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Solar irradiance modulation of Equator-to-Pole (Arctic) temperature gradients: Empirical evidence for climate variation on multi-decadal timescales

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ABSTRACT

Using thermometer-based air temperature records for the period 1850–2010, we present empirical evidence for a direct relationship between total solar irradiance (TSI) and the Equator-to-Pole (Arctic) surface temperature gradient (EPTG). Modulation of the EPTG by TSI is also shown to exist, in variable ways, for each of the four seasons. Interpretation of the positive relationship between the TSI and EPTG indices suggests that solar-forced changes in the EPTG may represent a hemispheric-scale relaxation response of the system to a reduced Equator-to-Pole temperature gradient, which occurs in response to an increasing gradient of incoming solar insolation. Physical bases for the TSI-EPTG relationship are discussed with respect to their connections with large-scale climate dynamics, especially a critical relationship with the total meridional poleward energy transport. Overall, evidence suggests that a net increase in the TSI, or in the projected solar insolation gradient which reflects any net increase in solar radiation, has caused an increase in both oceanic and atmospheric heat transport to the Arctic in the warm period since the 1970s, resulting in a reduced temperature gradient between the Equator and the Arctic. We suggest that this new interpretative framework, which involves the extrinsic modulation of the total meridional energy flux beyond the implicit assumptions of the Bjerknes Compensation rule, may lead to a better understanding of how global and regional climate has varied through the Holocene and even the Quaternary (the most recent 2.6 million years of Earth's history). Similarly, a reassessment is now required of the underlying mechanisms that may have governed the equable climate dynamics of the Eocene (35–55 million years ago) and late Cretaceous (65–100 million years ago), both of which were warm geological epochs. This newly discovered relationship between TSI and the EPTG represents the "missing link" that was implicit in the empirical relationship that Soon (2009) recently demonstrated to exist between multi-decadal TSI and Arctic and North Atlantic climatic change.

1. Introduction

A study of Sun–climate relationships is, in the strictest sense, a search for self-consistent dynamic evidence that connects variable solar magnetic activity with robust measures of regional- and hemispheric-scale climate and other relevant variables including surface and atmospheric temperature and precipitation (see Weng, 2005; Soon, 2009; Gray et al., 2010; Soon et al., 2011; Weng, 2012a,b for a broad overview and relevant references). To understand large-scale ocean–atmosphere circulation dynamics and their impact on climate, many authors stress the importance of Equator-to-Pole temperature gradients and heat fluxes as fundamental and robust expressions of the Earth's coupled land–ocean–atmosphere climate system (*e.g.*, Stone, 1978; Farrell, 1990; Lindzen, 1994; Jain et al., 1999; Pierrehumbert, 2002; Enderton and Marshall, 2009; Vallis and Farneti, 2009; Lee et al., 2011; Huang et al., 2012; Karamperidou et al., 2012; Rose and Ferreira, in press; Weng, 2012a). Building on this research, our study provides empirical evidence for a physical relationship between varying total solar irradiance (TSI) and the Northern Hemispheric Equator-to-Pole Temperature Gradient (EPTG), based on instrumental data records and extrapolative analyses. This new empirical evidence may constitute the "missing link" suggested by earlier research that showed an empirical link between TSI and Arctic and North Atlantic climatic changes (Soon, 2009).

It is our thesis that the observed relationship between TSI and EPTG represents the large-scale thermal and dynamic relaxation

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response of the coupled ocean–atmosphere climate system to the externally imposed multi-decadal variation in solar irradiance. Although known changes in TSI are not exceptionally large (on the order of a few tenths of a percent of the TSI over the last 400 years), they are sufficient to constitute an actual change in the total radiant energy added or subtracted to the climate system. Rather than being a mere redistribution of shortwave radiation energy, as in the case of Sun–Earth orbital changes that have been well-studied for the warm interglacials and ice ages of the quaternary (Laskar et al., 1993, 2011), the possibility exists for a direct increase or decrease in the total poleward energy transport. This implies that both the oceanic and atmospheric heat transports can simultaneously increase or decrease as a result of variations in TSI.

Latitudinal insolation gradients are the key drivers and/or modulators of the differential latitudinal temperature gradients. Moreover, the varying latitudinal distribution of insolation in response to orbital changes at Milankovitch frequencies also played a dominant role in controlling climate change during the Holocene and the glacial-interglacial changes of the Quaternary (Raymo and Nisancioglu, 2003; Kukla and Gavin, 2005; Liu et al., 2008; Davis and Brewer, 2009).

Our hypothesis is testable by measurement and compilation of the key physical signatures of ocean and atmosphere heat transport. These empirical data can then be compared with the implicit assumptions of the Bjerknes compensation, which assumes the maintenance of a constant total poleward energy transport that then provides an internally self-regulating inverse relation between oceanic and atmospheric heat transport fluxes (Bjerknes, 1964; Shaffrey and Sutton, 2006; Enderton and Marshall, 2009; Rose and Ferreira, in press; Zelinka and Hartmann, 2012). We discuss the available empirical evidence from actual oceanographic observations and assimilated atmospheric and oceanic circulation, and thermal conditions from climate models, which together suggest the possibility that a simultaneous increase in poleward oceanic and atmospheric heat transport did in fact occur during the most recent warming period since the mid-1970s.

From theoretical formulations, Stone (1978) isolated the ‘solar constant’ as one of the most important drivers of the total meridional heat transport, and also one that is largely independent of the dynamical adjustment processes internal to the Earth climate system. Enderton and Marshall (2009), however, cautioned that Stone (1978)’s general conclusion should be modified to incorporate changes in the meridional gradients of albedo under the scenario of cold climate regimes that are associated with significant changes in polar ice cap size and sea-ice cover. Donohue and Battisti (2012) estimated that for the current climate, the direct meridional distribution of incident radiation contributed about 65% of the absorbed solar radiation, while the 35% contribution from net planetary albedo is apportioned to be 30% by atmospheric reflection and only 5% by surface reflection. Using numerical models in relation to the effects of ocean geometry, Vallis and Farneti (2009) have attempted an even more general exploration of the properties of meridional energy transport oceanic diapycnal diffusivity, moisture content of the atmosphere, distribution of solar radiation, and the rotation rate of the Earth. Importantly, Vallis and Farneti (2009) concluded that there is no *á priori* constraint on the total meridional heat transport in the coupled ocean–atmosphere system of the Earth. In other words, to gain a more complete and correct interpretation of the available instrumental and proxy records of climatic variations, it may be necessary to relax the assumption of the Bjerknes compensation for poleward atmospheric and oceanic heat transport.

In this regard, our discussion sheds light on similar queries raised in the recent review by Wunsch (2010, p. 1965): “What [is] surprising is that one rarely if ever sees the question raised as to how the global heat budget is then maintained [if the meridional oceanic heat transport is diminished]? Does the atmosphere respond by increasing its transport – getting warmer and/or wetter – as in Bjerknes (1964) compensation?” These are important fundamental questions that we seek to answer.

Turning to hydrological effects of changing TSI, Agnihotri et al. (2011) proposed the time derivative of TSI as a relevant metric for studying hydrologic changes and variations. Kukla and Gavin (2005) argued for the importance of the intensification of the hydrologic cycle, both through an increased meridional insolation gradient and through warming of tropical oceans and cooling of the polar regions. They argued that these processes control the inception of major glaciation in Northern Hemisphere land areas, including the Last Glacial Maximum. Such a physical boundary condition (*i.e.*, the persistent increase in the meridional insolation gradient as a result of a specific Sun–Earth orbital configuration) for high northern latitude glaciations can be expected for Sun–Earth orbital configuration of low obliquity coinciding with perihelion in Northern Hemisphere winters. Davis and Brewer (2011) proposed a new framework to encompass all sources of changes in the latitudinal insolation gradient, noting that orbital, solar-, and lunar-induced forcings are all strongly connected to the atmospheric and oceanic circulation of the Earth system. Our study supplements this important discussion by identifying a more realistic physical constraint on TSI. In this context, the framework of Davis and Brewer could add a fresh insight to the underlying mechanisms and feedbacks governing the Equable climate dynamics[1] of the Eocene (35–55 million years ago) and late Cretaceous (65–100 million years ago) warm epochs (*e.g.*, Sluijs et al., 2006; Greenwood et al., 2010; Eberle and Greenwood, 2012; Kroeger and Funnell, 2012; Pross et al., 2012). Observations suggest that the direct modulation of the total ocean–atmospheric meridional heat transport by changes in TSI is rooted in the intrinsic variability of the Sun’s magnetic activity. Therefore, our proposed mechanism provides an efficient and realistic way to warm the high-latitude polar regions and mid-latitudes that does not create concomitantly large temperature changes in the tropics. To explain the Early Eocene warming, for example, Huber and Caballero (2011) were forced to postulate perhaps unrealistic atmospheric CO_2 levels of 2240 or even 4480 ppm for the Early Eocene (see Hong and Lee, 2012 on the paleo-CO_2 constraints of no more than 1500 ppm) that warmed not only the Arctic and Antarctic regions but also the tropics significantly (up to 40–50 °C were simulated in the tropics). We may add that with the new palynological evidence that confirms mild winter temperatures greater than 10 °C at Wilkes Land coast, Antarctica during the early Eocene epoch (Pross et al., 2012), our hypothesis of an efficient TSI-induced modulation and control of the Equator-to-Pole heat transports should be seriously considered.

2. TSI and Northern Hemisphere EPTG data: sources and physical motivations

The solar radiation parameter adopted here is based on the comprehensive reconstruction of total solar irradiance (TSI) by Hoyt and Schatten (1993), which derives from multiple solar activity proxies (see discussion below). Scafetta and Willson

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[1] Farrell (1990) pointed out that the thin Earth’s atmosphere is remarkably effective in transferring heat between the equator and pole. Without the poleward dynamic heat flux and heat flux divergence, the Equator-to-Pole temperature gradient is estimated to be 109 °C with a very warm equator of 50 °C. Farrell notes that because of the short (less than monthly) time scale of radiative forcing in a non-rotating atmosphere, EPTG should be even much smaller than what is observed today. Thus, the puzzle for the Earth’s climate system is indeed “not that equable climates occur, it is that they are not the norm.” (*p.* 2987)

(2009, 2012, private communication) have updated and re-scaled this TSI series through 2010. Note that since 1979, satellite-based cavity radiometers have measured the absolute level of TSI to lie between 1360 and 1375 W m^{-2}, while physical modeling yields a theoretical value of 1379.9 W m^{-2} (Fontenla et al., 2011). We have used the newer value of TSI obtained by ACRIM-3 (Active Cavity Radiometer Irradiance Monitor-3) which indicates that from 1979 to 2011, TSI ranged between 1360 and 1363 W m^{-2} (Willson, 2011). This value is consistent with the suggested calibrated values of about 1361 W m^{-2} by the PREMOS (Precision Monitoring Sensor onboard the PICARD satellite mission) experiments (W. Schmutz, 2012, private communication[2]) and also with the value of 1360.8 ± 0.5 W m^{-2} estimated by Kopp and Lean's (2011) total irradiance monitor (TIM). Based on their comprehensive nature, we believe the estimates from Hoyt and Schatten/Scafetta and Willson to be the most reliable estimates of TSI currently available (see further discussion below).

The impact of uncertainties in the absolute value of TSI on globally averaged surface air temperature, or on the derived EPTG, is not discussed in detail here. Nevertheless, an acknowledgment of the uncertainty in TSI is a prerequisite for the proper assessment of the dynamic evolution of the weather–climate system. In addition, knowledge regarding the long-term variation in solar spectral irradiance (*e.g.*, see discussion of the impacts of solar UV variations on the response of the coupled stratosphere-troposphere chemistry and dynamics in Soon, 2009; Gray et al., 2010; Hood and Soukharev, 2012), such as reported by Fontela et al. (2011), must be incorporated into future studies to progress our understanding of Sun–climate relationships.

Before 1979, TSI was reconstructed using proxies for solar magnetic activity and its variability, including empirical results from long-term monitoring of Sun-like stars (Baliunas et al., 1995; Lockwood et al., 2007; Hall et al., 2009). Our reason for choosing the TSI reconstruction from Hoyt and Schatten (1993) is mainly because their work involves the most diverse types and ranges of proxy values for solar irradiance estimation—sunspot cycle amplitude, sunspot cycle length, solar equatorial rotation rate, fraction of penumbral spots, and the decay rate of the approximate 11-year sunspot cycle. Their assumption was that each of these slightly different proxies will most likely capture some part of the underlying factors responsible for modulating the solar magneto-convection-induced processes that affect TSI. In an *á priori* sense, we note that all these magneto-fluid dynamical processes on the Sun need not strictly follow an 11-year-like cycles of high-and-near-zero in sunspot numbers as that specified artificially by the paleoclimate modeling community (see Figure 5 of Schmidt et al., 2011). We judge that this multi-proxy approach to TSI reconstruction is more likely to be consistent with the physical modeling of solar irradiance outputs of Fontenla et al. (2011), who adopted as many as nine solar features[3] describing the range of magnetic fields in the networks and active regions. Moreover, the TSI reconstruction by Hoyt and Schatten (1993) may facilitate a more self-consistent study of the multidecadal modulation of the EPTG because the solar equatorial rotation rate exhibits considerable change in the early 20th century (see Figure 1 of Hoyt and Schatten, 1993).

Moreover, the TSI reconstruction of Hoyt and Schatten (1993) using multiple solar-variability proxies is more consistent with the work of Fontenla et al. (2011) than other TSI reconstructions, which are often based on a model with sunspot blocking and faculae brightening, or alternatively, are based solely on geomagnetic activity indices. Evidence suggests that even the “quiet” part of the Sun may simply consist of small-scale magnetic fields that vary in both mean strength and spatial distribution which in turn may or may not relate to the dark magnetic spot activity variations (Caccin et al., 1998; Schuhle et al., 2000; Trujillo Bueno et al., 2004; Orozco Suarez et al., 2007; Kleint et al., 2010; Schnerr and Spruit, 2011; Orozco Suarez and Rubio, 2012; Stenflo, 2012; Stenflo and Kosovichev, 2012).

It is relevant to note that in Shapiro et al. (2011), the amplitude of the total solar irradiance change between the Maunder Minimum and current conditions was determined to be 6 ± 3 W m^{-2}—a value significantly larger than estimates by some other authors but in good agreement with the estimate of Zhang et al. (1994), based on their study of the Sun and other Sun-like stars. The results of Shapiro et al. (2011) are consistent with the amplitude of total solar irradiance used here that was deduced independently by Hoyt and Schatten (1993). Another recent paper by Judge et al. (2012), however, argued that the TSI estimates by Shapiro et al. (2011) may have been overestimated by a factor of two which further adds to the uncertainty to the correct estimate for the amplitude of TSI variations over the past 400 years.

Instead of using mean global air temperature, as is the usual choice, our primary motivation for considering the EPTG is that EPTG constitutes a more fundamental description/expression of the global climate system and of climate dynamics in general (see Lindzen, 1994; Karamperidou et al., 2012; Weng, 2012a). Lindzen (1994) interpreted the global mean surface temperature to be simply a residual product of the change in the Equator-to-Pole temperature distribution while, importantly, the EPTG contains more useful information on climate dynamics than does the global mean air temperature. The new theoretical analyses by Rose and Ferreira (in press) tend to support this interpretation. Furthermore, Karamperidou et al. (2012, p. 4156) highlighted the fact that “the magnitude of the post-1976 trend of [EPTG] is not as striking as the one of the global mean temperature anomalies during the same period … rather, it is comparable to [the EPTG] of the 1870–1940 period.” A recent study of sea-level pressure and sea surface temperature by van Loon et al. (2012) identifies a relatively steeper pressure and temperature gradient between the Arctic and lower latitude regions of the Atlantic during the 1878–1944 interval compared to the much weaker or reduced gradient at the 1944–2008 period. van Loon et al. (2012) interpreted this result to indicate the clear dependence of the surface pressure and temperature gradients (and hence the strength and intensity of the quasi-stationary wave and baroclinic eddies in the North Atlantic region) on the phases of the 80–100 years Gleissberg solar activity cycles.

We also note that the derived EPTG may offer a superior interpretation and attribution of the processes responsible for the changes in global air temperature that have been observed since 1976. The EPTG probably is the best available index/proxy for the 1979–1998 warming, especially when one considers the great complexity and difficulty involved in removing potential non-climatic or socio-economical influences from the surface thermometer data records (*e.g.*, McKitrick and Michaels, 2007; Fall et al., 2011; McKitrick and Tole, 2012).

3. Calculation of the EPTG

To calculate the EPTG indices, we have modified the method used by Jain et al. (1999) and Karamperidou et al. (2012) by deleting the areal weighting. Our rationale is that we are interested in the gradient that exists in the meridional direction only.

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[2] Werner Schmutz is PI of PREMOS/PICARD; this also was noted on page 5 of the PMOD/WRC 2010 Annual Report.

[3] These features are (1) dark quiet-Sun inter-network, (2) quiet-Sun inter-network, (3) quiet-Sun network lane, (4) enhanced network, (5) plage (that is not facula), (6) facula (*i.e.*, very bright plage), (7) sunspot umbra, (8) sunspot penumbra and (9) hot facula.

Thus, each latitudinal band is averaged in the zonal direction and the EPTG is calculated as the slope of these zonal averages. Mathematically, this is equivalent to an unweighted regression slope

$$EPTG = \frac{\sum_{i=1}^{n} (T_i - \overline{T}) \left(\theta_i - \overline{\theta}\right)}{\sum_{i=1}^{n} \left(\theta_i - \overline{\theta}\right)^2} \tag{1}$$

where θ_ι is the latitude and T_i is the temperature of the ith zonally averaged grid box (n total boxes) and the overbar indicates a hemispheric/latitudinal band average. The summation holds over all the 72 × 18 longitude-latitude boxes available from the gridded 5° × 5° surface air temperature database of the University of East Anglia. By including latitudinal weights to account for areal averaging, as applied by Jain et al. (1999), the tropics are given undue and unwarranted influence (*i.e.*, one-half of the Northern Hemisphere lies between 0° and 30°N) which obscures the true meridional gradient. Again, we stress that we are interested in computing the Equator-to-Pole temperature *gradient*, which is independent of the decreasing area toward the Pole. Thus, the areal weighting used by Jain et al. (1999) and Karamperidou et al. (2012) is not appropriate for our analysis and has been removed.

Other formulations of the EPTG exist (see Figure 5 of Davis and Brewer, 2011). Gitelman et al. (1997) defined their 'meridional temperature gradient' as the difference in temperature between the 30° to 35° latitudinal band and the 50° to 55° latitudinal band, later changing this to range between the 0° to 25° latitudinal band and the 65° to 90° latitudinal band (Rind, 1998; Gitelman et al., 1999). Braganza et al. (2003) defined the EPTG as the temperature difference between the 22.5° and 37.5° latitudinal band and the 52.5° to 67.5° latitudinal band. We argue that the calculation of a hemispheric slope is preferable to the rather arbitrary selection of latitudinal bands for, as Gitelman et al. (1999, p. 16,709) noted, the EPTG "is sensitive to the choice of latitudes used to define it" with "substantial differences in behavior on timescales from interannual to multidecadal." These points also are well-taken by Jain et al. (1999), who note that observational data are sparse poleward of about 70°N and equatorward of about 15°N, which adversely affects the calculation of the gradient. To remedy this, we have further examined the gradient from 0° to 30°N, 30°N to 60°N, and 60°N to 90°N, in addition to the entire hemisphere, to identify relative contributions and to examine data inconsistencies in these regions. Note too that these other formulations of the EPTG are consistent with our modification of Jain et al. (1999) to remove the adjustment for the decreasing area toward the Pole.

An arguably better measure of the EPTG – calculation of the temperature difference between the tropical surface and the polar upper-troposphere/tropopause – was proposed by Lindzen (2012). Lindzen's argument is that this metric better measures the meridional transport of heat along isentropic surfaces (see Figure 10 of his paper) as poleward transport of energy occurs through baroclinic eddies. We will examine this measure and its relationship to TSI in a subsequent paper.

Monthly, seasonal, and annual mean values of the EPTG were calculated using the gridded 1850-to-2010 instrumental surface temperature record available from the University of East Anglia's Climatic Research Unit (HadCRUT3—Brohan et al., 2006; Rayner et al., 2006; downloaded 16 August 2009). We place less emphasis on the early part of the record (prior to 1920) due to the sparseness of the data; most notably, poor spatial sampling in the Arctic region. It is worth noting that other researchers have also limited their analysis to exclude the early years—Gitelman et al. (1999) started after 1854, while Gitelman et al. (1997), Rind (1998), and Braganza et al. (2003) began in 1880 and Jain et al. (1999) began in 1898. Although other observational databases could have been used, Gitelman et al. (1999) achieved nearly identical results using both HadCRUT3 data and the GISS dataset (Hansen and Lebedeff, 1987). Details of our computation of EPTG metric, and the sensitivity and comparison of the metric with other data records (*i.e.*, the 20th century reanalysis of Compo et al., 2011, and the University of Alabama-Huntsville MSU lower troposphere temperature dataset) will be reported in a separate paper.

To emphasize multi-decadal variation, a 10-year running mean filter was applied to the raw EPTG series only (but not to the TSI series). We further note that our main focus is to study physical relationships between solar irradiance and climate dynamics on multidecadal timescales and a 10-year running mean filter specifically avoids effects related to short-term weather variability. Soon (2009) and Soon et al. (2011) provide additional physical arguments for separation of the multidecadal-to-centennial scale variability from weather variability. Note that the TSI series is not smoothed as there is a strong 11-year solar cycle that might be aliased into lower frequency signals if it were smoothed. Ultimately, the distinction between the so-called "top-down" solar forcing-climatic response scenario from the "bottom-up" scenario will be likely important and useful. This is because the "bottom-up" solar-climatic connection pathway may operate more efficiently and dominantly in the multidecadal to centennial timescales while the "top-down" scenario will more obviously manifest under the powerful control of the 11-year solar irradiance contrasts between the 11-year solar activity maxima and minima (see Hood and Soukharev, 2012; van Loon and Meehl, 2012 and references therein).

It is important to note that since the HadCRUT3 data are anomalies from a standard period, our values of the EPTG are anomalies from the average Equator-to-Pole temperature gradient, which is strongly negative (*i.e.*, the Pole is colder than the Equator) and on the order of −0.5 °C/degree latitude. Positive values therefore indicate gradients which are less negative (warmer Pole and/or colder Equator) while negative values indicate an enhanced EPTG (warmer Equator and/or colder Pole).

Correlation can be problematic when temporal autocorrelation is high, as is often the case with many environmental variables (*e.g.*, Yue et al., 2002; Hamed, 2009; 2011). Yue et al. (2002) and Hamed (2009, 2011) argue that non-parametric correlation coefficients such as Spearman's Rho (Spearman, 1904) or Kendall's Tau (Kendall, 1938) are preferable to the often-used Pearson's Product–Moment Correlation Coefficient. We agree with such concerns and, to remedy this potential problem, we have employed both the coefficient of determination (*i.e.*, the square of the Pearson product-moment correlation coefficient) and Kendall's Tau to judge the magnitude of the statistical correlation. In addition, we have limited the correlation analysis to the period from 1880 to 2010 to reduce the impact of the early, data-sparse years (*i.e.*, 1850–1879).

Due to serial autocorrelation in the data, assessment of statistical significance must include its effect on the coefficients. Here, we use an 'effective sample size' to accommodate temporal autocorrelation by augmenting the 'effective degrees of freedom' (see Laurmann and Gates, 1977; Thiebaux and Zwiers, 1984). Rather than simply using the total number of years minus one as the degrees of freedom, autocorrelations determined that independence occurred at a lag of 14 years. This reduced our 'effective sample size' to 10 rather than the 131 years of the record (*i.e.*, 1880–2010). Thus, the 'effective degrees of freedom' that we used to assess statistical significance reflects this smaller sample size.

4. Results and discussion

The relationship between the TSI and the annual-mean Northern Hemisphere EPTG over the instrumental surface air temperature period from 1850 to 2010 (Fig. 1) shows that variation in TSI can

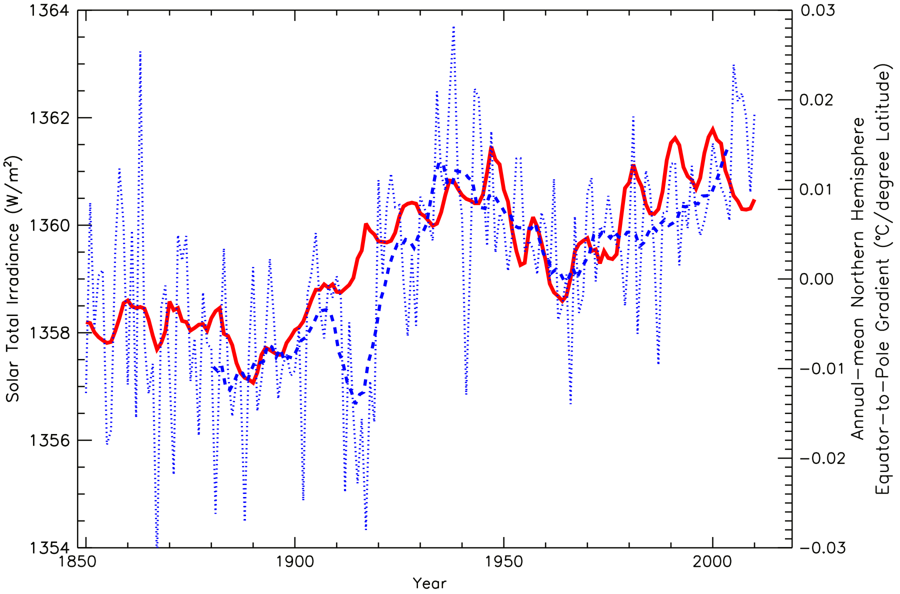

Fig. 1. Annual-mean EPTG over the entire Northern Hemisphere (°C/degree latitude; dotted blue line) and smoothed 10-year running mean (dashed blue line) *versus* the estimated total solar irradiance TSI (W m^{-2}; solid red line) of Hoyt and Schatten (1993; with updates by N. Scafetta) from 1850 to 2010. We emphasize the relationship especially on multi-decadal timescales and report the TSI correlations only with the smoothed EPTG series with 10-year running means (since 1880) in Table 1. Increased TSI is related to decreased temperature gradients between the Equator and the Arctic (*i.e.*, more positive EPTG values) and *vice versa*. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Table 1

Square of the Pearson product-moment correlation coefficient (*i.e.*, the coefficient of determination) and Kendall's Tau non-parametric correlation coefficient between total solar irradiance (TSI) and Northern Hemispheric EPTGs (smoothed by a 10-year running mean) from 1880 to 2010 (1850–1879 was discarded for analysis due to a lack of data reliability).

	Coefficient of determination				**Kendall's Tau**			
	0–30°	**30–60°**	**60–90°**	**0–90°**	**0–30°**	**30–60°**	**60–90°**	**0–90°**
Annual-mean	0.04	0.37	**0.50***	**0.70***	0.11	0.42	**0.53***	**0.63***
Winter	0.34	0.22	**0.48***	**0.57***	0.36	0.24	0.42	**0.54***
Spring	0.17	0.45	0.16	**0.62***	0.23	**0.47***	0.30	**0.58***
Summer	0.27	0.01	0.42	**0.60***	−0.31	0.03	0.38	**0.51***
Autumn	0.00	0.12	0.36	**0.50***	0.02	0.24	**0.52***	**0.53***

Values that are statistically significant at a Type I error level of 0.05 using an 'effective degrees of freedom' of 10 are denoted by an asterisk (see text).

explain 36% of the yearly mean EPTG with Kendall's Tau of 0.43. The explained variance increases to 70% and Kendall's Tau increases to 0.63 when a 10-year running mean is applied to smooth the EPTG (which accentuates multi-decadal-scale variation; see Table 1). Soon (2009) and Soon et al. (2011) have previously shown that variability at multi-decadal timescales on the order of 40–80 years is prominent in most solar and climatic records.

Fig. 2 offers evidence that the multi-decadal variation in the Northern Hemisphere EPTG is more prominently expressed in the 60°N–90°N zonal band, with most of the variability in the Northern Hemisphere EPTG being caused by the variability in the polar region (*i.e.*, 89% of the variance explained in the 10-year smoothed time-series). This strong latitudinal dependence of the TSI-EPTG relation is expected owing to relatively faster thermal responses at the 60–90°N bands than the mid-latitude (30°N–60°N) and tropical (0°–30°N) bands. The statistical analyses reported in Table 1, however, suggest that the correlations between TSI and latitudinal surface temperature gradients computed over the midlatitude bands (30°N–60°N), especially for the spring season, are also statistically robust and hence physically plausible. We note that the lack of statistical correlation between the EPTG and TSI within the tropical band (0°–30°N) does not contradict our hypothesis. Consequently, we examine a possible connection between the Northern Hemisphere EPTG and the strength of the northern component of the tropical Hadley circulation as deduced by Liu et al. (2012) below.

When grouped into winter (DJF), spring (MAM), summer (JJA), and autumn (SON), the relationship between TSI and the EPTG shows that despite large interannual variability, multi-decadal-scale oscillations are quite prominent in the winter and spring and, more surprisingly, in summer as well (Fig. 3). About 60% of the variation in the 10-year smoothed EPTG for these three seasons can be explained by the TSI and the value of Kendall's Tau lies between 0.51 and 0.58 (Table 1). Variability at the 40- to 80-year time-scale is well-represented during the summer despite high solar incidence angles over the Northern Hemisphere which should produce weaker temperature contrasts between the tropics and the high Arctic.

The coefficients of determination (*i.e.*, r^2) between TSI and the seasonal air temperature gradients between the Equator and the Arctic are consistent with the results of Soon (2005) and other seasonal energy budget studies of Arctic surface temperatures (*e.g.*, Semmler et al., 2005). Moreover, additional multi-decadal climate signatures have been discovered in the Arctic and

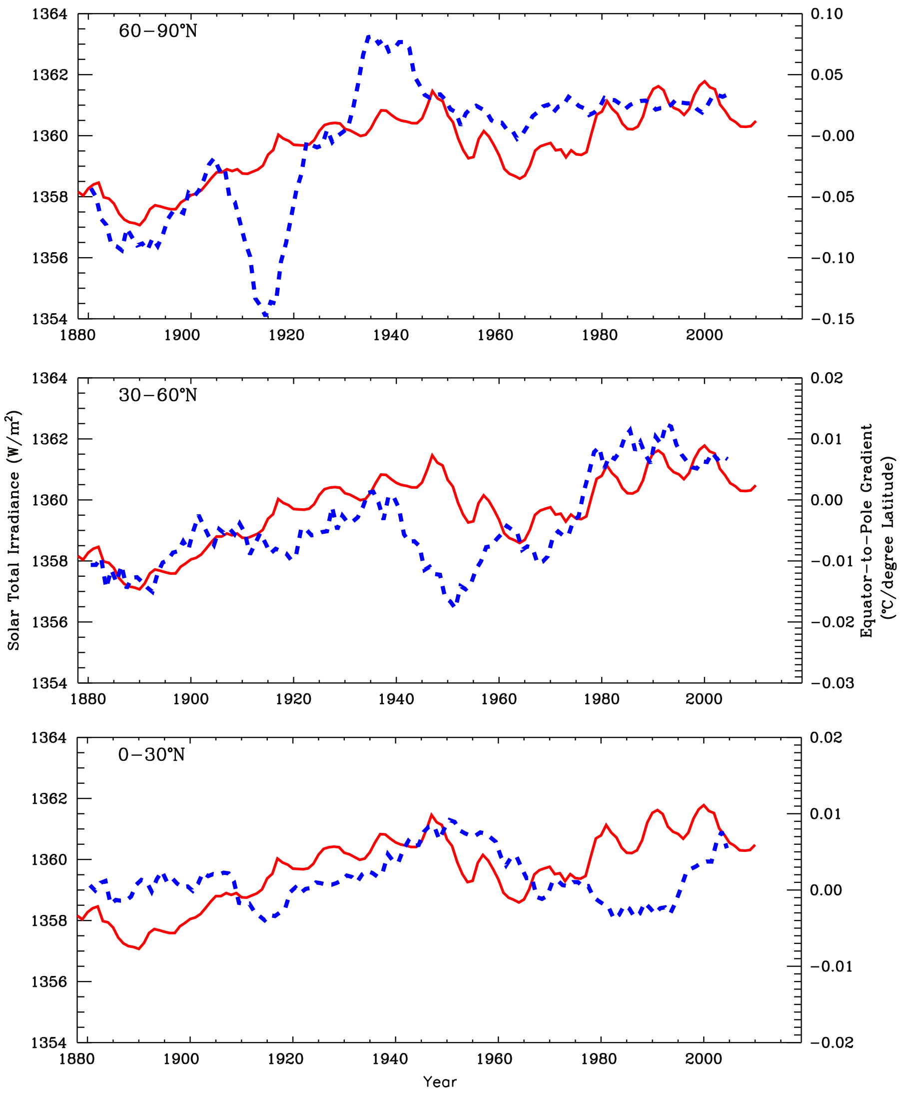

Fig. 2. Northern Hemisphere EPTGs for the three latitude bands: 0–30°N, 30–60°N, and 60–90°N, smoothed by 10-year running means (°C/degree latitude; dotted blue curves) *versus* the estimated total solar irradiance TSI (W m^{-2}; solid red curves) of Hoyt and Schatten (1993; with updates by N. Scafetta) from 1880 to 2010. Increased TSI is related to decreased temperature gradients between the Equator and the Arctic (*i.e.*, more positive EPTG values) and *vice versa*. Owing to the large dynamic range of the surface temperature gradients across the latitudinal bands, the vertical scales in the three latitudinal bands are different in each panel. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

nearby impacted and remotely teleconnected regions (see Soon, 2009; Soon et al., 2011). Soon et al. (2011) found an unexpected multi-decadal summer climate connection with TSI over East Asia that they interpreted as forced by the circum-global teleconnection pattern of summer circulation (Ding and Wang, 2005). We wish to add that the emphasis on summer season-associated climate dynamics may have empirical supports from paleoclimate proxy data where relative variations in summer temperature on multidecadal to centennial timescales are often found to be larger than those during winter season (see *e.g.*, Jiang et al., 2005; Kamenos, 2010). Cohen et al. (2012) described a recent phase of boreal winter cooling between 1988 and 2010 that was likely preconditioned and forced by warming tendencies in the preceding summer and autumn seasons. Alexeev et al. (2012) noted that the persistent 1960s–1980s Arctic cooling tendency in the upper troposphere and lower stratosphere switched to a warming tendency around 1990 (see Figure 7 in their paper). The authors suggest that this switch is consistent with the well-known multi-decadal variations in near-surface-subsurface climatic and oceanographic conditions that dominate the Arctic and North Atlantic. An exciting challenge for the future is to establish a sound model for the physical processes that underlie the observed empirical correlations between TSI and EPTG.

We argue that the strength and physical consistency of the observed Sun–climate relationship suggests strongly that a causal link exists. We have provided evidence that the association between TSI and EPTG may be more than just a random chance occurrence. Thus, the following interpretations are proposed and a possible testable consequence of putative physical relationships is suggested.

We contend that the observed relationship between TSI and EPTG in this paper is based on the latter representing the large-scale thermal and dynamical relaxation response of the coupled ocean–atmosphere climate system to incoming solar irradiance. Soon et al. (2011) posited evidence of just such a Sun–climate link operating in the East Asian monsoonal region. The empirical evidence shown in Soon et al. (2011) supports the idea that multi-decadal variation of incoming solar radiation is not limited solely to TSI (or the top-of-the-atmosphere solar insolation). Rather, the intensity of solar radiation reaching the surface has a persistent multi-decadal oscillatory character that depends on the nature of changing atmospheric transmissivity, including the effects of clouds, pollution, aerosols, etc.

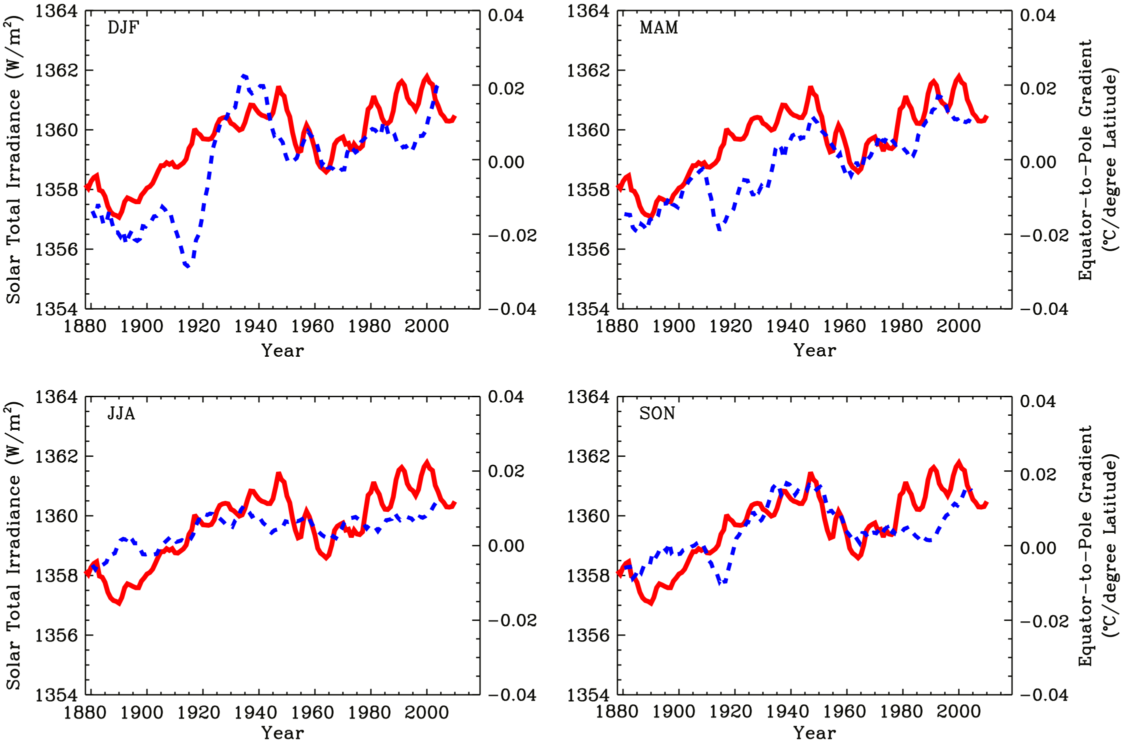

Fig. 3. Northern Hemisphere EPTGs for four seasons (DJF, MAM, JJA and SON) smoothed by 10-year running means (°C/degree latitude; dotted blue curves) *versus* the estimated total solar irradiance TSI (W m^{-2}; solid red curves) of Hoyt and Schatten (1993; with updates by N. Scafetta) from 1880 to 2010. Increased TSI is related to decreased temperature gradients between the Equator and the Arctic (*i.e.*, more positive EPTG values) and *vice versa*. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Our premise, therefore, is that as TSI increases, the projected insolation gradient between the tropic and Arctic regions increases proportionately, thereby leading to an increase in the poleward atmospheric and/or oceanic heat transport[4] which decreases the surface temperature gradients between the Equator and the Arctic (*i.e.*, towards more positive values of the EPTG index shown in Figs. 1–3). In contrast, the poleward heat transport decreases when TSI decreases thus causing an increase in the Equator-to-Arctic temperature gradient[5] (*i.e.*, towards more negative values of the EPTG index). Although multi-decadal scale changes in TSI are only on the order of a few tenths of a percent (see summary discussion in Section 2), these changes represent an actual increase/decrease in the total radiative energy being added to/subtracted from the climate system, not simply a mere redistribution of solar energy (*i.e.*, with no large net change in incoming solar radiant energy) as occurs through Sun–Earth orbital changes at 19-to-23 kyr, 41 kyr to 100 kyr time-scales (*i.e.*, Milankovitch variables). This suggests a physical basis for a direct increase or decrease in the total poleward energy transport as a result of direct variations in the incoming solar radiation. We add that our postulated mechanism may be able to provide the necessary increase (rather than decrease) in "energy" or "heat" that is needed for the production of glacial epochs, as originally proposed by Tyndall (1872) and Croll (1890)[6] and as more recently highlighted in Kukla and Gavin (2005), who focused solely on orbital-induced modulation of the incoming insolation.

This testable hypothesis is considered to be the key physical relationship that underlies our proposed Sun–climate connection. Available empirical evidence supports an increase in both oceanic and atmospheric poleward heat transport, especially in the recent warming since the 1980s. Thus, the goal is to reconcile these facts with the implicit assumptions of the Bjerknes compensation, which assumes maintenance of a *constant* total poleward energy transport controlled by an internally self-regulating inverse relation between oceanic and atmospheric heat transport fluxes (see Bjerknes, 1964; Shaffrey and Sutton, 2006; Enderton and Marshall, 2009; Rose and Ferreira, in press; Zelinka and Hartmann, 2012). In this regard, the observations of Czaja and Marshall (2006, p. 1509) are very encouraging: "Our results suggest that the oceanic and atmospheric heat transport might themselves change rather modestly in very different climate states. In other words, climate variability may be associated with only small departures from a fixed background [atmospheric and oceanic heat transport] curves."

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[4] In this, our initial study and analysis, the specific effects from local and regional insolation gradients that may potentially drive and/or modulate specific atmospheric and oceanic circulation phenomena will not be discussed. For example, Lindzen and Pan (1994) pointed out the mechanism in which orbital control on the off-equator maximum heating in the summer hemisphere can lead to strong modulation of the Hadley circulation intensity and hence lead to a significant modulation of the Equator-to-Pole heat fluxes in the opposing winter hemisphere. See also the new discussion paper by Liu et al. (2012) where the evidence for the variations in the strength and width of the Hadley Circulation on multidecadal to centennial scales is given.

[5] Here, we argue that TSI drives the insolation gradient and the EPTG is the relaxation response.

[6] From Kukla and Gavin (2004, p. 28), we find that Tyndall (1872, p. 154) noted that "So natural was the association of ice and cold that even celebrated men assumed that all that is needed to produce a great extension of our glaciers is a diminution of the sun's temperature. Had they gone through the foregoing reflections and calculations, they would probably have demanded *more* [sic.] heat instead of less for the production of a 'glacial epoch'." From Kukla and Gavin (2005, p. 1555), we find that Croll (1890) noted that "A general reduction of temperature over the whole globe certainly would not produce a glacial epoch. Suppose the sun were extinguished and our globe exposed to the temperature of the stellar space; this would certainly freeze the ocean solid from its surface to its bottom, but it would not cover the land with ice."

Vallis and Farneti (2009) have noted correctly that no *á priori* reason exists to suppose that the total poleward heat transport must have remained constant throughout any period of Earth's history. Nonetheless, surprisingly few attempts have been made to estimate the total meridional heat transport of the Earth's climate system over any time scale, though over short recent periods some authors have partitioned heat flow into its atmospheric and oceanic components, from both *in situ* and/or satellite observations (see Trenberth and Caron, 2001; Wunsch, 2005). Wunsch (2005) noted that the calculation of the total meridional heat transport by Trenberth and Caron (2001) is ultimately based on constraints set by the Earth Radiation Budget Experiment (ERBE), data that cover only 3 years of observations (1987–1989).[7] Despite this limitation, the available data indicate that the maximum atmospheric heat transport lies between 3×10^{15} and 5×10^{15} W at around 36°N, while the oceanic heat transport reaches a comparable figure between 0° and about 28°N with a maximum of 2×10^{15} W at low latitudes (Wunsch, 2005). Considering a maximum total meridional heat transport of 6×10^{15} W at around 40°N and with surface area poleward of 40°N of about 5.6×10^{13} m^2 (*i.e.*, about 100 W m^{-2}), the incoming solar radiation of about 340 W m^{-2} (*i.e.*, the solar constant divided by 4) is more than sufficient to account for the poleward energy transport budget. This calculation suggests that there is no need to invoke any energy "amplification" to explain solar climate forcing – as is often required and discussed within a so-called "radiative forcing-feedback" framework – concerning how the solar TSI or radiation can affect or modulate weather–climate changes on Earth.

Huang (2005, p. 279) cautioned against assuming that the oceanic transport component is not important beyond the tropics just because much of the atmospheric transport is in the form of latent heat and because the ocean provides atmospheric water vapor that is circulated poleward[8]: "Thus, the heat transport process starts from the ocean, and it ends in the atmosphere, so the latent heat flux loop is really a coupled mode." The new analyses of Rose and Ferreira (in press) support this "relay-transport" picture of Huang (2005) in that "the climatic impact of OHT [Ocean Heat Transport] depends on its effect on the greenhouse properties of the atmosphere [*i.e.*, through enhanced deep moist convection within midlatitude storm tracks], rather than its ability to increase the total poleward energy transport" (Rose and Ferreira, in press, p. 1). Huang (2005) also clarified that it is not the heat flux *per se* that is important for the discussion on climate and climate variability; but rather, the divergence of those heat fluxes on local and regional scales. Pierrehumbert (2002) noted that despite the expected large increase in dry static energy transport resulting from the high Equator-to-Pole temperature gradient during the Last Glacial Maximum, the significant drop in the latent heat transport associated with the cooler subtropics led to very little overall increase in the poleward heat flux transported from the tropics, as is indeed reflected in some computer climate simulations (*e.g.*, Murakami et al., 2008).

What evidence is available to show how the atmospheric and oceanic meridional heat fluxes transport energy poleward? Detailed discussion of that question is limited because it is nearly impossible to accurately partition the differing sources of the heat transport associated with, *inter alia*, the Hadley circulation, atmospheric eddies or various oceanic surface currents, and subsurface meridional overturning circulation. As a first step towards that end, we are nonetheless encouraged by the plausible relationship that existed between the total Northern Hemisphere EPTG index and the northern component of the strength of the Hadley circulation (as deduced by Liu et al., 2012) from 1871 to 2008.

Observational, model-derived, and theoretical/numerical analyses can also shed light on the increased atmospheric poleward heat transport that must have been associated with the Arctic warming during the last quarter of the 20th century. Using the available observational and assimilated data records, the analyses of Graversen et al. (2008), Smedsrud et al. (2008), Zhang et al. (2008), Yang et al. (2010), Screen and Simmonds (2010), and Alexeev et al. (2012),[9] despite some disagreements in the details,[10] all point to a net increase in the atmospheric heat flux to the Arctic since 1979. For example, Smedsrud et al. (2008, see their Figure 1a) and Yang et al. (2010, see their Figure 1) confirm increases in atmospheric heat transport to the Arctic and in its decadal variation, respectively. Alexeev et al. (2012) have documented a more coherent and consistent warming in the lower stratosphere (200–70 mb), especially above the Canadian Arctic, as compared to variations in the lower and middle troposphere. They argued that the warming of the lower stratosphere, and the inferred overall weakening of polar vortex, is consistent with the coherent multi-decadal variability found for the Arctic and North Atlantic near-surface climate and oceanic variables on timescales of 50–80 years. Theoretical studies using mainly climate models of various complexity (Caballero and Langen, 2005; Langen and Alexeev, 2007; Hwang and Frierson, 2010; Cvijanovic et al., 2011; Wu et al., 2011; Zelinka and Hartmann, 2012) also confirm an increased poleward atmospheric energy transport resulting from a generic global-scale warming.[11] Although they focused only on interannual variability, Huang et al. (2012) also examine this issue, and suggest that the ocean exhibits a 'memory' for transferring both the atmospheric angular momentum and its total energy between tropics and polar regions.

The existence of increased oceanic heat transport into the Nordic Seas and its subsequent entry into the Arctic Basin has been confirmed by both oceanographic observations and data-assimilated modeling efforts (*e.g.*, Orvik and Skagseth, 2005; Polyakov et al., 2005; Hansen et al., 2008; Holliday et al., 2008; Sarafanov et al., 2008; Hakkinen and Rhines, 2009; Jackson et al., 2010; Polyakov et al., 2010a, 2010b; Toole et al., 2010; Willis, 2010; Robson et al., 2012). Hakkinen and Rhines (2009) discuss the observational evidence from 1990 to 2007 that shows an increased penetration of warm and saline subtropical waters toward the Nordic Seas which, in turn, is noted as the key region that supports the Atlantic Meridional Overturning Circulation

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[7] We note that the ERBE radiation budget data studied by Trenberth and Caron (2001) covers the interval from February 1985 to April 1989.

[8] The interpretive framework suggested by Huang (2005) in separating the poleward heat flux into three components – (1) atmospheric sensible heat flux, (2) oceanic sensible heat flux and (3) atmosphere–ocean–land coupled latent heat flux – is likely more physically reasonable. Huang (2005) summarized that "in both hemispheres, poleward heat flux is carried by three components that work like a relay team. In the subtropics the oceanic sensible heat flux is the dominating contributor to the poleward heat flux divergence, and in mid-latitudes the latent heat flux divergence is the dominating contributor. Finally, in high latitudes the atmospheric sensible heat flux divergence dominates."

[9] We caution that the claim by Alexeev et al. (2012, p. 217) that "Graversen et al. (2008) found such an elevated warming in the winter and summer temperature trends, which they argued was not strongly linked to poleward atmospheric heat transport" is opposite to what Graversen et al. (2008) actually concluded in their paper. Instead, Graversen et al. (2008, p. 53) said that "We concluded that changes in atmospheric heat transport may be an important cause of the recent Arctic temperature amplification".

[10] For example, both Screen and Simmonds (2011) and Alexeev et al. (2012) note that an instrumental artifact arises from the switch between two different satellite radiance databases during 1997 in the 40-year European Center for Medium-Range Weather Forecasts Re-Analysis product. This disjunction adversely affects the reliability of atmospheric temperature profiles for the Arctic region that uses this product.

[11] Here, only research resulting from analyses without any direct radiative forcing from increasing CO$_2$ concentrations has been cited to avoid impacts arising from changes in atmospheric constituents.

(MOC), involving the creation, sinking and southward-flow of water at intermediate and deeper depths. The Atlantic MOC is the main modulator of how heat and salt (freshwater) are transported into and from the northern North Atlantic Ocean and the Arctic Basin (see Latif et al., 2004, 2006). Citing the observational results of Belkin et al. (1998), Hakkinen and Rhines (2009) added that the observed oceanographic conditions and poleward penetration of the subtropical warm and saline waters in the northern North Atlantic Ocean for the 1990s and mid-2000s were perhaps not a unique phenomenon. As they state, "A longer time series exists from the Faroe-Shetland Channel which shows that even higher upper ocean salinities were encountered in the 1930s until about 1940…when a major warming occurred in the Atlantic subpolar zone" (Hakkinen and Rhines, 2009, p.10). The climate modeling study of Robson et al. (2012) suggests further that the rapid warming of the North Atlantic Ocean in the mid-1990s was primarily a result of "a surge in the northward ocean heat transport". In addition, Polyakov et al. (2005, 2010a, 2010b) have tracked how the Arctic Basin was warmed by the penetration of warm and saline Atlantic waters of intermediate depths (150–900 m) through the 1990s, culminating with the intense warming and heating of the Arctic Ocean from below that occurred in 2007.

Similarly, much research has focused on the Pacific component of Arctic water as well. Shimada et al. (2006) documented a positive, atmospheric circulation-sea ice, motion feedback-induced influx of warm Pacific water that occurs in summer at relatively shallower (50–100 m) depths and within less saline (as compared to the Atlantic intermediate-depth waters) waters that flow through Bering Strait and into the Canadian Basin of the Arctic. It is this influx of warm Pacific water that caused the sea surface warming and maximum melting of sea ice there around 1998–2003. Woodgate et al. (2010) estimated that heat fluxes carried by the influx of Pacific waters through the Bering Strait increased from about $2–3 \times 10^{20}$ J yr^{-1} in 2001 to a maximum of $5–6 \times 10^{20}$ J yr^{-1} in 2007. They suggest that the amount of heat flux was "somewhat greater than the incoming shortwave solar [radiation] input into the Chukchi Sea" and would have been enough to account for one-third of the 2007 Arctic sea ice loss (Woodgate et al., 2010, p.5). Bourgain and Gascard (2012, p.1) offer another independent data analysis when they conclude:

> "Observations confirmed the existence of warm pulses of the Atlantic water mass propagating into the Arctic basin. However, no warming trend of the Atlantic water in the Eurasian basin was identified over the 1997–2008 time period. In contrast, the Summer Pacific water was getting warmer … [and] appears to be a serious candidate for contributing partly to the drastic summer sea ice extent and thickness decrease observed recently in the Arctic and in the Canadian basin in particular."

Clearly, Bourgain and Gascard (2012) disagree with Polyakov et al. (2010a). But it is important to note that Polyakov et al. (2010a) place strong emphasis on the importance of the role of multi-decadal variability within the North Atlantic and Arctic. In this sense, their conclusion is fully consistent with the multi-decadal variations in both surface temperature and salinity of the North Atlantic subpolar gyre that were shown by Reverdin (2010).

Despite the patchy nature of these adventitious, historical oceanographic data records, these results are consistent with a simultaneous increase in both atmospheric and ocean meridional heat transport in the Arctic Basin during the late 20th century. Such a fact, which has yet to be fully confirmed, would indicate violation of the Bjerknes compensation rules (see Czaja and Marshall, 2006; Shaffrey and Sutton, 2006; Enderton and Marshall, 2009; Vallis and Farneti, 2009; Zelinka and Hartmann, 2012 for additional insights).

Further evidence concerning how the Equator-to-Pole heat and moisture fluxes change on multi-decadal to centennial timescales arises from a study by Lund et al. (2006). These authors found that the Florida Current, and by inference the Gulf Stream, probably flowed at a substantially reduced rate of about 3 ± 1 Sv during the Little Ice Age (about 1200–1850 AD). This would be consistent with a reduced poleward heat and moisture transport during a relatively cold period of reduced TSI. Such an empirical deduction is not inconsistent with the qualitative scenarios sketched by Mörner (2010) concerning the multidecadal-to-centennial-scale modulation of the flow dynamics of the Gulf Stream, including even the increasing southward penetration of cold Arctic-originated water, during cold intervals of the Little Ice Age owing to the mass, energy and angular momentum readjustments from the increasing Earth rotation rate. However, the caution posited by Huybers and Wunsch (2010, p. 1) is clearly valid; namely, that "few features of the paleo-circulation in any period are yet known with certainty."

5. Conclusion

We assert that strong evidence exists to support the reality of a physical Sun–climate connection, as manifest in the multi-decadal co-variations of TSI and EPTG. A similar relationship also exists between fluctuations in TSI and other regional-scale climate variables such as surface air temperature. Our study clearly implies a necessity to account for the persistent nature of this external solar irradiance forcing. Many previous studies have amply documented relevant physical relationships, which range across seasonal, decadal, multi-decadal, centennial and millennial timescales. The empirical relationships regarding modern climate that are shown in this paper have great potential for application to the interpretation of climate variability in other geological epochs, before the modern era of instrumental and satellite-borne measurements. We suggest that fruitful exploration of the topic might first be made using records from the data-rich Holocene epoch.

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