# Variable solar irradiance as a plausible agent for multidecadal variations in the Arctic-wide surface air temperature record of the past 130 years

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[1] This letter offers new evidence motivating a more serious consideration of the potential Arctic temperature responses as a consequence of the decadal, multidecadal and longer-term persistent forcing by the ever-changing solar irradiance both in terms of total solar irradiance (TSI, i.e., integrated over all wavelengths) and the related UV irradiance. The support for such a solar modulator can be minimally derived from the large (>75%) explained variance for the decadally-smoothed Arctic surface air temperatures (SATs) by TSI and from the time-frequency structures of the TSI and Arctic SAT variability as examined by wavelet analyses. The reconstructed Arctic SAT time series based on the inverse wavelet transform, which includes decadal (5–15 years) and multidecadal (40–80 years) variations and a longer-term trend, contains nonstationary but persistent features that are highly correlated with the Sun's intrinsic magnetic variability especially on multidecadal time scales. **Citation:** Soon, W. W.-H. (2005), Variable solar irradiance as a plausible agent for multidecadal variations in the Arctic-wide surface air temperature record of the past 130 years, *Geophys. Res. Lett.*, *32*, L16712, doi:10.1029/2005GL023429.

## 1. Introduction

[2] The Arctic climate system, both regionally and taken as a whole, exhibits considerable variability on timescales ranging from sub-seasonal, to seasonal, to multidecadal. Despite limitations, new efforts have recently produced a trustworthy record for the surface air temperature (and pressure) that is representative for the Arctic as a whole extending back some 100–130 years. The Arctic-wide SAT record carefully compiled by *Polyakov et al.* [2003] is used for current research but it may be cautioned that a climatological definition of the Arctic [*Przybylak*, 2000] needs not be strictly limited to setting a southern latitudinal border e.g., at 62°N as practically done by *Polyakov et al.* [2003].

[3] The question explored in this letter is whether solar radiation has any role in the decadal, multidecadal and longer-term variations of the Arctic SATs and if so, how does that compared with increasing levels of anthropogenic $CO_2$ in the air?

[4] Several recent studies have found significant correlations between various solar and climatic variables, albeit with emphasis on different spatial domains and temporal scales and even differing aspects of the interrelated, external solar forcing. For example, *Douglass and Clader* [2002] identified a definite solar signal in the global temperature series of the lower troposphere since 1979. *White et al.* [2003] examined the nature of plausible decadal-scale solar responses emphasizing coherent signals in global (40°S to 60°N) ocean diabatic heat storage, upper ocean surface temperature, and atmospheric air temperatures. *Kodera and Kuroda* [2002] sketched mechanisms for the transmission of the direct impact of the solar UV irradiance forcing in the upper stratosphere and stratopause region to lower stratosphere and troposphere. *Mayewski et al.* [2005], from analyses of atmospheric circulation-sensitive chemicals in ice cores from both Arctic and Antarctic regions, recently suggested that zonal winds are strengthened near the edge of the Arctic (and also Antarctic) polar vortex when solar irradiance increases on annual to multidecadal timescales. *Mayewski et al.* [2005] noted that the Siberian High, Kara Sea Low and westerly flow over mid-to-high latitudes are intensified during more active phase of sunspot cycles.

[5] *Ruzmaikin and Feynman* [2002] offered evidence of a sun-climate link emphasizing the pathways through solar modulation of the Arctic Oscillation (AO). *Kodera* [2003] showed that the North Atlantic Oscillation (NAO)'s sea level pressure (SLP) signals are more narrowly confined to the Atlantic sector during low solar activity winters but for winters coinciding with higher solar activity the NAO-related anomalies are more extended over the whole Northern hemisphere. (Kodera has previously shown, based on a shorter set of available atmospheric data over 1961–1999 rather than the full 1900–1999 interval reported by *Kodera* [2003], that the NAO-related signals are more vertically confined to the troposphere for low solar activity phase and expand to the stratosphere during high solar activity phase.) Kodera also found key evidence that the spatial SLP structures during the prolonged high NAO epoch of 1903–1928 are more narrowly confined to the Atlantic sector of the polar region (and did not extend into the Eurasian continent). During the most recent epoch of high NAO indices from 1973–1998, the high-pressure and low-pressure anomalies of the NAO pattern extended to cover wide regions of Europe, the Mediterranean Sea, and the polar regions. These two high NAO epochs coincide with periods of low and high solar activity, respectively. This observation suggests that multidecadal variation in solar irradiance may exert an indirect


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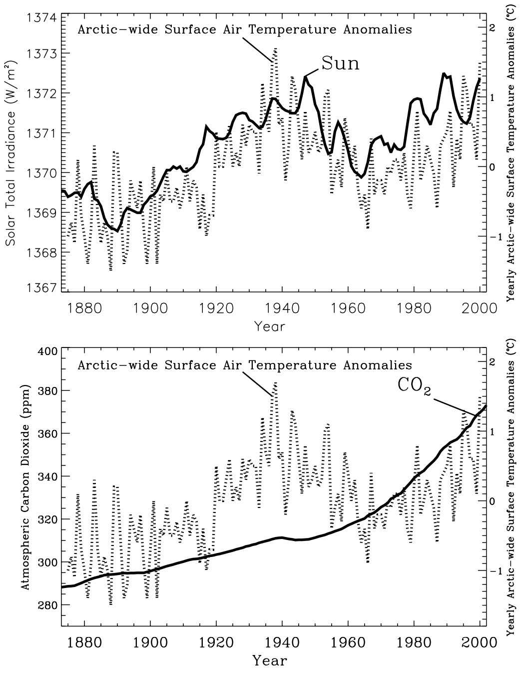


**Figure 1.** Annual-mean Arctic-wide air temperature anomaly time series (dotted lines) correlated with the estimated total solar irradiance (top panel; solid lines) and with the atmospheric carbon dioxide, $CO_2$, mixing ratio (bottom panel; solid lines) from 1875 to 2000.

influence on climate by modulating prominent modes of atmospheric variability such as the NAO or AO [see also *Lohmann et al.*, 2004].

[6] Over the Arctic, multidecadal-scale variations could significantly modulate the 'fast' physical processes in the large-scale Arctic atmospheric circulation, Arctic ocean, sea ice, and interactions among them that operate predominantly on timescales from weeks to a few years [*Polyakov et al.*, 2003]. Earlier, *Polyakov and Johnson* [2000] demonstrated that both the multidecadal oscillation and a decadal-mode associated with the AO were uniquely positive in the early 1990s which synchronously acted to produce conditions over the Arctic with extremely high positive vorticity and a prolonged cyclonic circulation regime in the central Arctic. As a result, the anomalously low atmospheric SLP, above normal SAT and rapid reduction of Arctic ice thickness observed during the early 1990s could be explained by the co-variations of these natural climatic oscillations.

[7] In this letter, we present a wavelet analysis of Arctic SAT anomalies showing that variations in TSI can explain a larger amount of the observed multidecadal variability than increases in atmospheric $CO_2$. Although multidecadal variations in TSI are focused in this first study, we wish to emphasize that solar irradiance forcing appears concurrently in the TSI and the related UV irradiance. We further assume that solar UV irradiance forcing, which intrinsically has much larger amplitude of variation in the decadal band than TSI, may be more effective in generating and modulating responses on decadal timescale, while the multidecadal and longer-term responses over the Arctic are more likely associated with the persistent forcing by TSI.

## 2. Data and Methods

[8] The composite Arctic-wide SAT anomaly (relative to the 1961–1990 mean) was constructed by *Polyakov et al.* [2003] using data from coastal land stations northward of 62°N, Russian drifting stations around North Pole, and drifting buoys from the International Arctic Buoy Programme. Both the annual mean and seasonally-averaged data series are studied and interpreted here. The annual TSI data are the composite record constructed by *Hoyt and Schatten* [1993] (and update from D. Hoyt, 2005) utilizing all five historical proxies of solar irradiance including sunspot cycle amplitude, sunspot cycle length, solar equatorial rotation rate, fraction of penumbral spots, and decay rate of the 11-year sunspot cycle. The annual values of global $CO_2$ mixing ratios are taken from the estimates given by the NASA GISS's climate modeling group at http://www.giss.nasa.gov/data/simodel/ghgases/.

[9] A wavelet transform was applied to reveal the multiscale characteristics of both the TSI and Arctic-wide SAT records. The specific version of the wavelet transform used in all the analyses presented here came from a generalized algorithm, called the gapped wavelet transform, that was designed to calculate the transform self-consistently even for time series with minor data gaps [*Frick et al.*, 2004].

## 3. Results

[10] Figure 1 shows the two plausible co-factors of Arctic SAT's recurring variability and persistent change examined in this paper — the correlation of the annual-mean Arctic-wide SAT with TSI and with atmospheric $CO_2$. Figure 1 suggests that the hypothesis of a $CO_2$-dominated warming of the Arctic is not likely consistent with the large decadal-and-multidecadal warming and cooling signals contained in the Arctic-wide SAT record. For example, although several $CO_2$-forced models may predict a persistently positive trend of the AO index of Arctic atmospheric circulation, *Overland and Wang* [2005] critically pointed out that the most recent 9 years (1996–2004) witnessed mostly neutral or negative AO despite the notable positive AO phase during the 1989–1995 interval earlier.

[11] Table 1 summarizes the correlation between the association of the solar TSI and annual-mean, winter, spring, summer and autumn Arctic SATs both for the raw, unfiltered yearly series from 1875–2000 and for the 10-year moving averaged series. The results are not surprising in that the annual-mean SAT series yielded the highest correlation. The relatively higher explained variances for the spring and winter SATs relative to the summer SAT may simply reflect the relatively higher variability during winters and springs and potentially more sensitive responses, because of the sharper temperature gradients between polar and equatorial regions, to any systematic solar irradiance change for these two relatively more solar radiation-deprived seasons over the Arctic. In contrast, no systematic pattern can be uncovered for the correlation between $CO_2$ and seasonal Arctic SAT series.

**Table 1.** Values of Pearson Correlation Coefficient, *r*, for the Correlation of Total Solar Irradiance (TSI) and Atmospheric $CO_2$ Series With Arctic Surface Air Temperatures for Both Yearly and 10-Year Running-Mean Series Over the 1875–2000 Interval

| | Annual Values | | 10-Year Running Means | |
|---|---|---|---|---|
| | TSI | $CO_2$ | TSI | $CO_2$ |
| Annual-mean | 0.64 | 0.44 | 0.89 | 0.47 |
| Winter | 0.54 | 0.32 | 0.83 | 0.38 |
| Spring | 0.53 | 0.44 | 0.88 | 0.64 |
| Summer | 0.41 | 0.28 | 0.77 | 0.41 |
| Autumn | 0.50 | 0.32 | 0.80 | 0.32 |

[12] The atmospheric $CO_2$ series explained roughly 8–22% (with one outlying explained variance of 41% for spring SAT) of the Arctic SATs (see Table 1). These explained variances by $CO_2$ are much less when compared to well over 75% of the 10-year running means of the Arctic annual-mean and spring SATs explained by the correspondingly smoothed TSI forcing factor. Any formal attempt to assert physical significance in such correlations is unwarranted since the true degree of freedom is neither known nor verifiable without additional physical insights. But if the effective degrees of freedom for the correlations over the past 115–125 years were at least 20, then all of the TSI correlations with Arctic SATs in Table 1 would be statistically significant at a 95% or higher level of confidence.

[13] Figure 2 shows the time-frequency distribution of wavelet coefficients and the time-averaged wavelet spectra for all series with significant power concentrated in the decadal (5–15 years) and multidecadal (40–80 years) timescales. To avoid both excessive crowding in the presentation and over-interpretation of wavelet time-frequency results, contours are plotted only for the three highest (or potentially physically meaningful) values. Significant trend powers exist at the longest timescale (unresolved, of course, but taken here to be the full length of data record of about 120 years) for both the solar TSI and Arctic SAT series. These results suggest the plausible interpretations of Arctic SATs as broadband responses and also clearly show that the TSI change over the 1875–2000 is best considered as an external forcing factor with very broadband characteristics. Such an interpretation sharply contrasts a linear one-to-one forcing-response relationship that assumes interactions on narrow spectral bands or frequencies, which often is used to evaluate a sun-climate link.

[14] Figure 3 shows the reconstructed Arctic SATs accounting for variations on the decadal (5–15 years), multi-decadal (40–80 years), and the longest trend scales by inverse wavelet transform. The residual series, shown in column 3 of Figure 3, are dominated by interannual variations and confirm that reconstructed series captured the Arctic SAT records well with variations from the three broadband scales. Results for the reconstructed SATs on individual scales suggest comparable magnitude contributed by both the decadal and multi-decadal variations in each record in the order of 0.5 to 1.0°C. Multi-decadal-scale variations are also entering the warming phase toward the end of the analyzed record at 1999–2000. This has implication for interpretation of further Arctic change and, in fact, offers a testing ground for data from 2001–2005, which were not analyzed here.

[15] Figure 3 also suggests an important role for the underlying warming trend line to explain the longest term changes in Arctic SATs over the 1875–2000 interval. It should be noted that the relatively large spring warming trend observed over the 1875–2000 interval, but in similar magnitude to trends for both winter and autumn SATs, is not consistent with the predicted scenarios of large summer sea-ice melt and maximum autumn and early winter warming trends by increasing anthropogenic $CO_2$ in the air. *Przybylak* [2000] has earlier hypothesized that the strong positive sea ice-albedo-temperature feedback expected from enhanced greenhouse effect is "as yet play only a minor role" in "enhancing" Arctic temperatures. Furthermore, several latest estimates of Arctic SATs from 1981 to 2003 [e.g., *Overland and Wang*, 2005] suggest contradictory winter cooling trends, especially over the Arctic sector from Barents to Chukchi Seas, that are not

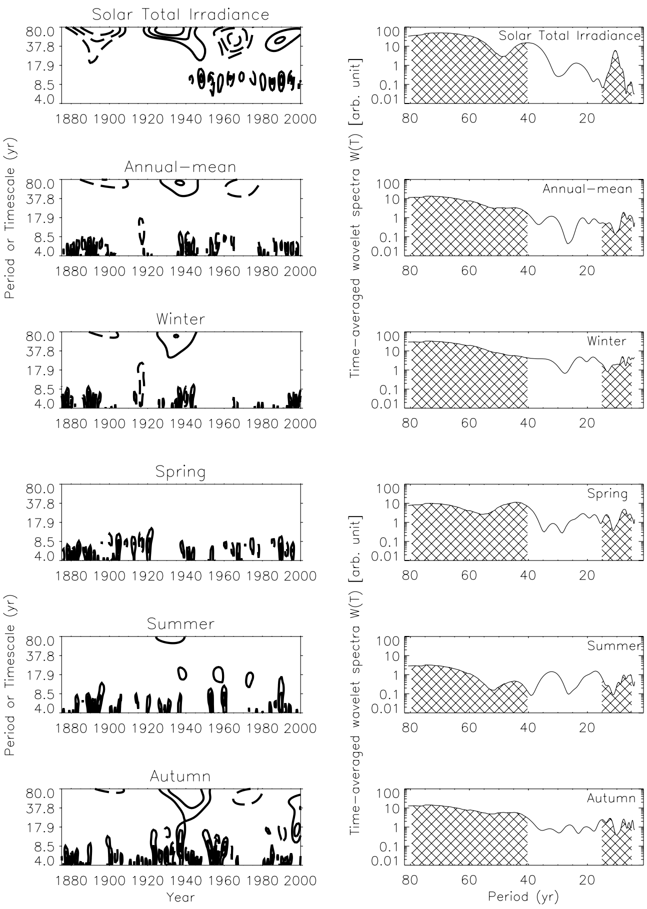


**Figure 2.** The time-frequency distribution of wavelet coefficients (left column) and the time-averaged wavelet spectra (right column) for all series. Negative contours/anomalies are dashed. Hatched areas under the time-averaged wavelet spectra are the broadband decadal (5–15 years) and multidecadal (40–80 years) forcing and response interaction scales assumed for the solar irradiance-Arctic SAT correlations studied here.

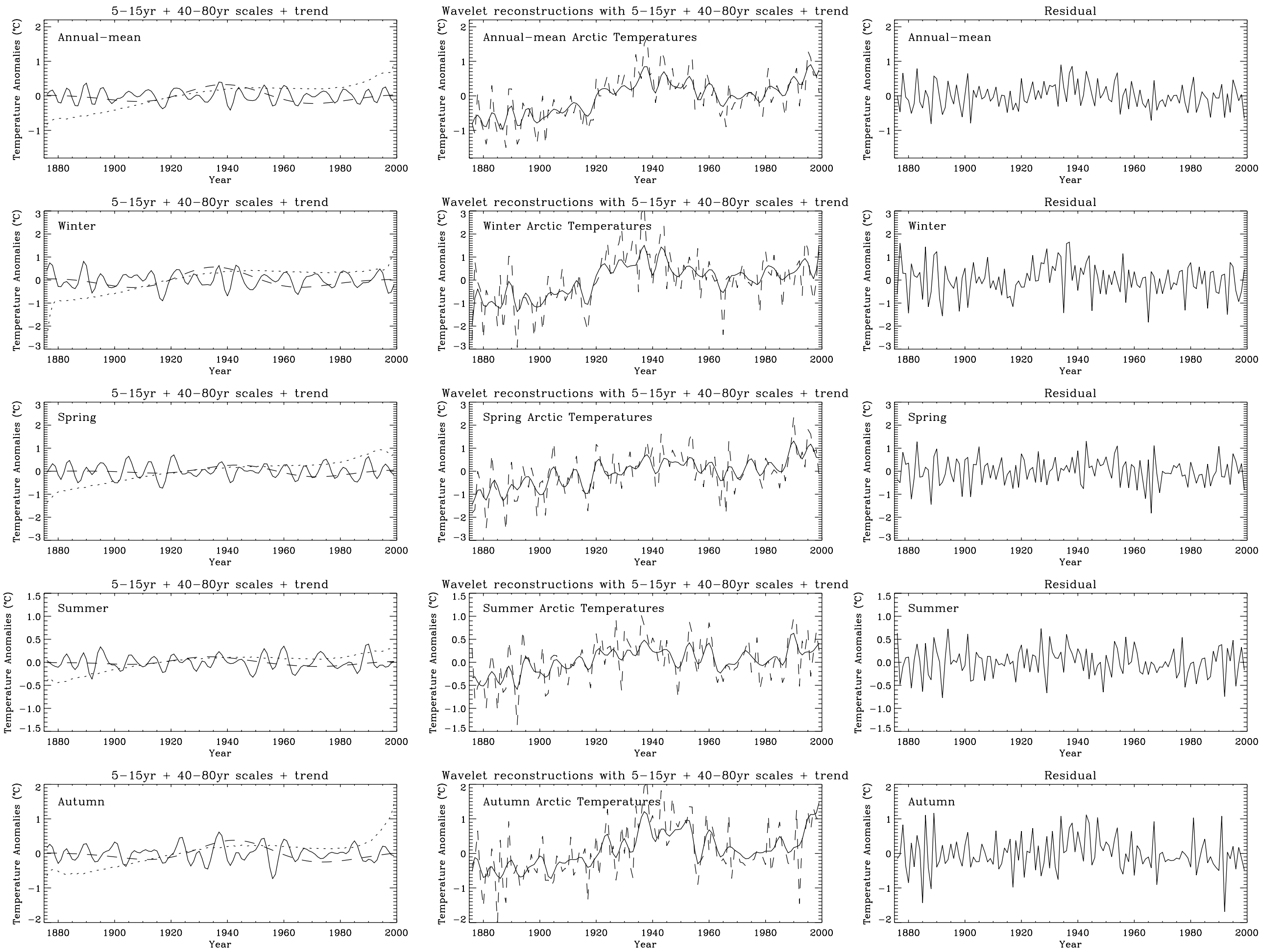

**Figure 3.** Reconstructed Arctic SAT anomalies accounting for variations on the decadal (5–15 years; solid lines), multidecadal (40–80 years; dashed lines) and the trend (dotted lines) scales by inverse wavelet transform. The results are shown individually in column 1, as the reconstructed sum (solid lines and original raw temperature records shown as dashed lines) in column 2, and as the residual between the original raw series and the wavelet reconstructed series in column 3.

easily reconciled with accelerating winter warming from anthropogenic $CO_2$ forcing.

## 4. Conclusions

[16] Two main results highlight the need for further research towards the proper quantitative evaluation of the hypothesis that multi-decadal- and longer-term variations of solar irradiance may provide significant forcing of Arctic-wide SATs through modulations on the operation regimes of the large-scale atmospheric circulation, ocean and sea ice over the Arctic. These results are the following:

[17] (1) Solar forcing explains well over 75% of the variance for the decadally-smoothed Arctic annual-mean or spring SATs, and

[18] (2) Time-frequency characteristics for the annual-mean or seasonally-averaged Arctic SATs are consistent with similar wavelet structures derived for the TSI forcing.

[19] In contrast, a $CO_2$-dominated forcing of Arctic SATs is inconsistent with both the large multidecadal warming and cooling signals and the similar amplitude of warming trends between cold (winter) and relatively warmer (spring and autumn) seasons found in the Arctic-wide SAT records.

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