



Cycles and trends in solar irradiance and climate[†]

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How—indeed whether—the Sun's variable energy outputs influence Earth's climate has engaged scientific curiosity for more than a century. Early evidence accrued from correlations of assorted solar and climate indices, and from recognition that cycles near 11, 88 and 205 years are common in both the Sun and climate.^{1,2} But until recently, an influence of solar variability on climate, whether through cycles or trends, was usually dismissed because climate simulations with (primarily) simple energy balance models indicated that responses to the decadal solar cycle would be so small as to be undetectable in observations.³ However, in the past decade modeling studies have found both resonant responses and positive feedbacks in the ocean-atmosphere system that may amplify the response to solar irradiance variations.^{4,5} Today, solar cycles and trends are recognized as important components of natural climate variability on decadal to centennial time scales. Understanding solar-terrestrial linkages is requisite for the comprehensive understanding of Earth's evolving environment. The attribution of present-day climate change, interpretation of changes prior to the industrial epoch, and forecast of future decadal climate change necessitate quantitative understanding of how, when, where, and why natural variability, including by the Sun, may exceed, obscure or mitigate anthropogenic changes. © 2010 John Wiley & Sons, Ltd. *WIREs Clim Change* 2010 1 111–122

The study of natural climate change induced by solar variability has matured significantly in the past few decades as a result of advances in observational, analysis, and modeling capabilities. Solar irradiance changes (including spectral and total variability) have been measured directly from space and interpreted in terms of their solar sources. With newly available modeled reconstructions of historical solar irradiance (albeit with large uncertainties), terrestrial studies are no longer relegated to using geophysically meaningless sunspot numbers as a proxy for solar irradiance, and direct comparisons of solar and other climate forcings are possible. Observations of the Earth have, at the same time, achieved sufficient quality and quantity (both temporally and spatially) to define with high-fidelity global and regional changes for comparison with the independently

measured solar irradiance. Climate and atmospheric responses to the solar cycle are now routinely detected using a range of empirical analysis techniques, with broadly consistent results throughout the terrestrial environment—including the ocean, surface, and atmosphere.⁶ Furthermore, solar-terrestrial analyses have expanded to include ozone,⁷ winds,^{8,9} and the hydrological cycle,¹⁰ affording new insights about likely mechanisms that engage both existing tropospheric circulation patterns and the overlying stratosphere.¹¹ General circulation climate models have expanded upwards (to ~80 km). They now incorporate more realistic stratospheric processes that respond directly to changing solar ultraviolet radiation and better simulate dynamical and radiative couplings of the stratosphere and troposphere that impart climate responses to solar variations.^{5,11–13}

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SPACE-ERA OBSERVATIONS

The unprecedented temporal and spatial coverage that space-based observing platforms have afforded during the past three decades has facilitated new understanding of both solar and climate variability and their

linkages. That the Sun's brightness varies continuously with a prominent ~ 11 -year cycle is now unequivocal, a result of direct solar irradiance observations made by multiple space-based radiometers since late 1978. That Earth responds measurably on decadal time scales to solar variability, as well as to other natural and anthropogenic influences, is also established and the magnitude of the responses quantified in global and regional temperatures, at the surface and in the overlying atmosphere.

Solar Irradiance

Independent space-based solar radiometers universally agree that solar irradiance is higher when the Sun is more active, as indicated by an elevated number of sunspots on its surface.¹⁴ Total solar irradiance (i.e., the spectrally integrated radiative output) increased $\sim 0.1\%$ from minima to maxima of the three most recent solar activity cycles, which peaked near 1980,

1990 and 2001. Also detected with high reliability are shorter-term irradiance changes of as much as 0.3% , associated with the Sun's rotation on its axis (with a period of approximately 27 days). Longer-term irradiance trends that may underlie the activity cycle (and manifest during solar minima) have not yet been reliably detected because the radiometers deployed prior to 2003 lack the needed calibration stability. As a result, different composite records of solar irradiance constructed with diametric assertions of instrumental behavior in independent radiometers differ in their absolute scale and temporal variations, including relative strengths during solar minima.¹⁵ The observational record of solar irradiance shown in Figure 1 is the average of three such composite records between 1985 and 2003, extended prior to 1985 with the Physikalisch-Meteorologisches Observatorium Davos (PMOD) composite¹⁵ and after

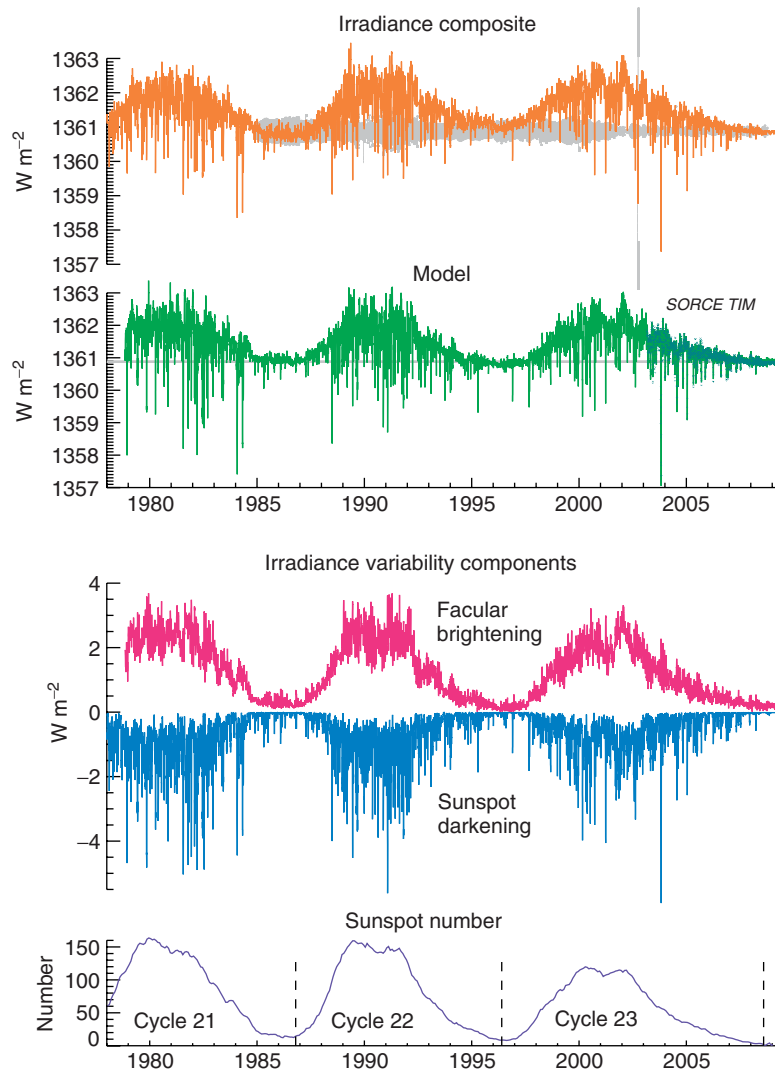


FIGURE 1 | Shown in the upper panel is a record of total solar irradiance obtained as an average of three different observational composites. In the second panel are irradiance variations estimated from an empirical model that combines the two primary influences of facular brightening and sunspot darkening. The symbols indicate direct observations made by the TIM instrument of the SORCE mission, used to determine the relative sunspot and facular components in the model, shown separately in the middle panel. Annual mean sunspot numbers shown in the bottom panel indicate overall levels of solar activity in cycles 21, 22 and 23, with times of minima indicated by the dashed lines. [Ref 57 provides details and sources of the various time series].

2003 with observations made by the Solar Radiation and Climate Experiment (SORCE).¹⁶

Evident in the record of total solar irradiance in Figure 1 is a dominant decadal cycle in phase with solar activity, represented by sunspot numbers. Actual cycle periods are 10.3, 9.7, and >12.3 years in cycles 21–23, respectively. Minor irradiance cycles occur near 13, 30 and 70 days, associated with the Sun's rotation on its axis. Within the uncertainties specified by the standard deviation of the three different composites (shown by the gray region in Figure 1), irradiance levels are equal during the three recent solar minima, indicating the lack of detection of an underlying irradiance trend in the past three decades. Trend detection may be possible in subsequent solar minima because current observations underway by the new state-of-the-art Total Irradiance Monitor (TIM) on SORCE (also shown in Figure 1) are a factor of 3 more accurate and repeatable than prior total solar irradiance measurements. Subsequent to SORCE, TIM is scheduled for flight on the Glory (2010-) and the National Polar-orbiting Operational Environmental Satellite System (NPOESS) (2013-) missions.

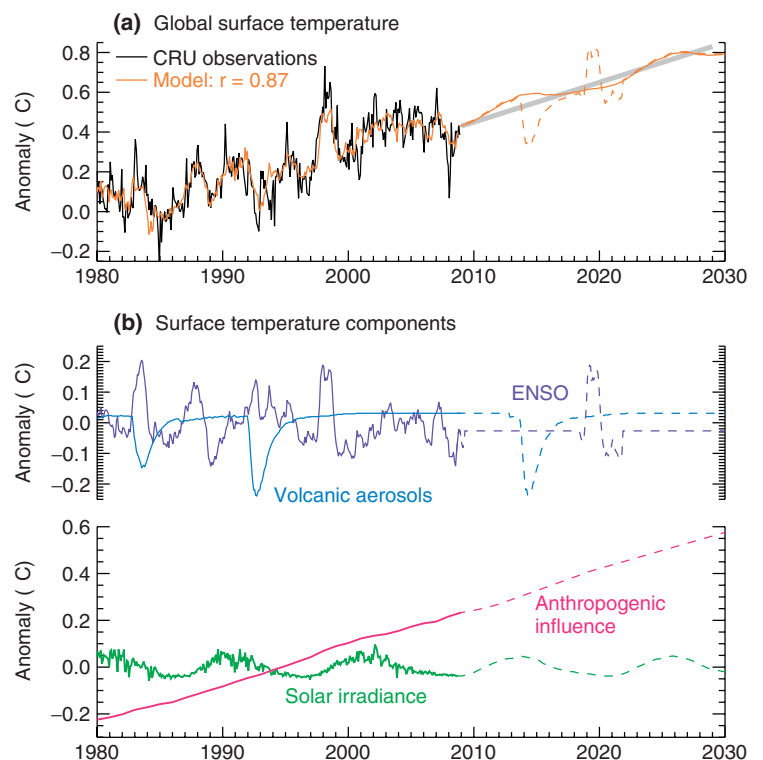
The complex temporal structure evident in the solar irradiance record in Figure 1 is well explained by two primary influences, each arising from the sub-surface dynamo¹⁷ that drives the Sun's fundamental activity cycle.¹⁴ Compact dark regions—sunspots—reduce the irradiance and produce, in particular,

the sharp irradiance decreases (of as much as 0.3%) that repeatedly punctuate the record. More extended, bright regions—faculae—enhance the irradiance. As Figure 1 shows, the sunspot and facular influences each undergo cyclic variations that track solar activity: an in-phase relationship of total solar irradiance with solar activity occurs because during solar maximum the average facular brightening of $\sim 2 \text{ Wm}^{-2}$ more than compensates the average sunspot darkening of 1 Wm^{-2} . An irradiance variability model in which the relative contributions of sunspots and faculae are specified by regression against the TIM observations (from 2003 to 2008, Figure 1) accounts for 93% of its measured variance and 83% of the variance in the entire composite. According to the model, whose variations are also shown in Figure 1, solar irradiance levels are approximately equal during the past three cycle minima, consistent with the average observational composite (taking into account the uncertainties).

Climate

An overall warming trend is apparent in the climate of the last two decades of the C20th.¹⁸ From 1980 to 2000, global surface temperatures increased at an average rate of 0.16°C per decade, with 1998 the warmest year on record, 0.6°C above the global average for 1951–1980. Figure 2 illustrates

FIGURE 2 | Compared in (a) are observed monthly mean global temperatures (black) and an empirical model (orange) that combines four different influences. In (b) the individual contributions of these influences are shown, namely ENSO (purple), volcanic aerosols (blue), solar irradiance (green) and anthropogenic effects (red). Together the four influences explain 76% (r^2) of the variance in the global temperature observations. Future scenarios are shown as dashed lines. Anthropogenic and solar contributions are extended into the future using knowledge of past behavior, assuming the same linear trend for anthropogenic gases of the recent past and future irradiance cycles similar to cycle 23. In lieu of the ability to forecast ENSO and volcanic activity, possible scenarios are based on past events [from Ref 52].



this trend in the instrumental record of monthly mean global (land plus ocean) surface temperature anomalies constructed by the University of East Anglia Climatic Research Unit (CRU).¹⁹ But a relative lack of warming characterizes the first decade of the C21st, even though greenhouse gas concentrations have continued to increase. Confounding expectations of a monotonically warming globe, the average warming rate from 2000 to 2008 subsided by almost an order of magnitude, and temperatures in 2008 were cooler than in 2002. These varying 'trends' in global temperatures arise in part from the influences of solar irradiance and other natural processes, which must be comprehensively assessed in order to properly ascertain Earth's response to the underlying anthropogenic influence.

Much surface temperature variability observed in the recent past appears to arise from causes that can be identified and their impacts quantified using auxiliary observations. Solar irradiance cycles, for example, produce warming of $\sim 0.1^\circ\text{C}$ during epochs of high-solar activity whereas a large volcanic eruption cools the globe by as much as ~ 0.3 to 0.4°C .²⁰ The El Niño Southern Oscillation (ENSO) atmosphere–ocean coupling in the tropical Pacific Ocean²¹ is a source of continual temperature fluctuations, a 'super' El Niño episode such as in 1997–98 producing global warming of $\sim 0.2^\circ\text{C}$. Figure 2 shows how the individual natural (solar, volcanic, and ENSO) and anthropogenic components, separated by multiple regression against the temperature observations, contribute to the evolution of net global surface temperatures.²² In addition to specified solar irradiance variations, this analysis uses a multivariate ENSO index constructed from observations of sea-level pressure, surface wind, surface sea, and air temperature, and cloudiness²³ and a volcanic aerosol index determined from observations of stratospheric aerosols.²⁴ The anthropogenic forcing is the net effect of multiple sources, including increasing concentrations of greenhouse gases [CO_2 , N_2O , chlorofluorocarbons (CFC)], the direct and indirect effects of tropospheric aerosols, landuse, and snow albedo changes,²⁵ with a significant net upward trend shown in Figure 2.

Direct linear association of natural and anthropogenic influences explains 76% of the variance in the observed global surface temperature during the past 30 years (and also in the past 120 years²²), Figure 2 shows how a model that combines these influences clearly identifies the cause of the rapid global temperature rise from 1992 to 1998 as the result of ENSO-induced warming following Pinatubo-produced cooling. The cause of the lack of overall warming in the last decade is also identified, the result

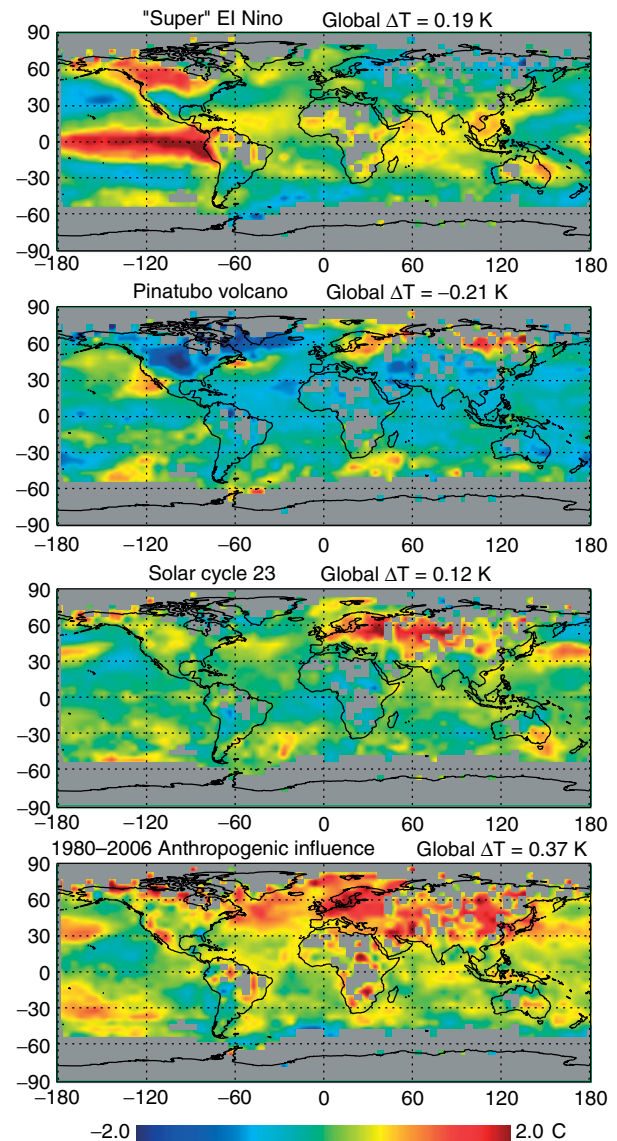
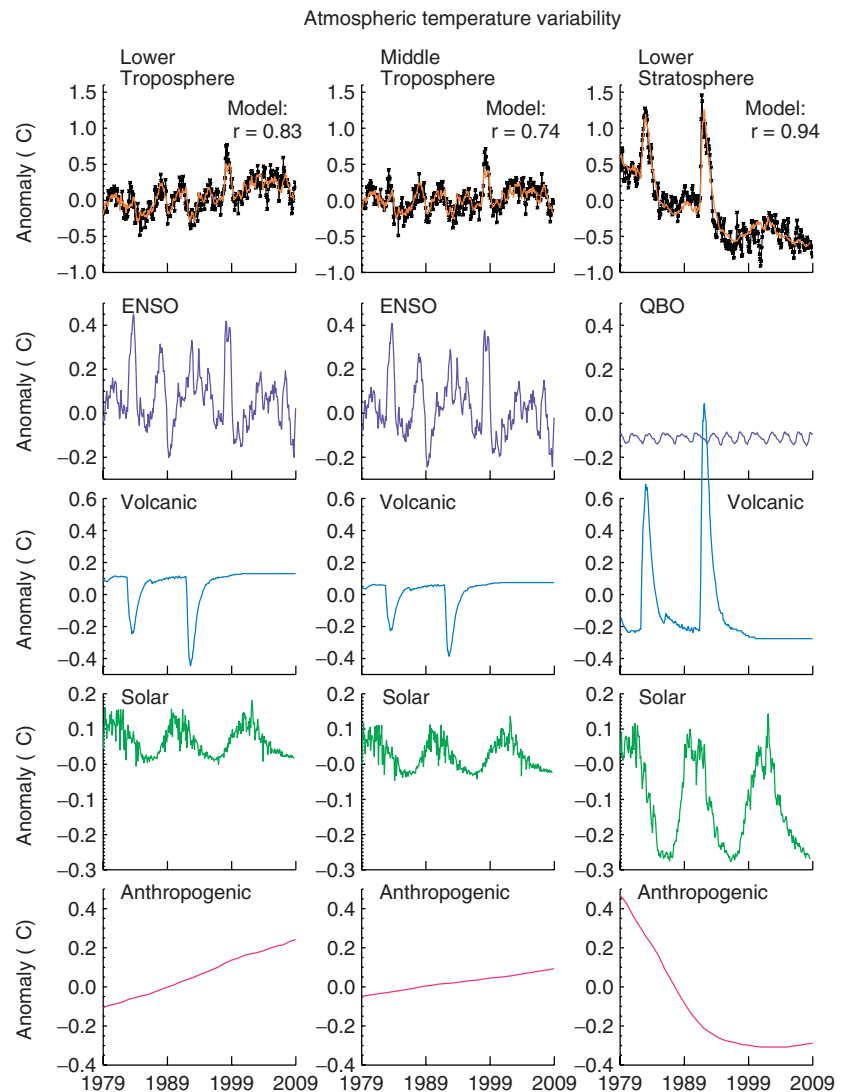


FIGURE 3 | Geographical response patterns in surface temperature are shown for the 1997–98 'super' ENSO, the Pinatubo volcano, solar cycle 23 and anthropogenic influences from 1980 to 2006, derived from the monthly surface temperatures on a $5'' \times 5''$ grid. Gray regions indicate lack of data [based on Ref 22].

of decreasing solar irradiance in the declining phase of cycle 23 from 2002 to 2009 and La Niña cooling countering anthropogenic warming. The natural and anthropogenic influences produce characteristic regional climate response patterns, shown (as annual averages) in Figure 3. A strong El Niño event mainly impacts lower latitudes, between $\pm 30^\circ$, but there is also strong North Pacific cooling and western continental US warming, consistent with strengthened Aleutian low. A large volcanic eruption produces widespread cooling from 40°S to 70°N , especially in the US and the North Atlantic Ocean. Strengthened

FIGURE 4 | Compared in the upper panel are the observed monthly mean global temperatures (black) of Earth's lower and middle tropospheres, and lower stratosphere with empirical models (orange) that combine four different influences, shown separately in the bottom four panels. Each of the four different sources contributes different modulation of Earth's atmospheric temperature at different heights above the surface. Relative strengths are deduced from multiple regression analysis. The ENSO, volcanic, solar and anthropogenic time series are described in Ref 22. The National Oceanic and Atmospheric Administration produced the Quasi Biennial Oscillation time series, available at <http://www.cpc.noaa.gov/data/indices/>. The Microwave Sounding Unit measured the temperature anomaly data,⁵⁸ which are available at <http://vortex.nsstc.uah.edu/data/msu/>.



westerly winds and a more positive phase of the North Atlantic Oscillation produce warming in the northern Eurasian continent.²⁶ The response to solar variability is strongest at midlatitudes (near 40°) in both the northern and southern hemispheres, in the vicinity of the interface of the Hadley and Polar cells.^{8,27} Anthropogenic forcing dominates northern hemisphere mid to high latitudes, including in the North Atlantic Ocean.¹⁸

Earth's atmosphere similarly responds to combinations of natural and anthropogenic influences, their relative importance changing with altitude above the surface.²⁷ This is evident in space-based observations of the atmosphere made simultaneously with the surface temperature record over the past 30 years and illustrated in Figure 4. Whereas ENSO is a dominant mode of internal variability in the troposphere, its influence on the lower stratosphere is comparatively

minimal. Volcanic aerosols that cool the troposphere (by as much as 0.3°C) warm the stratosphere (by more than 1°C). The modest 0.1°C decadal temperature cycle of solar irradiance grows to three times larger in the lower stratosphere. In contrast, the dominant warming trend associated with anthropogenic influences at the surface weakens to a minimal middle tropospheric trend and reverts to cooling in the lower stratosphere. In the analysis shown in Figure 4, the stratosphere cooling is actually modeled better by changes in CFCs than by increases in greenhouse gases. This suggests that cooling from CFC-related ozone depletion may dominate greenhouse gas cooling of the stratosphere.

Whereas incoming solar energy (i.e., solar radiative forcing) maximizes in zonal bands that track the annually varying subsolar point, climate responds to variations in this energy with maximum warming

in midlatitudes, especially over northern hemisphere land, and some regional cooling. The forcing and response patterns differ because solar variability modulates tropospheric circulation patterns already established by mean solar heating and simultaneously engages stratospheric–tropospheric radiative and dynamical couplings (via ozone heating),²⁷ each with approximately equal climate impacts.¹¹ During high-solar activity, the primary meridional circulation system in the troposphere, the Hadley cell, weakens in strength and expands in latitude (due to reduced upflow at the equator related to a warmer stratosphere that stabilizes the atmosphere's temperature profile). Midlatitude storm tracks strengthen and move northward, possibly associated with the modulation of the North Atlantic Oscillation by solar-induced changes in the polar stratosphere. Enhanced radiative heating in the midlatitude cloud-free zones during high-solar activity may alter lower latitude moisture, temperature and rainfall.^{5,28} Zonal inhomogeneities occur as well, implicating an ENSO-like response pattern of differential warming in the east and west tropical Pacific.^{29–31} Furthermore, climate responds to solar variability with distinct seasonality because dynamical processes are not as large in summer as in winter due to the reduced latitudinal gradient of solar energy input (the annual patterns shown in Figure 3 are actually the average of the different winter and summer responses).

HISTORICAL EVIDENCE

How consistent are the space-era climate forcings and responses with those in the past? Detecting and interpreting linked cycles and trends in solar and terrestrial variability become increasingly difficult on centennial and millennial timescales because of the paucity of direct observations. Space-based irradiance observations commenced only near the end of 1978, as did global remote sensing of the Earth's atmosphere. Surface temperature measurements at multiple sites have been combined to specify global and regional surface temperatures since about 1850.^{19,32} But knowledge of solar irradiance variations prior to 1978 and of climate variations prior to 1850 must be obtained indirectly, from proxy records in archives such as ice cores and tree rings.³³ Information about historical ENSO, volcanic, and anthropogenic influences needed to interpret and simulate past climate change must also be reconstructed from appropriate proxy records.

Solar Irradiance

Sunspots are the only direct record of solar activity prior to the space era, except for selected

solar observations since about 1950 (e.g., radio flux, magnetic fields³⁴). Solar activity exhibits a predominantly upward trend in recent centuries, evident in increasing strengths of the 11-year activity cycle. Since, as Figure 1 shows, sunspots reduce net total solar irradiance, the challenge in reconstructing past irradiance changes is to ascertain the long-term evolution of emission from the bright faculae, which more than compensate the sunspot darkening during the solar cycle. Solar interior structural changes are also postulated to alter irradiance, augmenting the magnetic sunspot and facular effects³⁵ but the physical reality of such a process remains under debate.^{36,37}

Space-era solar observations coincide with an epoch of activity cycles having higher than average amplitude and shorter than average period. There have been many attempts to reconstruct solar irradiance variations since the seventeenth-century Maunder Minimum, using the sunspot record, auxiliary evidence from Sun-like stars,³⁸ direct associations with cosmogenic isotopes and geomagnetic activity,³⁹ simulations with solar models of magnetic flux redistributed from sunspots to faculae⁴⁰ and hypothetical solar interior structural changes.³⁵ Figure 5 compares such reconstructions with the evolution of solar activity evident in sunspot numbers. In the reconstructions, the assumed longer-term irradiance changes manifest as slowly varying components underlying the 11-year activity cycle.

Linking the reconstructed irradiances to $\Delta^{14}\text{C}$ cosmogenic isotopes in tree rings, also shown in Figure 5 (and $\Delta^{10}\text{Be}$ in ice cores), remains the only viable way to estimate solar irradiance variations prior to 1610, and a number of such time series have been produced by assuming a direct linear relationship of irradiance and cosmogenic isotopes.^{41,42} But verifying this assumption requires further research to quantify the relationship between the (open) magnetic flux expelled from the outer solar atmosphere and the (closed) magnetic flux whose fields are anchored below the solar surface.⁴³ Open flux modulates the heliosphere thereby controlling the flux of galactic cosmic rays that produce cosmogenic isotopes, whereas closed flux accounts for the sunspots and faculae whose variations alter irradiance. How the solar dynamo alters and organizes the proportion of open and closed fluxes, and sunspot and facular regions, is not known.

Climate

Global (and regional) surface temperature fluctuations in the past 120 years reflect, as in the space era, a combination of solar, volcanic, ENSO, and

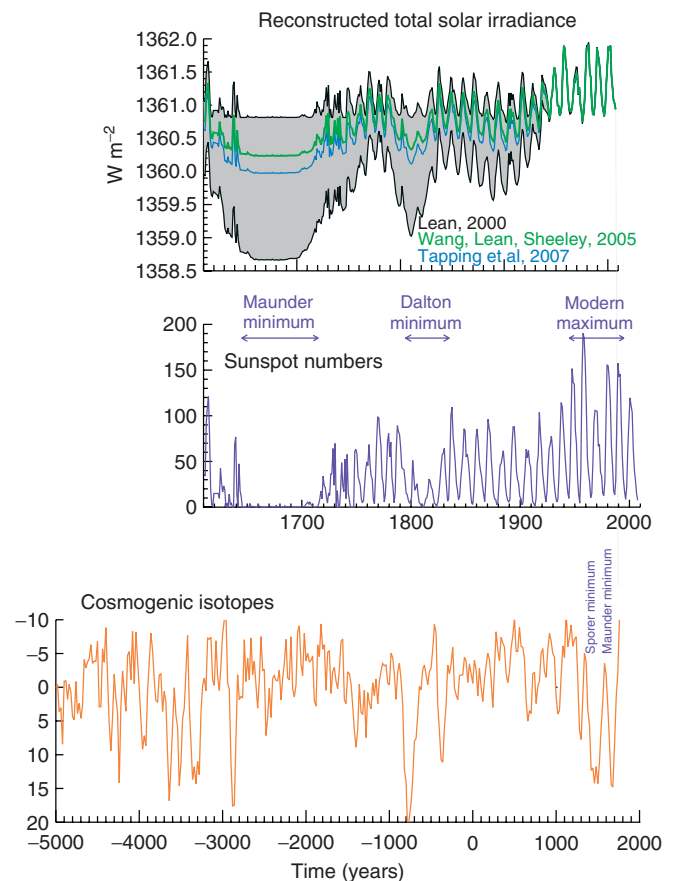


FIGURE 5 | Reconstructions of total solar irradiance with different assumptions about the strength of the background component that underlies the activity cycle are compared since the Maunder Minimum.[57 provides details].

anthropogenic influences, with relative contributions shown in Figure 6.²² The adopted solar brightness changes in this scenario are based on a solar surface flux transport model; although long-term changes are $\sim 50\%$ larger than the 11-year irradiance cycle, they are significantly smaller than the original estimates based on variations in Sun-like stars and geomagnetic activity. Cycles and trends in the natural and anthropogenic influences, also shown in Figure 6, collectively impose equivalent (and at times competing) cycles and trends on climate. A 2–3 years quasi-cycle is attributed primarily to ENSO fluctuations. Decadal variability is present in volcanic aerosols (whose peak influences of El Chicon and Pinatubo are separated by 11 years) and solar variability, and possibly modulates ENSO. Only in the anthropogenic influence is there a sufficiently large upward trend over the past 120 years to explain global surface temperature variations self-consistently with the space-era components. Accordingly, trends in solar irradiance in the past century contribute global warming of 10% or less.

Prior to 1850, proxy indicators of surface temperature have been compiled, assimilated and interpreted to estimate changes over the last two millennia.³³ A combination of solar variability and

volcanic eruptions appears to explain fluctuations in global surface temperature of $\sim 0.2^\circ\text{C}$ on centennial time scales,⁴⁴ inferred from paleoclimate records in multiple archives (tree rings, ice cores, corals, and stalagmites). These paleo data therefore suggest, like the instrumental record (Figure 6), that the much larger (almost 0.8°C) industrial global surface temperature increase is not the result of natural changes in either solar or volcanic activity.

There is a prominent cycle near 205 years in many paleoclimate indicators and also in solar activity. Correlations between solar activity and climate, often arising from this common cycle, are ubiquitous in the past 10,000 years, especially in drought and rainfall.^{45–48} Figure 7 illustrates the broad consistency of multiple paleoclimate Sun–climate associations with the contemporary response pattern of surface temperature to the solar irradiance cycle. Areas vulnerable to the hydrological cycle—monsoons, rainfall, drought—appear especially sensitive to solar-driven climate change, which is implicated in the cultural histories of the Mayans, precolonial societies in East African and Chinese Dynasties. Although the sheer volume and the high fidelity of the empirical evidence may suggest a prominent solar

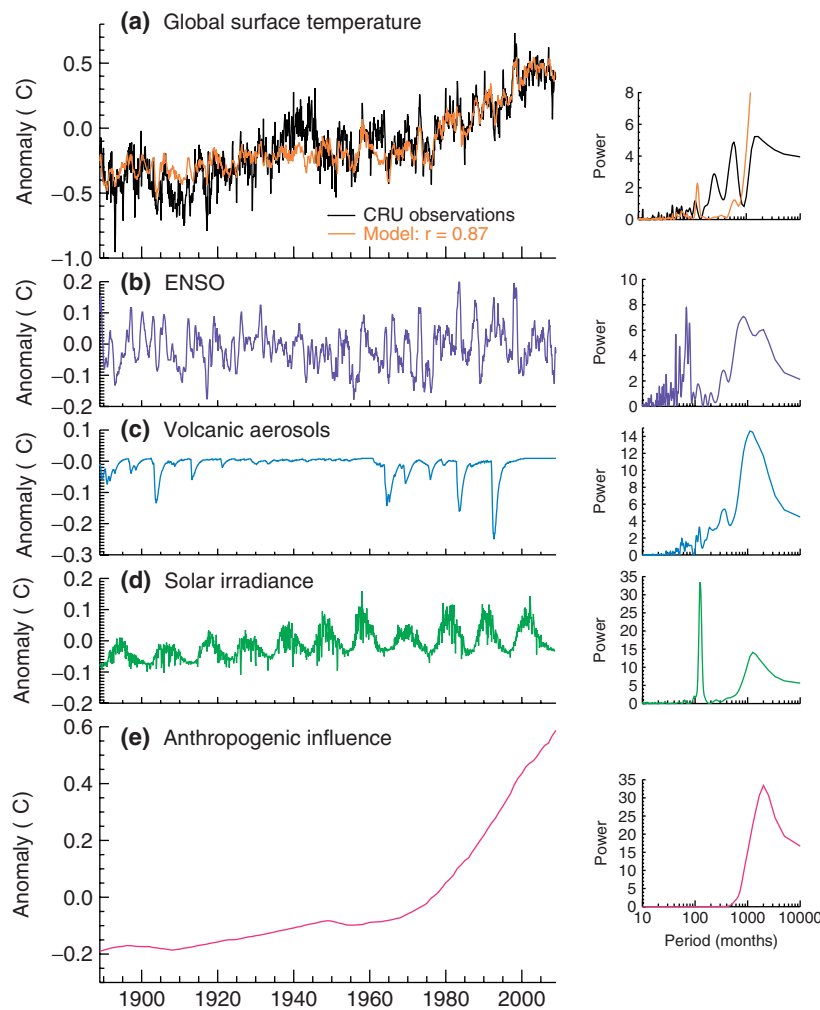


FIGURE 6 | Compared with the CRU monthly mean global temperature time series (hadcrut3vcgl) in (a) is an empirical mean global temperature time series (hadcrut3vcgl) is an empirical model obtained from multiple regression for the period from 1889 to 2008, inclusive.²² The value of r is the correlation coefficient for the global temperature observations and empirical model. Reconstructions of the contributions to the monthly mean global surface temperatures by individual (b) ENSO, (c) volcanic, (d) solar, and (e) anthropogenic influences (at appropriate lags) are also shown. The periodograms on the right illustrate cycles present in the monthly mean values of each of the four sources of global temperature variance.

impact on global climate, Figure 7 cautions that the corresponding global response is typically an order of magnitude smaller than the strongest site-specific Sun–climate linkages (with increases of as much as 1°C during the solar cycle).

Claims that the Sun has caused as much as 70% of the recent global warming (based in part on the attribution of radiometric trends to real solar irradiance changes⁴⁹) presents fundamental puzzles. It requires that the Sun's brightness increased more in the past century than at any time in the past millennium, including over the past 30 years, contrary to the direct space-based observations. And it requires, as well, that Earth's climate be insensitive to well-measured increases in greenhouse gases at the same time that it is excessively sensitive to poorly known solar brightness changes. Both scenarios are far less plausible than the simple attribution of most (90%) industrial global warming to anthropogenic effects, rather than to the Sun.

FUTURE SCENARIOS

How might the Sun and climate evolve in future decades? Long-range forecasts project global temperature increases in the range $1.5\text{--}4^{\circ}\text{C}$ by the end of the C21st, in response to a continuing anthropogenic influence.¹⁸ But in the immediate future, natural influences, including by the varying Sun, will likely alter Earth's surface temperature sufficiently to amplify or mitigate this expected global warming trend. Near-term climate forecasts aid such applications as land management and crop productivity,⁵⁰ energy usage, tourism, and public health.⁵¹ Initial predictions of solar cycle 24 indicated that its maximum activity might exceed that of cycle 23 but subsequent forecasts contrarily suggest that cycle 24's amplitude will be moderate to low relative to the historical sunspot record.⁵³ High levels of solar irradiance near the peak of cycle 24 ($\sim 2012\text{--}2013$) would exacerbate the warming anticipated from increasing anthropogenic influences. Alternatively, that the Sun may be entering

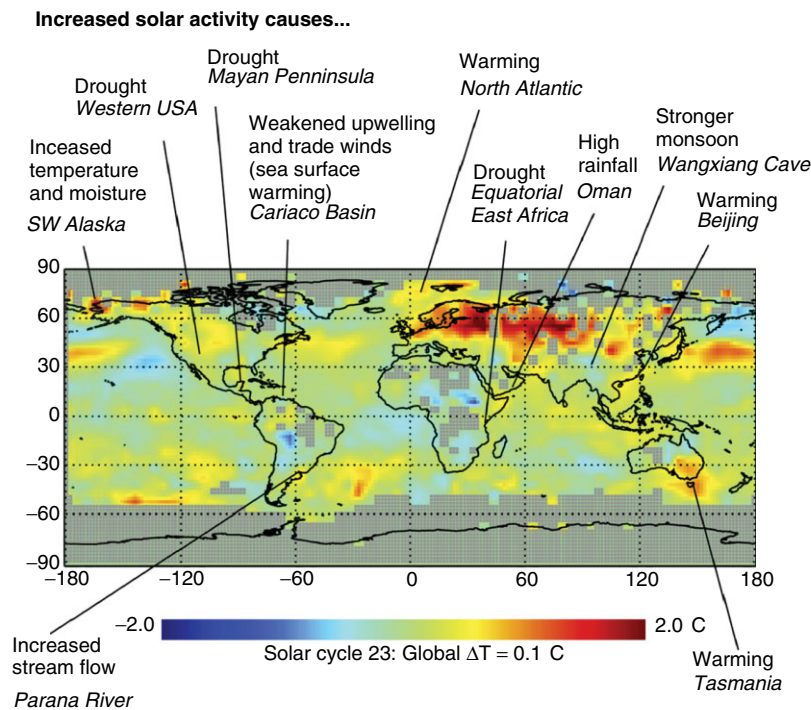


FIGURE 7 | Superimposed on the geographical response pattern of observed surface temperature to solar irradiance changes in cycle 23 (Figure 3) are the responses evident in published analyses of paleoclimate records from specific sites. Gray regions indicate lack of data.

an extended period of low activity,⁵⁴ possibly countering anthropogenic global warming, is also speculated.

Solar Irradiance

Predictions of the strength of activity of future solar cycles have large uncertainties.¹⁷ Forecasting solar irradiance is even more difficult, requiring additional knowledge of the partitioning of magnetic flux into sunspots (which decrease irradiance) and faculae (which increase it). This partitioning may not be linear for all solar activity levels—for example, it has been suggested that high activity might produce saturation of total solar irradiance.⁴⁰

Even though solar cycle 23 was less active (in terms of sunspot numbers, Figure 1) than cycles 21 and 22, total solar irradiance increased by about the same amount ($\sim 0.1\%$). A plausible scenario is that future solar irradiance cycles will also have amplitudes near 0.1% , as shown in Figure 2 with cycle 24 commencing at the beginning of 2009. Since direct solar irradiance observations cover only three solar cycles, it is unknown when (and why) solar magnetic activity might deviate from the current pattern in which facular brightening dominates sunspot darkening by a factor of approximately two. Also unknown is the likelihood of the Sun entering an extended period of anomalously low activity like the seventeenth-century Maunder Minimum (Figure 5). The current historically low levels of solar activity and high-cosmic ray fluxes are motivating such

speculation but the ‘historical’ context pertains only to the relatively recent period since about 1960. As Figure 5 shows, neither current levels nor cycle length is anomalous in the multi-century perspective.

Climate

One approach for forecasting climate in future decades is to estimate the effect from expected changes in the individual natural and anthropogenic influences (such as those identified in Figures 2 and 6). This approach assumes that climate will continue to respond linearly to these influences, as parameterized using past observations.⁵² The future climate scenario in Figure 2 suggests an average warming rate of 0.17°C per decade in response to projected solar irradiance cycles similar to cycle 23 and an anthropogenic forcing of 0.37 Wm^{-2} per decade (the trend in the recent past). The warming trend is comparable to the 0.2°C per decade warming forecast by Ref 18 also shown in Figure 2, but opposite to recent projections of Ref 55 who forecast an absence of warming in the next decade based on the weakening of the Atlantic Ocean meridional overturning circulation.

Global warming will probably not proceed at a constant rate in the immediate future. As the anthropogenic influence continues and solar irradiance increases from the onset to the maximum of cycle 24, global surface temperatures are projected to increase 0.14°C in the five years from 2009 to 2014 (at an average rate of 0.3°C per decade). Global

annual temperatures in 2014 will be 0.7°C warmer than the 1951–1980 base period, but the estimated annual temperature increase of 0.2°C from 2004 to 2014 (Figure 2) is smaller than the 0.3°C warming that Ref 56 predict over the same interval. From 2014 to 2019, global annual surface temperatures are expected to increase only minimally (0.03°C), as declining solar irradiance cancels much of the anthropogenic warming, analogous to the recent period from 2002 to 2008 when decreasing solar irradiance during the descending phase of solar cycle 23 countered much of the anthropogenic warming. Although ENSO fluctuations and volcanic eruptions are not predictable on decadal time scales, Figure 2 illustrates the effects on global surface temperature of a Pinatubo-like eruption with peak impact in 2014 (near solar cycle 24 maximum) and a super ENSO with maximum impact in 2019, mimicking a similar sequence that occurred from 1992 to 1997.

CONCLUSION

Dismissal of Sun–climate associations was, until recently, de rigueur because climate models were not been able to replicate them. But the increasingly extensive, broadly self-consistent empirical evidence accruing in multiple high-fidelity datasets of present and past climate, combined with new appreciation of the complex mechanisms, now precludes this. Climate models are instead challenged to reproduce this comprehensive empirical evidence.

Solar-related fluctuations are apparent at the Earth's surface (including the ocean) and atmosphere. Although solar irradiance cycles impart only modest global mean surface temperature changes (of ~0.1°C), they are nevertheless sufficient to alter climate 'trends' on decadal time scales and must therefore be understood and quantified for more reliable near-term climate forecasts and rapid detection of the anthropogenic component to aid global change policy making. Evidence from empirical Sun–climate linkages and recent model simulations suggest that climate responses to radiative forcings are complex and holistic, engaging the troposphere, stratosphere, surface, and ocean in multiple dynamical and radiative

adjustments that alter existing circulation patterns, in ways as yet only poorly parameterized numerically.

Understanding of how, when, where, and why climate responds to solar variability is incomplete. Among the many remaining questions are what is the long-term amplitude of irradiance changes, how does the spectrum change in concert with the total, how can we better quantify the relative roles of direct and indirect processes, the mechanisms of stratosphere and troposphere coupling, and the amplitude and profile of ozone changes, are responses to solar radiative forcing altered by the presence of other forcings, such as by elevated volcanic aerosols or concentrations of greenhouse gases, what are the relative strengths, timings and spatial distributions of dynamical and radiative responses, how much larger are (equilibrium) climate response than shorter-term (more transient) responses?

As the only external climate forcing directly specified independently of climate models, solar irradiance variations promise a touchstone for advancing understanding of climate change. When climate models can reproduce the multiple, complex responses embodied in the empirical evidence, confidence will increase in their ability to simulate climate changes in response to other radiative forcings, including by greenhouse gases.

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