than 1000 years). The challenge of this research, then, must lie in the identification of relevant and/or dominant centers of climatic action (COAs; Table 1 lists acronyms used in this paper) and interactions among those COAs (Christoforou and Hameed, 1997; Rodionov et al., 2005; Huth et al., 2006; Lim et al., 2006). Huth et al. (2006) found a general tendency for atmospheric circulation modes[1] to be more zonal, with COAs covering wider areas and

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Table 1. List of Acronyms Used in This Paper

Acronym	Definition
TSI	total solar irradiance
UV	ultraviolet
BP	Before Present
COAs	centers of (Climatic) action
SST	sea surface temperature
SLP	sea level air pressure
EPG	equator-to-pole surface temperature gradient
AMO	Atlantic Multidecadal Oscillation
NPMO	North Pacific Multidecadal Oscillation
PDO	Pacific Decadal Oscillation
NAO	North Atlantic Oscillation
ENSO	El Nino–Southern Oscillation
MOC	meridional overturning circulation
THC	thermohaline circulation
ISOW	Iceland–Scotland Overflow Water
GIN Seas	Greenland-Icelandic-Norwegian Seas
ITCZ	Intertropical Convergence Zone
SPCZ	South Pacific Convergence Zone
GISP2	Greenland Ice Sheet Project 2
MIS	marine isotope stage
GCM	general circulation model
CMIP3	Coupled Model Intercomparison Project Phase 3
NCAR	National Center for Atmospheric Research
IPCC	United Nations Intergovernmental Panel on Climate Change

teleconnection among different regions spanning longer distances when solar activity is strong. The hard task of separating the dynamics of the teleconnection from the actual physical mechanisms at COAs must be kept in mind as well.

In this paper, climate refers to the systematic persistence of weather patterns and fluctuations that involve: (1) seasonal and annual cycles (i.e., not just time-averaged weather statistics); (2) local and regional air pressure systems; (3) topography, landscape, and the storage and exchange of heat/energy through atmospheric and oceanic circulation; and (4) delayed actions. All these persistent local and regional actions and variations take place prior to any global mean radiative forcing or any cohesive global mean temperature and precipitation responses. In other words, the weather-mediated climate variation and change will be viewed as local and regional "inter-seasonal" variations that cover time intervals from months and years to tens of millennia. The basic mechanisms involved are not unlike the original orbital theory of climate change by Milutin Milankovitch, published in the early 1940s, which emphasized high-latitude, light-sensitive COAs to explain global-scale glaciation and deglaciation events and transitions. A key emphasis of this insolation–weather–climate framework are the differential responses at different latitudes to insolation changes (Davis and Brewer, 2009) in addition to responses arising from effects of the four seasons. Thus, it is suggested that persistent insolation forcing, when maintained over multidecadal to centennial timescales, accounting for both the systematics of the Sun–Earth orbital geometry (Loutre et al., 1992) and the irradiance variability intrinsic to magnetic variation of the Sun (e.g., Soon, 2007), is both necessary and sufficient to explain the observed climatic variation on multidecadal to centennial timescales.

It can be further added that an all-inclusive theory of climate change should also account for the newly proposed theory of independent hemispheric responses to solar forcing by Huybers and Denton (2008), whereby a Northern Hemispheric response is sensitive to both the local summer insolation intensity and the latitudinal insolation and temperature gradients (Davis and Brewer, 2009), while a Southern Hemispheric response is more sensitive to local summer duration.

In the framework of climatic forcings and responses, an understanding of both the spectral peaks and the seemingly gap-less continuum of weather–climate operation will be sought. Huybers and Curry (2006) recently re-initiated such research by seeking to connect the annual and Milankovitch cycles to the in-between continuum temperature variability in terms of the response to deterministic insolation forcing. Coincidentally, the multidecadal to centennial timescales discussed in the present study are similar to the recognized transitional timescale of Huybers and Curry (2006), who proposed that the annual cycle, with assistance from the ocean-storage delays, served to extend the continuum temperature variability from months to decades, while the Milankovitch orbital forcing cycles, with assistance from nonlinear ice-sheet dynamics, drove the continuum temperature variability to higher-frequency timescales of millennia.

This view of local and regional origins of wide spatial climatic co-variations and responses is consistent with the emphasis on relatively high net solar radiation reaching the surface at various locations in the Pacific Ocean (e.g., Stanhill and Cohen, 2008), or at other warm-pool regions (e.g., Pavlakis et al., 2008), as a driving force for the fast-coupled air-sea responses that are coherent over broad spatial extent (Meehl et al., 2008; van Loon and Meehl, 2008). Finally, an important practical concept of the "modulated annual cycle," which accounts for the intrinsic nonlinearity of the weather–climate forcings and feedbacks, has been recently developed by Wu et al. (2008).

Both d'Orgeville and Peltier (2007) and Zhang and Delworth (2007) showed the intimate multiscale coupled interactions and connections among dominant timescales and patterns of climate variability involving the Pacific Decadal Oscillation (PDO), the related North Pacific Multidecadal Oscillation (NPMO), and the Atlantic Multidecadal Oscillation (AMO). Although d'Orgeville and Peltier (2007) did not commit to any particular mode as the leading variable, Zhang and Delworth (2007) suggested a lagged North Pacific response to the AMO forcing of about 13 years that is connected through a chain of dynamical atmospheric teleconnections (induced first from AMO-related northward oceanic heat transport) and then amplified by the positive local air–sea feedback over the central and western North Pacific. Zhang and Delworth (2007) further deduced that a regime shift of the North Pacific opposite to the 1976–1977 shift might be expected soon, following the switch of the AMO to a positive phase around 1995.

Three inter-related causes support a strong control of natural multidecadal-to-centennial scales of climate variation through a solar–Arctic connection mechanism:

> Cause A: A persistent and systematic variation of the solar TSI and related insolation gradient modulates the atmospheric heat transport from the tropics to the Arctic, and hence modulates the Arctic temperature change itself with little or no delay.
>
> Cause B: Thermal perturbations lead to both natural modulation of the Arctic sea ice and transport of fresh water through the Bering Strait, and from the Arctic through both the Greenland Sea and Denmark Strait and the Canadian Arctic Archipelago pathways to deep water formation sites spread across the North Atlantic from the Greenland–Icelandic–Norwegian (GIN) Seas to the east and at the Labrador Sea in the west.
>
> Cause C: Further effects are: (1) thermal, freshwater, and salinity perturbation of the Atlantic MOC-THC; (2) the delayed connection of about 5 to 20 years with the tropical Atlantic SST and the InterTropical Convergence Zone (ITCZ); and (3) coupling of the affected tropical Atlantic processes feeding back to the MOC-THC.

It is important to note that current climate models are not yet able to account for all the empirical and proxy evidence and relations noted here (e.g., Zhang and Delworth, 2007; Alexander, 2009). Kravtsov and Spannagle (2008), for example, make use of the fact that the AMO signals contained in the *difference* (suggesting that climate models have failed to account for the AMO) between the observed SST and the multimodel ensemble-mean SST from the CMIP3 (Coupled Model Intercomparison Project Phase 3) database, suggesting that AMO is a natural climatic signal plausibly related to the oceanic thermohaline circulation (THC). Davis and Brewer (2009) pointed out that climate models may overemphasize the seasonal response to insolation changes when compared to the differential latitudinal response which, in turn, translates into an incorrect representation of the latitudinal temperature gradient that is fundamental for capturing climate dynamics (Lindzen, 1994; Jain et al., 1999). Such a zero-order climate modeling barrier has been recently reframed by Rind (2008, p. 855) as "the consequences of not knowing low- and high-latitude climate sensitivity."

Finally, two further assumptions regarding the multidecadal- to centennial-scale solar–Arctic connection mechanism. First, the solar–Arctic mechanism borrows from recent studies by van Loon and Meehl (2008) and Meehl et al. (2008), which focus on coupled surface responses in the Pacific region to the Sun's decadal peaks, giving rise to their hypothesized solar-induced, hydrology-amplified climatic responses. Multidecadal to centennial responses could represent the envelope of the responses to the solar decadal peaks. However, the mechanism proposed here specifies responses in the Arctic and Atlantic basins and postulates equivalent and related responses elsewhere. Second, the solar–Arctic mechanism assumes the importance of a significant coupled thermal–salinity–cryospheric interaction involving the Arctic and many other climatic COAs around the world. Behl and Kennett (1996) discussed the connections of anoxic events in the Santa Barbara basin with the Dansgaard–Oeschger warm interstadials recorded in the GISP2 core for the past 60 kyr, and Wang et al. (2008) discussed the strong coupling between the East Asian Summer Monsoon system and the North Atlantic, especially during the cold glacial interval between 75 to 10 kyr BP. However, different regions may not be so optimally teleconnected at a much warmer interglacial time when there is little Arctic or Northern Hemisphere volume of ice, such as during the MIS stage 5d (Zhou et al., 2008).[2]

This paper offers support for the proposed solar–Arctic mechanism for climate variations on multidecadal to centennial timescales. The mechanism can also be compared and contrasted with two other promising Sun–climate connection scenarios via the decadal solar UV and TSI mechanisms reviewed below.

THE DECADAL SOLAR UV AND TSI MECHANISMS

Kodera (2004) showed a dynamical response of the Indian summer (i.e., July–August) monsoon that perhaps can be traced to the downward-propagating effects of wave-mean flow interactions through the forcing by relatively stronger solar decadal UV radiation in the mesosphere and stratosphere. Kodera and Shibata (2006), using a unique and powerful new diagnostic technique, showed how enhanced solar heating in the tropical lower stratosphere, while suppressing convective activity in the equatorial region, enhances convective activity in off-equatorial regions and ultimately produces a change in the meridional circulation in the tropical troposphere. The analyses by Claud et al. (2008) show added spatial complexity to this dynamical coupling of the Indian summer monsoon system to the 11-year solar activity cycle. Such a proposed top-down response to solar decadal UV forcing on the Indian summer monsoon offers a remote teleconnection to both the climatic variations and trends in the Pacific equatorial cold tongue region and the North Atlantic (Selten et al., 2004; Compo and Sardeshmukh, 2008) through what is known as the circumglobal wave teleconnection mechanism (e.g., Branstator, 2002; Watanabe, 2004; Ding and Wang, 2005).

Van Loon and Meehl (2008) and Meehl et al. (2008), through the powerful combination of data analyses and climate modeling experiments, showed how the fast and closely coupled surface responses to changing solar surface radiation between solar activity maxima and minima could add to the top-down responses through the solar UV mechanism proposed by Kodera and colleagues. Specifically, van Loon and Meehl (2008) showed that the coupled surface responses in the Pacific to TSI variation is such that in solar peak forcing years, the sea level air pressure (SLP) is above normal in the Gulf of Alaska and south of the equator, which in turn produces stronger southeast trade winds across the equatorial Pacific and causes increased upwelling and hence cooling SST tendencies broadly across the Pacific Ocean. Using two GCMs at NCAR, Meehl et al. (2008) sketched a coupled response to peaks of solar decadal TSI forcing that involves increased latent heat flux and evaporation, which in turn is carried to the Pacific Intertropical convergence zone (ITCZ) and South Pacific convergence zone (SPCZ) to intensify both precipitation regimes. The resulting solar response patterns resemble La Niña-like events, but yet are distinct from them, mainly by virtue of their different vertical profile of responses, especially in the stratosphere (van Loon and Meehl, 2008).

Modeling experiments conducted by Emile-Geay et al. (2007) suggest that the powerful ENSO coupled air–sea interaction system can serve as a mediator[3] of the persistent solar TSI forcing on climate over the Holocene. Their sensitivity calculations, with the intrinsic solar TSI variation ranging from 0.05% to 0.2% to 0.5% over the Holocene, coupled with the orbital forcing effect, generated El Nino–like SST anomalies at times of decreased TSI, which is consistent with the empirical results by van Loon and Meehl (2008).

In summary, Kodera and colleagues proposed a top-down forcing-response scenario for a Sun–climate decadal connection that more directly involves the decadal solar UV forcing, while van Loon, Meehl and colleagues sketched a bottom-up forcing-response scenario for their Sun–climate connection on decadal timescale, which invokes decadal solar TSI forcing.

The strength of the bottom-up scenario of coupled surface air-sea responses to a persistent solar TSI forcing by van Loon, Meehl, and colleagues is that it offers a better explanation for why the multidecadal- to centennial-scale variability can be found in such a diverse range of climate-proxy archives from the bottom of the sea to high mountain tops (Table A1, Appendix). In contrast, it is harder to conceive of a spatially coherent and temporally persistent near-surface response over long distances, wide geographical conditions, and different topographic settings if the initial meteorological and climatic impact centers are rooted in the tropical mesosphere and stratosphere as a response to the decadal solar UV forcing.

Although the decadal signal for solar irradiance forcing of global-averaged surface temperature has recently been confirmed by Tung and Camp (2008), the actual scenario for a physical connection has not been identified. Lim et al. (2006) found that solar irradiance modulation of local and regional relative humidity, in combination with the related climatic distribution of clouds and water vapor over the tropical Atlantic, is sufficient to explain the observed tropical Atlantic decadal oscillation.

RESULTS AND DISCUSSION

Empirical Evidence and Mechanistic Explanation for Interrelated Causes and Responses A, B, and C

Soon (2005) showed evidence of natural climate variations on multidecadal to centennial timescales through a solar–Arctic connection mechanism. Figure A1 (Appendix) updates the previously published solar TSI–Arctic surface air temperature correlation in Soon (2005).[4] The results presented by Kauker et al. (2008) strongly support the multidecadal variations of the Arctic surface temperature from the Arctic Atlantic, to the Arctic Pacific and then to the Arctic Greenland/Iceland sectors (the chart is available upon request). Figure 1 shows that the solar TSI–Arctic-wide temperature correlation can also be found on a much smaller regional scale, as demonstrated by similar TSI–temperature correlations for two coastal stations of southern Greenland: Godthab Nuuk in the west and Ammassalik to the east. It is important to note that available oceanographic data at Fyla Bank off Godthab Nuuk show that the early 20th century surface thermometer warming was

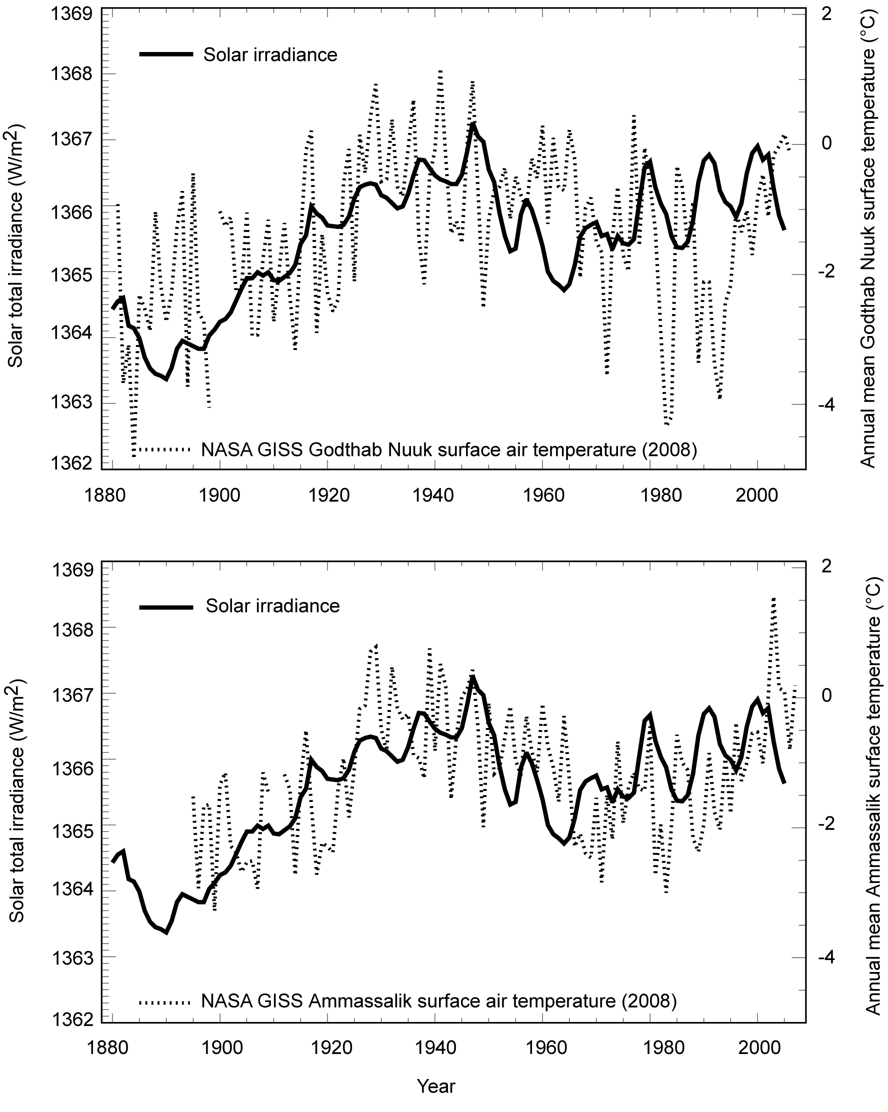

Fig. 1. The annual mean estimates of total solar irradiance (solid line) compared with the surface temperature records from two coastal Greenland stations: Godthab Nuuk (dotted curve; top panel) and Ammassalik (dotted curve; bottom panel) from about 1881 to 2007 (from "after homogeneity adjustment" records in http://data.giss.nasa.gov/gistemp/station_data/). This result adds regional details to the TSI-Arctic-wide surface temperature correlation identified in Soon (2005).

detected around 1920 at the surface ocean (Holland et al., 2008). Such a consistent pattern of correlations on different spatial domains and scales is an important ingredient for a physical solar–Arctic connection.

Another important update and extension is the new result by Jiang et al. (2005) showing the consistent role for solar irradiance forcing in triggering and maintaining the multidecadal to centennial variation of the SSTs around the North Icelandic Shelf over the last 2000 years. Jiang et al. (2005) further noted the relatively stronger temperature responses during winters than summers, which is consistent with the result outlined in Soon (2005). High-resolution proxy annual-mean and wintertime SSTs from a coral record at Bermuda (Goodkin et al., 2008a, 2008b) showed enhanced multidecadal-scale variability during the late 20th century when compared to variability near the end of the Little Ice Age. These results, together with the evidence on the sensitivity of Arctic Ocean ice cover and thickness to atmospheric poleward energy flux by Soderkvist and Bjork (2004) in their coupled ocean–ice–atmosphere column model, support the proposed solar–Arctic connection Cause A. The enhanced poleward atmospheric transport scenario is supported by the consistent increases in wind stress trends over the Arctic basin shown for annual mean, winter, and summer values for 1948-2006 (Hakkinen et al., 2008). Indirect evidence for variable poleward heat transport for earlier periods (i.e., before 1950) can be found in the multidecadal variation of the equator-to-pole (EPG) surface temperature gradient as well as the multidecadal-scale modulation of the phase of the EPG annual cycles (Jain et al., 1999).

Graversen et al. (2008), in their close examination of the vertical pattern of recent Arctic warming, concluded that much of the observed Arctic warming aloft is related to changes in poleward atmospheric heat and moisture transports rather than from near-surface snow and ice albedo feedbacks, as has been modeled and suggested in climate model experiments with increased atmospheric CO_2. This result is consistent with the theoretical and modeling studies by Alexeev et al. (2005), Winton (2006), and Cai and Lu (2007), where poleward heat transports, plausibly linked to differential latitudinal response to insolation changes, are shown and argued to be more important in explaining polar warming than direct surface snow and ice albedo feedbacks. Smedsrud et al. (2008) showed that indeed the poleward atmospheric energy flux to the Arctic has increased overall for the last 50 years, from 1956 to 2006, which is consistent with solar–Arctic connection Cause A, but they emphasized that the tendency for a net increase over more recent decades has slowed. L'Heureux et al. (2008), Overland et al. (2008), Serreze et al. (2008), Zhang et al. (2008), and Lindsay et al. (2009) all provided updated data series up to 2007 and discussion of the key role played by the recent shift in spatial patterns of atmospheric forcing and the strengthened poleward atmospheric heat transport directly or indirectly reaching the central Arctic. Polyakov et al. (2005) showed evidence for the enhanced North Atlantic warm water intrusion into the Arctic Ocean and Barents Sea, while Shimada et al. (2006) documented the influx of warm Pacific summer waters into the Arctic Ocean via the Bering Strait in order to account for the observed rapid changes in the Arctic climate system. Serreze et al. (2008) argued that the near surface–based Arctic amplification signal through snow and ice albedo feedbacks may soon be emerging if the Arctic Sea continues to lose its ice, and emphasized that their results are not in conflict with those of Graversen et al. (2008).

Finally, direct hydrographic data from the northeast North Atlantic and Nordic Seas in Holliday et al. (2008) showed not only the reversal of the 1960 to 1990s freshening trend but also seem to offer practical short-term forecasts for temperature and salinity around the Fram Strait region for Atlantic inflow conditions to the Arctic Ocean. A similar forecast based on short-term hydrographic tendencies for Labrador Sea regions has also been proffered by Yashayaev (2007) and Yashayaev et al. (2007), but Yashayaev and Loder (2009) recently reported a sudden atmospheric cooling and enhanced production of Labrador Sea water in the fall–winter 2007–2008 season, which disrupted the steady warming around the region since 1994. Similarly, Vage et al. (2009) documented a surprising return of winter deep convection to the subpolar gyre in both the Labrador and Irminger Seas, apparently without going through a phase of preconditioning. This most up-to-date situation in the Labrador Sea should points to the need for caution when attempting to forecast any near- or long-term changes in the northern North Atlantic and Arctic.[5]

Empirical evidence supporting the solar–Arctic connection Cause B may be found in the important synthesis of observational data in Polyakov et al. (2008), demonstrating the multidecadal variability of climate variables in the Arctic and their interconnections, which include the Arctic surface air temperature, upper 150-m Arctic Ocean freshwater content, fast ice thickness, intermediate Atlantic water core temperature of the Arctic Ocean, and upper 300 m North Atlantic water salinity. Here, one might interpret that a warmer Arctic (detected in both air and ocean-water temperatures) led to above-normal melting of Arctic sea ice and excess flushing of Arctic freshwater to the Nordic seas and the subpolar North Atlantic basins. The observational data of Polyakov et al. (2008) are consistent especially with the newly reconstructed freshwater content data series over the northern Atlantic by Pardaens et al. (2008).

Dima and Lohmann (2007) independently sketched a dynamically consistent framework for the AMO, and were able to fill in some important feedbacks and delay factors. They show the hemispheric wavenumber-1 sea level air pressure pattern to be related to the Fram Strait sea ice export, which, in turn, affects the THC/MOC oceanic circulation and hence the sea surface conditions in both the North Atlantic and North Pacific. Dima and Lohmann (2007) spelled out the role of the THC adjustment to freshwater forcing, the Atlantic SST response to MOC, and the oceanic adjustment in the North Pacific as key delays in the chain, while the ocean-atmosphere-sea ice interactions in the Atlantic, Pacific, and Arctic oceans served as the crucial negative feedbacks to sustain the AMO oscillation on timescales of about 70 years. Jungclaus et al. (2005) also proposed a scenario of Arctic–North Atlantic interactions with the multidecadal variability of Atlantic MOC/THC based on the outputs of their 500-year GCM control, unforced, run. The important extension of climate modeling experiments by Grosfeld et al. (2008) shows that, in addition to attributing the origin of the 60–70 year scale oscillation to the Atlantic Ocean, there is possibly a separate and distinct scale of about 80–100 years that is intrinsic to the Pacific Ocean.

The paper's argument for a multidecadal- to centennial-scale variability adopts and accepts most of the detailed physical processes outlined in Dima and Lohmann (2007), but the solar–Arctic connection picture given here also includes a more direct emphasis on climatic modulation by the Arctic (i.e., the call for direct involvement of Arctic-wide surface temperature and sea ice and fresh water in the Arctic basin, with emphasis on pathways for freshwater exchanges and transports, rather than merely sea ice export from the Fram Strait); and a wider range of spatial-temporal scales beyond the more limited 70- to 80-year variability set in the Dima and Lohmann (2007) framework, because the memory and turning points for the multiscale oscillation in this solar–Arctic connection picture appear to be decided more by the external TSI forcing. For this reason, the phrase "multidecadal to centennial timescales"[6] is used throughout this paper.

Adding to these processes is the current emphasis on the effects of influx of low-salinity Pacific water through the Bering Strait (Aagaard et al., 2006; Shimada et al., 2006; Keigwin and Cook, 2007) in perturbing the ice and freshwater environment over the Arctic Ocean. These effects are non-negligible and may at times have played a more prominent role than at present (e.g., Wadley and Bigg, 2002; Yang, 2005, 2006; Dickson et al., 2007). Finally, Peterson et al. (2006) and Serreze et al. (2006) confirmed the roles of net precipitation, river discharge, and sea ice attrition as important freshwater sources, compared to the relatively minor contributions of glacial melt. The modeling study by Wu and Wood (2008) suggests that the recent freshening trend over the subpolar North Atlantic can be explained by a redistribution of freshwater within the Arctic and subpolar North Atlantic and that the redistribution was probably carried out by a perturbed ocean circulation in the subpolar seas and triggered by deep convection in the Labrador Sea.

Both the Arctic sea ice extent data derived by Zakharov (in Johannessen et al., 2004) and the Icelandic sea ice extent (Zhang and Vallis, 2006) provide evidence in support of the inverse relation between Arctic temperature and sea ice extent for about the past 100 years, as proposed in Cause B of this solar–Arctic connection. Quantitative reconstruction by Kauker et al. (2008) also support a significant ice loss over the Arctic basin from 1916 to 1955, although they suggested that the ice loss of this period was somewhat less extensive than the recent loss from mid-1960s to mid-1990s.

In the context of the proposed solar Arctic-mediated climate variation mechanism, it is assumed that the sea ice export is not exactly the same as freshwater export from the Arctic and that more sea ice export from the Arctic basin may be more related to colder conditions within the Arctic, not unlike the notable ice-rafting events and episodes seen throughout the Quaternary (e.g., Bond et al., 1997, 1999; Vidal et al., 1997; Darby and Zimmerman, 2008; Hill et al., 2008; or counter-views and interpretations by Andrews et al., 2006), or in the summer of 1695 recently re-interpreted by Gil et al. (2006), as well as the great salinity anomaly events of the 1970s, 1980s, and 1990s, modeled and discussed in Zhang and Vallis (2006). But importantly, it is recognized that extra exports of sea ice, episodic or otherwise, or a more continuous nature of the freshening and flushing of water from the Arctic basin to the northern North Atlantic basins (e.g., Condron et al. 2009) would serve as key negative feedbacks for the MOC/THC oscillation. Dickson et al. (2007) highlighted the potentially greater importance of combined ice and freshwater outflows from the Arctic Ocean basin through the Canadian Arctic Archipelago/Nares Strait/Baffin Bay/Davis Strait pathways under a warm Arctic and low-ice-volume climatic regime.[7] Detailed computer modeling (Proshutinsky et al., 2002; Moon and Johnson, 2005; Dukhovskoy et al., 2006; Condron et al., 2009) shows how the oscillations between the anticyclonic and cyclonic

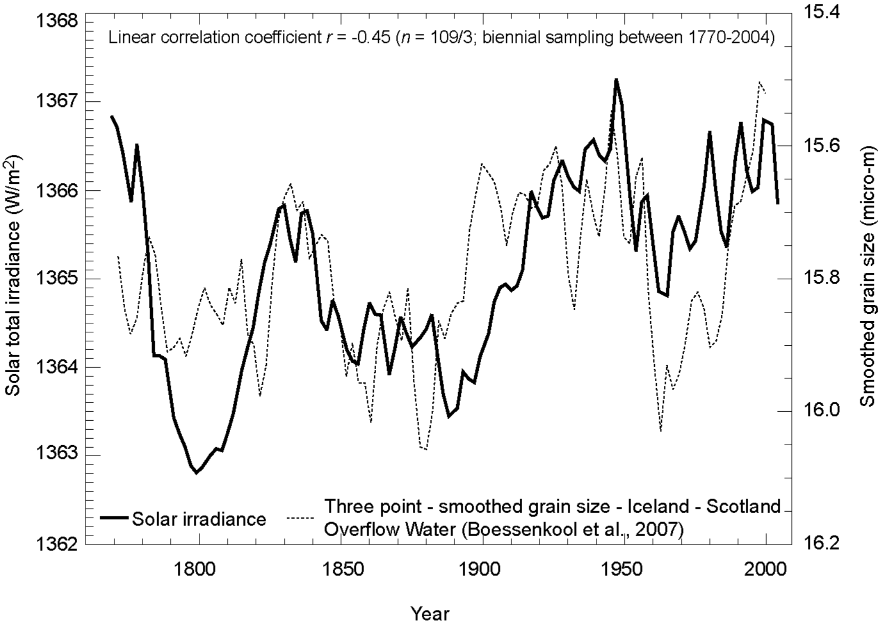

Fig. 2. The annual mean estimates of total solar irradiance (solid line) correlated with the three-point smoothed mean grain-size index (dotted line) of Boessenkool et al. (2007) from about 1770 to 2004. The grain-size index is a proxy for the flow speed of the near-bottom Iceland–Scotland Overflow Water (ISOW) which is, in turn, related to the deep water formation in the Labrador Sea to the west. Smaller mean grain size suggests slower ISOW, and larger grain size implies faster ISOW.

circulation regimes, involving contraction and expansion of the Beaufort Gyre, are affecting how Arctic sea ice and freshwater are stored and released to the northern North Atlantic Ocean.

Figure 2 records plausible evidence for a connection between TSI solar forcing in producing the thermal-freshwater-salinity–related effects on deep-ocean flow of the northern North Atlantic for the full 1770–2004 A.D. interval. It uses new mean grain-size data from Boessenkool et al. (2007) that represents the near-bottom flow speed of Iceland-Scotland Overflow Water (ISOW). It should be further noted that Bossenkool et al. (2007) suggest that the vigor of ISOW is controlled by the transport and characteristics of the Labrador Sea water farther to the west (Jungclaus et al., 2005). The correlation between TSI and the three-point smoothed grain-size index shown in Figure 2 has a correlation coefficient of r = -0.45, which even with the reduced degrees of statistical freedom would still constitute a significant correlation. In comparison, Boessenkool et al. (2007) showed a correlation between the grain size with a seven-year smoothed NAO index for the selected (rather than the full data shown in Fig. 2) interval of 1885–2004 with an r value of only -0.42 (n = 55). Although it is not the intent of this paper to explain the correlation, but merely to demonstrate plausibility, the apparent correlation in Figure 2 suggests a slower ISOW flow speed with increasing TSI. Finally, the solar–Arctic connection in Cause

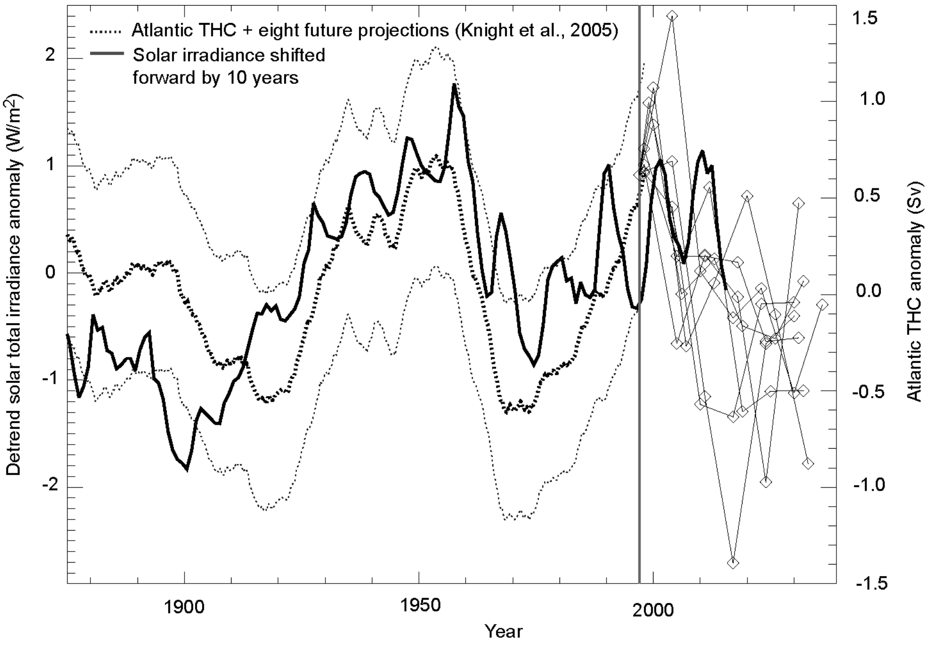

Fig. 3. The detrended total solar irradiance anomaly series shifted forward by 10 years (thick solid line; see also the same shift in Fig. 4) to show correlation with the maximum of the zonal mean of the Atlantic Meridional Overturning Circulation at 30°N deduced by Knight et al. (2005) (dotted grey lines with the upper and lower bounds as the "uncertainty" limits). Grey diamond symbols connected with thin solid lines are the eight-member forecasts for the 35 years offered by Knight et al. (2005). A detrended solar TSI series was used in order to compare more fairly with the normalized measures of SST and THC anomalies used in Knight et al. (2005). See Kravtsov and Spannagle (2008) for a discussion of the details of the detrending of datasets for the construction of AMO-related SST changes, and Vellinga and Wu (2004) for a discussion of why the maximum MOC index is a useful proxy for the Atlantic THC for the study of AMO, but the index is clearly not useful for assessing interannual THC variability.

B outlined here may also find support from the specific documentation of the 75- to 80-year period from the Holocene history of drift ice within the northern North Atlantic region by Moros et al. (2006).

In the search of a physical mechanism and understanding of a Sun–climate connection, one need not be automatically hunting for maximum possible statistical correlations between any two variables (e.g., Soon et al., 2000). For example, Zhang et al. (2007) showed how an equally good fit of the observed detrended Northern Hemispheric temperature time series can be achieved with relatively high correlations, and yet each of the good fits was obtained under dramatically different heat flux redistribution and transport scenarios. Such a reality suggests that high correlations between variables do not imply correct identification of a physical mechanism given that multiple physical processes could well be responsible for establishing a quasi-mean state or any deviation from the mean.

Figures 3 and 4 show the empirical support for the proposed solar–Arctic connection Cause C. In Figure 3, the maximum MOC index (i.e., centered around 30–35°N

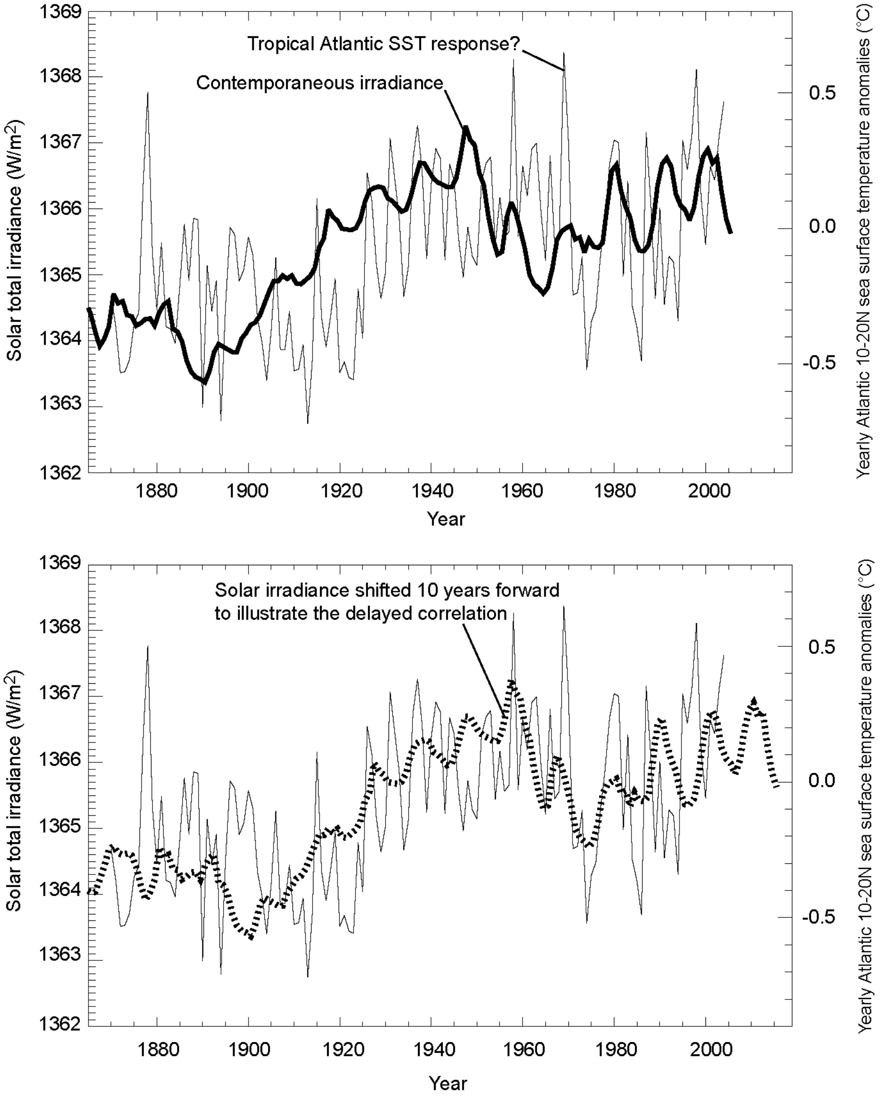

Fig. 4. The annual-mean estimates of total solar irradiance (TSI) versus the tropical Atlantic SST at 10-20°N from 1870 to 2004 (top panel), and with the solar TSI advanced forward by 10 years (bottom panel) in order to illustrate the delayed connection of the tropical Atlantic SST to solar TSI forcing effects initiated first within the Arctic and North Atlantic basins.

roughly 1000 to 2000 m below surface) as deduced from the SST distribution by Knight et al. (2005) is plotted with the TSI series shifted forward by 10 years, corresponding to the estimated delayed response in lower latitudes. Figure 4 shows a similar comparison with tropical Atlantic SST at around 10–20°N. The chosen delay time of 10 years is only a rough estimate for the thermal-cryospheric-salinity and mechanical wind stress effects occurring within the Arctic and northern North

Atlantic basins to propagate southward. But it is clear from both empirical evidence (Curry et al., 1998; Molinari et al., 1998) and careful ocean modeling (Yang, 1999) that a physical delay of some 5 to 20 years is reasonable. Yang (1999), for example, pointed out a five-year delay for decadal variations in the Labrador Sea and the tropical Atlantic dipole index set by coastally trapped waves, rather than the probably longer advection time through the Deep Western Boundary Current (Goodman, 2001). In the AMO framework of Dima and Lohmann (2007), a delay of 10–15 years was deduced for the time it will take for the freshwater forcing on both the North East Atlantic deep water and Labrador Sea deep water convection sites to affect the MOC circulation. Jungclaus et al. (2005) deduced an optimal lead time of 12 years for changes in the convection intensity in the Labrador Sea to affect the MOC/THC. Finally, Latif et al. (2006) offered evidence and argument for the atmospheric NAO index to lead the Atlantic Dipole Index[8] by 5 to 20 years, where this index is proposed as a good proxy for THC/MOC circulation. Based on inland temperature proxy data, the finding by Eichler et al. (2009) of 10- to 30-year delays between the solar forcing proxy and Siberian Altai Mountain region temperature throughout the 1250–2000 AD period is consistent with the proposed solar–Arctic and Atlantic MOC-mediated mechanism.

Additional Mechanistic Explanation for Interrelated Causes and Responses A, B, and C

The wind-driven subtropical and subpolar gyre circulations both across the Pacific and Atlantic Oceans may be also important for the plausible solar-induced feedbacks and delays to help sustain the multidecadal to centennial variations (e.g., Wu et al., 2003; Zhang and Vallis, 2006; Hasegawa et al., 2007; Qiu et al., 2007; DiLorenzo et al., 2008; Guan and Huang, 2008; Alexander, 2009; Saenko, 2009). The modeling study by Wu et al. (2003), for example, shows that in the North Pacific, the multidecadal memory may be rooted in the slow adjustment of the subtropical/subpolar gyre in response to wind stress imposed in the central North Pacific and the slow growth/decay of the SST anomalies that propagate eastward in the Kuroshio Extension region. Saenko (2009) showed the important climatic impacts of wind stress, especially those around regions poleward of 30°, with oceanic heat transport accounting for only a small fraction of total poleward energy transport, and where, if one were to remove that wind stress forcing, surface temperatures at high-latitude regions could drop by more than 10°C with the mean position of the simulated sea ice edge moving equatorward and reaching latitude 40°N. The important study by Guan and Huang (2008), which emphasizes mechanical energy in order to sustain the THC, shows how adding the wind-driven gyre not only leads to a more complete modeling of the physical processes related to THC, but also changes the threshold value of the THC dynamical bifurcation property greatly. Therefore, both fresh water and wind forcing will be key elements for the current solar– Arctic connection picture.

It may not be straightforward to explain the seemingly counterintuitive relationship of stronger Atlantic maximum MOC with increased TSI forcing indicated in Figure 3. But the plausibility of a decreased equator-to-pole surface density (i.e., from an enhanced thermal and fresh water perturbation and modulation of the convective sinking regions for deep water formation spread across the North Atlantic with increased TSI forcing) leading to stronger, rather than weaker, thermohaline circulation was studied by Nilsson and Walin (2001) and Nilsson et al. (2003). The theory of Nilsson, Walin and colleagues viewed the slow upwelling of dense water overall in the low latitudes and the Southern Ocean (see also Visbeck, 2007; Toggweiler and Russell, 2008), rather than high-latitude production and sinking of dense water as the rate-limiting branch of THC.[9] The Nilsson et al. theory showed, with a reasonable model of interval wave mixing, that the vertical diffusivity would increase with decreasing surface equator-to-pole density contrast, and that would deepen the thermocline and, in turn, lead to a stronger THC.

The proposed Cause C mechanism must necessarily include coupling with the multidecadal- to centennial-scale variations of the Atlantic Intertropical Convergence Zone, as noted in several proxy archives (Nyberg et al., 2001; Poore et al., 2004; Peterson and Haug, 2006; Black et al., 2007) and in climate modeling experiments (Vellinga and Wu, 2004; Chiang and Bitz, 2005; Zhang and Delworth, 2005). In general, these studies have highlighted a robust shift of the ITCZ southward during North Atlantic cooling and slower MOC/THC and a northward ITCZ shift during the opposite phase of stronger MOC/THC and warmer North Atlantic-Arctic conditions. The most important aspect of these studies that focused on the tropical Atlantic is the related feedbacks to the MOC/THC itself. Vellinga and Wu (2004) placed a greater emphasis on the role of low-latitude fresh water through the ITCZ variability on a centennial timescale for feeding back to the THC circulation. This emphasis may also be ultimately related to the THC variability theory of Nilsson and Walin (2001) and Nilsson et al. (2003). There is little doubt that both the ITCZ and inter-hemispheric SST gradient proposed by Vellinga and Wu (2004) are dominant weather–climate processes operating on seasonal and interannual timescales that can feed back and couple to the solar TSI–induced Arctic–high latitude processes emphasized in this paper. But it is harder to find justification in available data that "sustained salinity anomalies slowly propagate toward the subpolar North Atlantic at a lag of 5–6 decades" to maintain the centennial-scale variability of Atlantic THC, as seen in model outputs by Vellinga and Wu (2004, p. 4498).

More Related Consequences and Impacts

Several important and related consequences and connections of multidecadal- to centennial-scale variations of the Atlantic MOC/THC have recently been pointed out by Dong et al. (2006), Goswami et al. (2006), Knight et al. (2006), Lu et al. (2006), Li and Bates (2007), Sutton and Hodson (2007), Timmermann et al. (2007), Chang et al. (2008), Denton and Broecker (2008), Feng and Hu (2008), Li et al. (2008), Ting et al. (2008), and Wang et al. (2009).

In Figure 11 of their study of the effects of a weakening Atlantic MOC/THC on the coupled ENSO system, Timmermann et al. (2007) made the remarkable observation that, during the positive phase of AMO, the annual cycles of the Nino-3 SST are intensified, while the ENSO-scale (i.e., 2 to 8 years) SST variability is relatively more muted, and the inverse occurs for the opposite phase of AMO. Such a nonlinear multidecadal modulation of the annual-cycle and ENSO signals, which was clearly noted by White and Liu (2008b), may ultimately be consistent with the new insight they offered concerning the non-linear alignment of El Niño/La Niña episodes with the combined signals from the 11-year solar cycle-generated 3rd (3.6-year) and 5th (2.2-year) harmonics. On millennial timescales, proxy data (Stott et al., 2002) from the western Pacific warm pool region suggest that El Niño conditions correlate with cooler-stadial conditions around Greenland and the North Atlantic, while La Niña conditions tend to correlate with warmer interstadials.

Denton and Broecker (2008) demonstrated the non-obvious connection between AMO and the retreating and advancing activity of 38 selected glaciers in the Swiss Alps with little or only slight delays in the glacier response. Such a tight coupling between glacier activity in the Swiss Alps and AMO was suggested to arise from the effects of AMO on European summertime temperatures. Chang et al. (2008) showed the active role played by MOC/THC in explaining abrupt climate events in the tropical Atlantic, including the rapid reduction of summer monsoonal wind and rainfall over West Africa. Knight et al. (2006) and Ting et al. (2008) showed the wide-ranging climatic impacts of the AMO, including rainfall over the Sahel and sea surface temperature over the main development region of Atlantic hurricanes (Fig. 4).

Goswami et al. (2006), Lu et al. (2006), Sutton and Hodson (2007), Feng and Hu (2008), and Li et al. (2008) found multidecadal modulation of Indian summer monsoon rainfall through empirical data analyses and modeling experiments. Although the AMO–Indian monsoon rainfall relationship is not fully robust, the general tendency is such that a positive AMO/MOC/THC phase, via both persistent tropospheric and near-surface response pathways, leads to more summer rainfall with modulated delay responses until the months of September and October. Li and Bates (2007) showed atmospheric GCM results that yielded relatively uniform, warmer winters in East China but a dipolar north–south positive–negative pattern of precipitation responses during the positive AMO phase and inversely for the negative AMO phase. Earlier, Tan et al. (2004) showed an interesting correlation between the warm-season temperature proxy for Beijing and the North Atlantic Drift ice index of Bond et al. (2001) covering the last 2650 years, but they did not offered a working mechanism. Wang et al. (2009) emphasized the influences of AMO on Asian monsoonal climate in all four seasons, producing weakened winter monsoons but enhanced summer monsoons related to AMO-modulated tropospheric heating anomalies.

Finally, the works by Braun et al. (2005), Weng (2005), and Dima and Lohmann (2009) support the present proposal by showing how the various key intrinsic timescales and physics related to this solar–Arctic connection can interact and connect dynamically from annual cycles to the noted millennial-scale oscillation of about 1470 years of the Dansgaard–Oeschger events noted during glacial intervals.[10] Weng (2005), using both ocean temperature data and a toy model, illustrated how in a nonlinear weather–climate regime that even a "small" change in TSI forcing will effectively interact with and couple to the seasonal forcing to generate and sustain climate responses and variations of multidecadal to centennial timescales.[11] Braun et al. (2005), using the Potsdam Institute's intermediate complexity coupled climate system model, showed how the 1470-year glacial climate cycle could be robustly and realistically generated solely from the periodic forcing of freshwater input into the North Atlantic Ocean in cycles of 87 and 210 years, which were identified by the authors as the solar Gleissberg and deVries/Suess activity cycles, respectively.[12]

Dima and Lohmann (2009) suggest that, instead of being the synchronization of the two basic solar cycles or any amplification of a weak direct 1500-year forcing of unknown origin by THC, the origin of the 1500-year cycle is best viewed as the rectification of an external solar forcing through dynamical connection to a threshold internal response of the THC. Their work emphasizes that observed millennial variability in paleo-proxy records should be considered as a derived dynamical mode of the climate system without physical processes on a fixed millennia timescale, regardless of whether this timescale is rooted in the Sun or in Earth climate system. This possibility certainly adds another layer of complexity in the study of the Sun–climate connection.

CONCLUSION

This paper proposes three interrelated causes for natural climate variations on multidecadal to centennial timescales through a solar–Arctic connection mechanism. The first, Cause A, is that a persistent and systematic variation of the solar TSI and related insolation gradient modulates the atmospheric heat transport from the tropics to the Arctic, and hence modulates the Arctic temperature change itself with little or no delays.

The second, Cause B, is that thermal perturbations lead to both natural modulation of the Arctic sea ice and to transport of fresh water through the Bering Straits and from the Arctic through both the Greenland Sea and Denmark Strait and the Canadian Arctic Archipelago pathways to deep water formation sites spread across the North Atlantic from the Greenland–Icelandic–Norwegian (GIN) Seas to the east and at the Labrador Sea to the west. The third, Cause C, is that further effects are: (1) thermal, freshwater, and salinity perturbation of the Atlantic MOC-THC; (2) the delayed connection of about 5 to 20 years with the tropical Atlantic SST and the InterTropical Convergence Zone (ITCZ); and (3) coupling of the affected tropical Atlantic processes feeding back to the MOC-THC. This three-part solar–Arctic climate variation mechanism emphasizes plausible physical arguments rather than statistical correlations.

The proposed solar–Arctic connection chains from Causes A–C have good empirical support, and this mechanism appears to explain the operation of coupled air–ocean–ice responses over broad areas connecting the Arctic and North Atlantic to other locations on multidecadal to centennial timescales. This proposal offers the opportunity for a rejectable scientific hypothesis of a physical Sun–climate connection. The new synthesis should be viewed as a step forward in the long quest to understand how the full weather–climate continuum varies on multidecadal to centennial timescales by highlighting the role of solar irradiance forcing upon the Arctic region, in not only sustaining and amplifying the natural climatic oscillation and variation, but also in the selectivity or specification of the broadband nature of the spatial and temporal scales of the climatic responses involved.

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NOTES

[1] Huth et al. (2006) cautioned that it may not be appropriate to use spatially fixed indices, such as the North Atlantic Oscillation (NAO; see however the study of Portis et al., 2001 for a new NAO index with spatially evolving domains) to study plausible solar activity responses since the majority of COAs change their locations depending on the solar cycle phases. In addition, Rodionov et al. (2005), in their careful classification of five types of atmospheric circulation for anomalously warm months and another five types for anomalously cold months in the Bering Sea, found that changes in the position of the Aleutian Low are more important than changes in its central pressure.

[2] The high alpine stalagmite $\delta^{18}O$ record of Holzkamper et al. (2004) covering the Eemian, however, still shows evidence for spectral peaks at 197, 109, and 21 years that can be associated with the Suess/deVries, Gleissberg, and Hale cycles of solar activity variations.

[3] White and Liu (2008b) recently reported how the 11-year solar radiative forcing drove not only the quasi-decadal signal in the tropical Pacific sea surface temperature (White and Liu, 2008a) but also was responsible for the 3.6-year ENSO signal and the 2.2-year quasi-biennial-oscillation signal. The 3.6-year and 2.2-year SST signals are interpreted and modeled as the third and fifth harmonics of the first-harmonic 11-year period quasi-decadal response to the 11-year solar radiative forcing. Usoskin et al. (2007) provided additional discussion and consideration of intrinsic solar activity variations on the interannual timescale, including the persistence of the third harmonics of the 11-year solar cycles.

[4] One should note that the absolute level of TSI since 1979 has been measured by satellite-borne cavity radiometers with values ranging from 1360 to 1375 W/m^2, and the resolution of this indeterminacy requires new measurements with radiometers with more precisely determined pinhole area versus surface area of the cavity radiometers. The absolute value of TSI used for this paper has been arbitrarily tuned so that the mean value for the 1979–present interval is roughly 1366.3 W/m^2 (N. Scafetta, 2007, private comm.; Scafetta and Willson, 2009).

To further comment on the estimates of TSI forcing, the IPCC (2007) AR4 WG 1 report's Section 2.7 (p. 188) has recently claimed:

> The estimates of long-term solar irradiance changes used in the TAR (e.g., Hoyt and Schatten, 1993; Lean et al., 1995) have been revised downwards, based on new studies indicating that bright solar faculae likely contributed a smaller irradiance increase since the Maunder Minimum than was originally suggested by the range of brightness in Sun-like stars (Hall and Lockwood, 2004; M. [sic] Wang et al., 2005).

Figure 2.17 on p. 190 of the IPCC (2007) WG 1 report provides a graphical summary that contrasts the previous estimate by Lean (2000) to the new estimate by Y.-M. Wang et al. (2005; including Lean as co-author). The comparison shows that the older estimate was 3.8 times larger for the deduced increase of radiative forcing from the Maunder Minimum to contemporary solar activity minima.

But is the quoted claim correct? Several facts clearly suggest that those statements from IPCC AR4 are neither accurate nor authoritative. First, it must be pointed out that, although Y.-M. Wang et al. (2005) may have given the impression that their paper actually gives a constraint on how large or small the brightness of the Sun should be, it does not. Their paper was based primarily on the so-called magnetic flux transport model that was never meant to model any irradiance change or any assessment of the energy budget of the whole Sun. The flux transport model does not even contain any radiative transfer calculation.

A similar limitation can be noted in the IPCC AR4's reference to Hall and Lockwood (2004), which was primarily a paper on solar and stellar magnetic activity rather than on how magnetism and light outputs of the Sun and sunlike stars are linked. Furthermore, it is somewhat puzzling that the following related papers were not cited or discussed: (1) Radick et al. (1998); (2) Giampapa et al. (2006); (3) Hall, Henry et al. (2007); 4) Hall, Lockwood, et al. (2007); and (5) Lockwood et al. (2007). The IPCC AR4 WG I Chapter 2 authors also ignored the key result published in Zhang et al. (1994) [previously cited in IPCC (2001) Third Assessment Report] that is clearly not outdated or superceded. Therefore, the IPCC AR4 quote highlighted here is not a defensible summary of the high-quality scientific research that has been done on TSI forcing.

[5] See the discussion in Vage et al. (2009) on the multiple factors contributing to the return of deep convection at the Labrador and Irminger seas during the winter season of 2007–2008 despite a fairly low or neutral NAO index and an increased flux of Arctic sea ice to the North Atlantic subpolar basin.

[6] Based on a study of the unforced internal variability of the Kiel Climate Model, Park and Latif (2008) recently proposed the separation of their "multidecadal-scale" (i.e., with peak spectral powers at roughly 50–100 years) and "multicentennial-scale" (i.e., with peak spectral powers at roughly 300–400 years) variability of the Atlantic MOC, in that the former can be shown to originate in the North Atlantic whereas the latter is driven in the Southern Ocean. The current state of ocean proxy-observation and modeling does not meaningfully warrant such a distinction at this time.

[7] See also discussion and estimates in Wadley and Bigg (2002), Jones et al. (2003), Cuny et al. (2005), Prinsenberg and Hamilton (2005), Kwok (2006, 2007), Munchow et al. (2006), Serreze et al. (2006), Zweng and Munchow (2006), Greene et al. (2008), and Condron et al. (2009).

[8] This dipole index was defined as the difference of the annual-mean SSTs from the 40–60°N, 60–10°W box and 40–60°S, 50°W–0° box in Latif et al. (2006), and is slightly different from a previous definition of the difference between the 40–60°N, 50–10°W box and 10–40°S, 50°W–10° box by Latif et al. (2004).

[9] See Guan and Huang (2008) for additional clarification on the key role played by wind stress and tidal dissipation as the external mechanical sources needed to support the MOC/THC, and see Adkins et al. (2005) for a suggestion of the thermobaric effects and geothermal heating in explaining the rapid change and instability observed for glacial deep ocean.

[10] See Bond et al. (1997) and Bond et al. (1999) for the discussion of the muted Dansgaard/Oeschger–like mode during the Holocene. See also the distinction and clarification for rapid and abrupt oscillations during glacial times and the Holocene in Alley (2007) and Denton and Broecker (2008).

[11] Weng (2005) was referring to the "80–90 Gleissberg cycle" timescale, but I agree with her that it is probably difficult or even pointless to be too specific because the objective of our common task is to understand not only any particular spectral features/characteristics, but also the broader scales of the weather–climate continuum.

[12] See Braun et al. (2008) for additional supports and arguments for their original paper.

APPENDIX 1

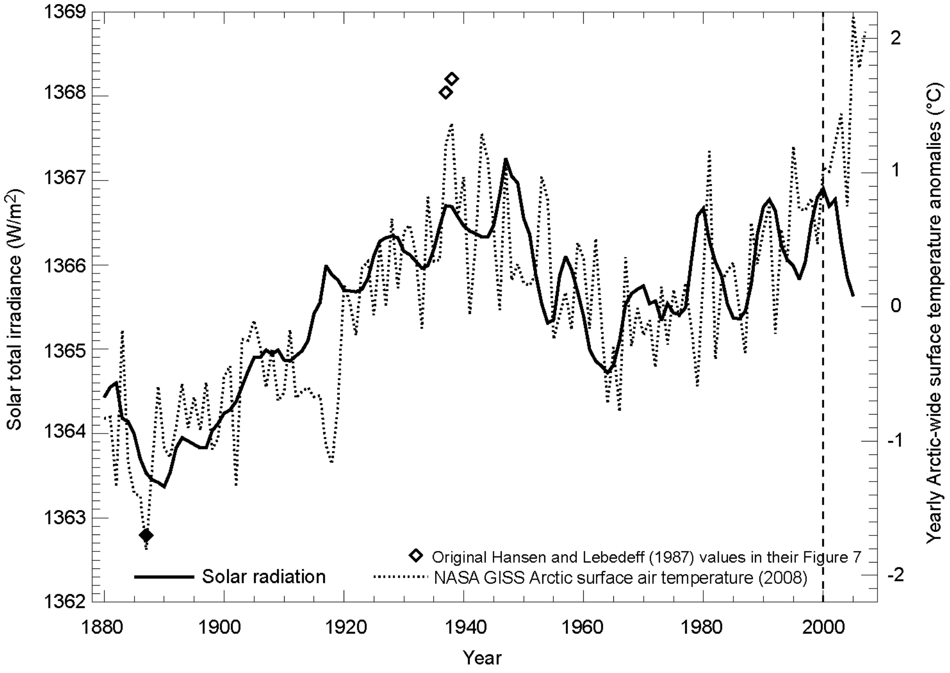

Fig. A1. Updated annual mean Arctic surface air temperature anomaly (dotted line) time series (from NASA GISS) correlated with the estimated total solar irradiance (solid line) of Hoyt and Schatten (1993) from 1880–2007. It should be noted that an updated time series from Polyakov et al. (2003) is unavailable at this time (Polyakov, private comm., July 24, 2008), so the NASA GISS Arctic (64–90°N) temperature series (http://data.giss.nasa.gov/gistemp/tabledata/ZonAnn.Ts+dSST.txt) is adopted for convenience. Although not strongly affecting the current study on multidecadal to centennial variability, there are apparent discrepancies between the relative highs of the Arctic temperature values for 1937 and 1938 in the current NASA GISS database compared to previously published values (marked by the open diamond symbols) from Hansen and Lebedeff (1987). In contrast, the value for the cool year at 1887 remained similar (closed diamond symbol) from the old and new NASA GISS records. It is not obvious how the urban heat island effect can play a dominant role in either the Arctic surface air temperature record of Polyakov et al. (2003) or NASA GISS. The vertical dashed line around the year 2000 marks the end year for the previously published result in Soon (2005).

APPENDIX 2

Table A1. References on Sun–Climate Oscillation Scales Detected in Multiproxy Archives with a Focus on the 80-Year and 200-Year (and the necessary 1500-year scale) Solar Variability

Reference	Location	Data	Proxy	Time intervals	Scales of variability detected
(0) Solar proxies and theories					
Pipin, 1999	Sun	Dynamo theory	Solar magnetism	General	Gleissberg and longer scales
Wagner et al., 2001	Greenland GRIP	^{10}Be ice-core	^{10}Be production rate	20-50 kyr B.P.	205-yr
Peristykh and Damon, 2003	World	$\Delta\,^{14}$C tree-ring chronology	^{14}C production rate	Last 12,000 yrs	88-yr, 208-yr, 2304-yr
Vonmoos et al., 2006; Vonmoos, 2005 Ph.D. thesis	GRIP	^{10}Be	^{10}Be production rate	304–9315 yr B.P.	88-yr, 205-yr
Horiuchi et al., 2008)	Dome Fuji, Antarctica	^{10}Be	^{10}Be concentration + flux	700-1900 A.D.	~200-yr
(1) The related 1500-yr scale (broadband 1000-2500 yr)					
Bond et al., 2001	N. Atlantic	Hermatite-stained grains	Ice-rafting events	Holocene	"1500-yr"
Bianchi and McCave, 1999	N. Atlantic	Sortable silt grain size (10–63 μm)	Iceland-Scotland Overflow water	Holocene	1500-yr
Farmer et al., 2008	N. Atlantic	Mg/Ca ratios in *G. bulloides*	SST	Last 12 kyr	500-yr
Andrews et al., 2009	Northern Iceland (multi-sites)	X-ray diffraction analysis of <2 mm sediment fraction	Drift ice	Last 12 kyr	670-yr
Hu et al., 2003	Arolik Lake (SW Alaska)	Biogenic silica	Aquatic productivity	Last 15 kyr	1500-yr?, 950-yr, 195-yr
Wollenburg et al., 2007	Arctic Ocean; Eurasian Basin	Fischer α	Biodiversity of benthic foraminifera	Last 24 kyr	1.57-kyr, 0.76-kyr (1.16-kyr, 0.54-kyr Holocene)
Kim et al., 2007	Off NW Africa	Alkenone, $\delta\,^{18}$O (*G. bulloides*)	SST, upwelling intensity, subtropical gyre	Last 10 kyr	2–3-kyr

(*table continues*)

Table A1. (Continued)

Reference	Location	Data	Proxy	Time intervals	Scales of variability detected
Moy et al., 2002	Lake Pallcacaocha (S. Ecuador)	Red-color intensity	ENSO activity	Holocene	1500-yr, 2000-yr
(2) North Atlantic + Greenland + Iceland					
Stuiver et al., 1995; Grootes and Stuiver, 1997	GISP2	$\delta^{18}O$ in ice	Surface temperature	Holocene part	210-yr, 70-yr, 11-yr, 6.3-yr
Yiou et al., 1997	GRIP	$\delta^{18}O$ in ice	Surface temperature	Holocene part	2-kyr, 180-yr, 150-yr, 120-yr
Ram and Stolz, 1999	GISP2	Laser-light scattering from ice	Atmospheric dust	92–14 kyr B.P.	91-yr, 197-yr + distributions
Mayewski et al., 1997	GISP2	Polar circulation index (glaciochemical data)	Atmospheric circulation	Last 110 kyr	1450-yr
Fischer and Mieding, 2005	North Greenland Traverse (NGT) ice cores	Na^+ concentration	Atmospheric circulation	1066–1993 A.D.	10.4-yr, 62-yr
Andrews et al., 2003	North Iceland	Sediment magnetic property, grain size	N. Atlantic oceanographic conditions	Last 12 kyr	~200-yr, 125-yr, 88-yr
Moros et al., 2006	North Iceland	Quartz content	Drift ice	Last 12 kyr	1.3-kyr, 75-80-yr
Sicre et al., 2008	North Iceland	Alkenones	SST	Last 2000 yr	20-25 yr
(3) Northern Europe + Europe					
Allen et al., 2007	Finnmark, Norway	Pollen + geochemical data	Vegetation history	Holocene	1810-yr, 1650-yr, 190-yr
Knutz et al., 2007	NW Europe/ British Ice Sheet	Ice-rafted debris events	Glacial margin/ meltwater surges/ Atlantic MOC	10–27 kyr B.P.	180–220-yr
Haltia-Hovi et al., 2007	Lake Lehmilampi, E. Finland	Varve thickness	Lake sedimentation -hydrology	Last 2000-yr	Match Δ 14C series
Swindles et al., 2007	Fermanagh, N. Ireland	Peat humification and plant microfossil	Hydrology	2850 yr BC to 1000 A.D.	265-yr + others

(*table continues*)

Table A1. (Continued)

Reference	Location	Data	Proxy	Time intervals	Scales of variability detected
Chambers and Blackford, 2001	Four mire sites in the UK	Wet-dry index	Hydrology	Last 2000-yr	80-yr, 200-yr
Holzkamper et al., 2004	Spannagel Cave, Austrian Alps	$\delta^{18}O$ in stalagmite	Hydrology	131–118 kyr B.P.	197-yr, 109-yr, 21-yr
Mangili et al., 2007	Pianico paleolake, Southern Alps	$\delta^{18}O$ in calcite varve	Hydrology	15,500 yr during Interglacial of 400 kyr B.P.	780-yr, 125 to 195-yr
(4) North America					
Yu and Ito, 1999	Rice Lake, North Dakota	Mg/Ca ratio of ostracode shells	Salinity/ drought frequency	Last 2100-yr	400-yr, 200-yr, 130-yr, 100-yr
Anderson, 1992	Elk Lake, Minnesota	Varve thickness	Aeolian activity/wind	2000-yr in 7.3 kyr-5.3 kyr B.P.	200-yr, 20 to 25-yr
Dean, 1997	Elk Lake, Minnesota	%Al, %Na in varved lake sediments	Aeolian activity	Last 1500-yr	400-yr, 84-yr
Wang et al., 2003	Fox Hill and Keller Farm loesses	Lightness parameter, % carbonate, %Fe	Persistent heat and moisture supply	30-14 kyr B.P.	800 to 1000-yr, 450 to 550-yr, 350 to 390-yr
Fortin and Lamoureux, 2009	Canadian Arctic and southeastern boreal regions	Lacustrine varve and boreal tree-ring width series	Hydrology + AMO	1550-1986 A.D.	64-yr, 20 to 40-yr
Schimmelmann et al., 2003	Santa Barbara basin	Six major grey flood deposits in varved sediments	Floods and droughts cycle	Last 2000-yr	200-yr
Douglas et al., 2007	Gulf of California	Biogenic silica, carbonate, TOC	Primary productivity, dissolution cycles	Last 10000-yr	150-yr, 200-yr, 350-yr
Patterson et al., 2004a, 2004b	Vancouver Island, NE Pacific	Sediment color (X-ray images), anchovy + herring scales	Hydrology, ocean biological productivity	1400-4700 yr B.P.	~75 to 90-yr among others
Springer et al., 2008	West Virginia	Sr/Ca ratios and $\delta^{13}C$ values in stalagmite	Hydrology, droughts	Last 7000-yr	715-yr, 550-yr, 455-yr, 210-yr
Hubeny et al., 2006	Pettaquamscutt River Estuary, Rhode Island	Fossil pigment Bchle (Bacteriochlorophyll e)	Modes of large-scale climate variations, NAO + AMO	1024-2004 A.D.	95.9-yr, 38.5-yr, 11.6-yr, 8-yr, 5.5-yr

(*table continues*)

Table A1. (Continued)

Reference	Location	Data	Proxy	Time intervals	Scales of variability detected
Asmeron et al., 2007	Southwestern U.S.	$\delta^{18}O$ values in stalagmite	Hydrology, circulation, droughts	Last 12,000-yr	1533-yr, 444-yr, 146-yr, 88-yr
McCabe et al., 2008	Yellowstone National Park	Tree-ring and instrumental data	Hydrology, precipitation, drought	Last 820-yr	~60-yr, ~20-yr
Wilson et al., 2007	Gulf of Alaska	Tree-rind width	Temperature	Last 1300-yr	18.7-yr, 50.4-yr, 90-yr, 38-yr, 24-yr, 14 to 15-yr, 9 to 11-yr
Wiles et al., 2009	Gulf of Alaska, Lake Erie	Tree-ring and lake water level	Hydrology, Lake Erie level	Last 265-yr	116-yr, 76-yr, 28 to 20-yr, 17 to 14-yr, 12-yr, 11.2-yr
(5) Gulf of Mexico (GOM) + Caribbean, Cariaco Basin					
Poore et al., 2004	Pigmy basin, northern GOM	Abundance of *G. sacculifer*	Atlantic ITCZ movements	Last 5000-yr	512-yr, 180-yr
Poore et al., 2004	Core RC12-10, western GOM	Abundance of *G. sacculifer*	Atlantic ITCZ movements	7.4 to 2.8 kyr B.P.	550-yr, 210-yr
Hodell et al., 2001 (Yucatan Peninsula)	Lakes Chichancanab and Punta Laguna	Bulk density and $\delta^{18}O$	Hydrology, drought cycles	Last 2600-yr	208-yr
Nyberg et al., 2001, 2002	SW Puerto Rico	Three mineral magnetic parameters, $\delta^{18}O$ of planktonic foraminifera	Hydrology, drought cycles, SST, SSS	Last 2000-yr	217-yr
Black et al., 2004	Cariaco Basin	$\delta^{18}O$ in planktic *G. bulloides*	SST and ITCZ-precip-related salinity	Last 300-yr	159-yr, 24-yr, 10.9-yr
Lund and Curry, 2004	South of Dry Tortugas	Planktonic foraminiferal $\delta^{18}O$	Florida current	Last 5200-yr	360-yr, 190-yr, 130-yr, 100-yr, and 80-yr
(6) Equatorial + Tropical Africa					
Russell and Johnson, 2005a	Lake Edward, Congo	% Mg in calcite of lake sediment	Salinity/water balance/ITCZ movements	Last 5400-yr	1500-yr
Russell and Johnson, 2005b	Lake Edward, Congo	% biogenic silica of lake sediment	Salinity/water balance/ITCZ movements	Last 5400-yr	725-yr, 125-yr, 63-72-yr, and others

(*table continues*)

Table A1. (Continued)

Reference	Location	Data	Proxy	Time intervals	Scales of variability detected
Stager et al., 1997	Lake Victoria, East Africa	Abundance of diatom species in lake sediment	Aridity/lake levels	Last 13 kyr	2350- to 2550-yr, 1400-yr, and others
Kuhlmann et al., 2004	Off NW Africa	Potassium intensity in sediment core	Proxy of terrigenous supply to marine sediment	Last 9 kyr	900-yr
Hanebuth and Henrich, 2009	Off NW Africa (Mauritania)	Dust supply/ accumulation	Turbidite activity	Last 11 kyr	900 ± 150-yr
(7) Indian Monsoon					
Neff et al., 2001	Hoti Cave, northern Oman	$\delta\,^{18}$O in dated speleothems	Regional precipitation/ Indian monsoon	9–6 kyr B.P.	1018-yr, 226-yr, 28-yr, 10.7-yr, 9-yr (untuned); 205-yr, 87-yr (tuned)
Agnihotri et al., 2002	Northeastern Arabian Sea	Biogenic proxies (C_{org} and N) and %Al	Intensity of Indian monsoon	Last 1200-yr	200 ± 20-yr, 105 ± 15-yr, 60 ± 10-yr
Gupta et al., 2005	Northwestern Arabian Sea, off Oman	Abundance of planktic *G. bulloides*	Indian monsoon	Last 11.1-kyr	1550-yr, 152-yr, 137-yr, 114-yr, 101-yr, 89, 83, and 79-yr
Fleitmann et al., 2003	Qunf Cave, southern Oman	$\delta\,^{18}$O in dated speleothems	Regional precipitation/ Indian monsoon	Last 11 kyr (with some data gaps)	220-yr, 140-yr, 107-yr, 11- and 10-yr (untuned)
Burns et al., 2002	Salalah region, Oman	Layer thickness, $\delta\,^{13}$C and $\delta\,^{18}$O	Regional precipitation/ monsoon rainfall	Last 780-yr	204-yr, 97-yr, 19.8-yr, 16.1-yr, 12.8-yr, and 6.6-yr (in $\delta\,^{18}$O spectra)
(8) East Asia + East Asian monsoon					
Wang et al., 2005	Dongge Cave, southern China	$\delta\,^{18}$O in absolutely dated stalagmite	Regional precipitation/ strength of Asian monsoon	Last 9000-yr	558-yr, 206-yr, 159-yr
Cosford et al., 2008	LianHua Cave, Hunan, China	$\delta\,^{18}$O in absolutely dated stalagmite	Regional precipitation/ strength of Asian monsoon	Last 7000-yr	220-yr, 83-yr, 50-yr

(*table continues*)

Table A1. (Continued)

Reference	Location	Data	Proxy	Time intervals	Scales of variability detected
Zhang et al., 2008	WanXiang Cave, Gansu, China	$\delta\ ^{18}O$ in absolutely dated stalagmite	Regional precipitation/ strength of Asian monsoon	Last 1810-yr	170-yr, 10.5-yr, 6.4-yr, 5.5-yr
Zhong et al., 2007	S. Tarim Basin, Xinjian, NW China	Mean grain size and other measures	Hydrology/ wet-dry cycles	Last 4000-yr	200-yr, 120-yr, 90-yr, and others
Lim et al., 2005	Cheju Island, Korea	Eolian quartz flux	Hydrology/ Asian dust	Last 6500-yr	1137-yr, 739-yr, 214-yr, 162, 137, 127, 111-yr
Ji et al., 2005	Qinghai Lake, Qinghai-Tibetan Plateau	Visible reflectance (redness record/iron oxide content)	Hydrology/ Asian and Indian monsoon	Last 18 kyr	293-yr, 200-yr, 163-yr, 123-yr
Ji et al., 2009	Qinghai Lake, Qinghai-Tibetan Plateau	Abudance of bacteriophae ophytina	Productivity of anoxygenic phototrophic bacteria (APB)	Last 18 kyr	Durations of APB peaks: 60- to 70-yr, 90- to 100-yr, 130- to 140-yr, 160- to 170-yr, 200- to 210-yr
Xu et al., 2006	Hongyuan, eastern Qinghai-Tibetan Plateau	$\delta\ ^{18}O$ in peat cellulose	Temperatures	Last 6000-yr	Quasi 100-yr
Tan et al., 2003	Shihua Cave, Beijing	Staglamite growth layers	Temperatures	Last 2650-yr	206-yr, 325-yr
Hong et al., 2000, 2001	Jinchuan, northeastern China	$\delta\ ^{18}O$ and $\delta\ ^{13}C$ in peat cellulose	Temperature and hydrology	Last 6000-yr	207 (205)-yr and other centennial to millennial scales
Wei et al., 2008	Beijing, China	Instrumental	Summer rainfall	1724–2005 A.D.	70-yr, 31-yr, 20-yr
Shen et al., 2006	Eastern China	Documentary records–Drought/ flood Index	Summer rainfall/PDO	1470–2000 A.D.	75- to 115-yr, 50- to 70-yr
Chu et al., 2008	Eastern China/ Korea	Documentary records	Snow events	Last 2000 years	281-yr, 103-yr
Raspopov et al., 2008	Tienshan Mountains and Tibetan Plateau	Tree-ring width	Summer temperature/ precipitation	600–2000 A.D.	~200-yr

(*table continues*)

Table A1. (Continued)

Reference	Location	Data	Proxy	Time intervals	Scales of variability detected
(9) Other regions and proxies (examples only)					
Eichler et al., 2009	Belukha Glacier, Siberian Altai Mountain region	$\delta^{18}O$ from glacier ice core	Temperature (March-November)	1250–2000 A.D.	205-yr, 86-yr, 10.8-yr
Sano et al., 2009	Northern Vietnam (Mu Cang Chai)	Tree-ring index	Hydrology, droughts	1470–2004 A.D.	54- to 79-yr, 3.2-yr, 2.5-yr, 2.0-yr
Ruzmaikin et al., 2006	Nile River	Water level	Hydrology	622–1470 A.D.	88-yr, 260-yr
van Beynen et al., 2008	Briars Cave, central Florida	$\delta^{13}C$ + Sr in stalagmite	Soil productivity/ precipitation	Last 4000-yr	170- to 180-yr and other scales
Dima et al., 2005	Rarotonga coral, Cook Islands, South Pacific	Sr/Ca in coral	SST	1727–1996 A.D.	~80-yr, ~25-yr
Gedalof et al., 2002	Pacific Ocean (north to south)	PC1 from Multiproxy—tree rings + corals	PDO (Oct–Mar) proxy	1840–1990 A.D.	~85-yr, ~23-yr, ~20-yr
Agnihotri et al., 2008	Peru margin	Ti	Ocean productivity	Last 2000-yr	250-yr, 83-yr 22- to 24-yr, 11- to 9.4-yr
(10) Southern Ocean and Antarctica					
Lamy et al., 2001	Core GeoB 3313-1, southern Chile	Iron content	Regional precipitation/ variability + shift of southern westerlies	Last 7700-yr	1750 yr + 1340-yr (ca. 1500-yr band), 950-yr + 820-yr (ca. 900-yr band)
Nielsen et al., 2004	Site TN057-17, Polar Front, East Atlantic Southern Ocean	Relative diatom abundances	Summer SST + sea ice presence	Last 12.5-kyr	1220-yr, 1070-yr, 400-yr, 150-yr
Delmonte et al., 2004	Vostok and Dome C, East Antactica	% coarse particles	Hydrology/ atmospheric circulation (dipolar oscillations)	9.8- to 3.5 kyr B.P.	180- to 210-yr, 130- to 150-yr (Dome C); 150- to 230-yr, 120- to 140-yr (Vostok)

(*table continues*)

Table A1. (Continued)

Reference	Location	Data	Proxy	Time intervals	Scales of variability detected
Leventer et al., 1996	Palmer deep basins/ Antarctic Peninsula	Multi-variables (including magnetic susceptibility, diatoms)	Temperatures	Last 6000-yr	quasi 200-yr and 2500-yr cycles
Masson-Delmotte et al., 2004	EPICA Dome C, East Antarctica	δ D in ice	Site temperature	Last 5000-yr	833-yr, 220-yr, and 60-yr
Watanabe et al., 1998, 1999	Site S25, Mizuho Plateau/ coastal East Antarctica	H_2O_2, nss SO_4^{2-}, NO_3^-	Atmospheric circulation	1890–1980 A.D.	11-yr
Goodwin et al., 2004	Law Dome/East Antarctica	Early winter sea salt (Na) aerosol concentration	Mid-latitude winter atmospheric variability	1301–1995 A.D.	10.5-yr, 3.9 + 3.2-yr, 2.33 + 2.18-yr
McConnell et al., 2007	James Ross Island, Antarctic Peninsula	Aluminum concentration and flux	Atmospheric circulation, aridity of dust source regions	1832–1991 A.D.	10.7- to 13.2-yr, 21.3-yr, 1.52-yr, 1.8-yr, 3.55- to 3.71-yr, 4.73-yr

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Acronyms employed: *A&A = Astronomy & Astrophysics*; *EPSL = Earth and Planetary Science Letters*; *G3 = Geochemistry, Geophysics, Geosystems*; *GRL = Geophysical Research Letters*; *GSA = Geological Society of America*; *JGR = Journal of Geophysical Research*; *JMSJ = Journal of the Meteorological Society of Japan*; *JQS = Journal of Quaternary Science*; *PNAS = Proceedings of the National Academy of Sciences of the USA*; *PPP = Palaeogeography, Palaeoclimatology, and Palaeoecology*; *QG = Quaternary Geochronology*; *QI = Quaternary International*; *QR = Quaternary Research*; *QSR = Quaternary Science Reviews*.