REVIEW: CLIMATOLOGY

The Sun's Role in Climate Variations

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Is the Sun the controller of climate changes, only the instigator of changes that are mostly forced by the system feedbacks, or simply a convenient scapegoat for climate variations lacking any other obvious cause? This question is addressed for suggested solar forcing mechanisms operating on time scales from billions of years to decades. Each mechanism fails to generate the expected climate response in important respects, although some relations are found. The magnitude of the system feedbacks or variability appears as large or larger than that of the solar forcing, making the Sun's true role ambiguous. As the Sun provides an explicit external forcing, a better understanding of its cause and effect in climate change could help us evaluate the importance of other climate forcings (such as past and future greenhouse gas changes).

How much the climate system is influenced by solar variability has long been a subject of controversy, due largely to the strictly empirical nature of the evidence. Observations of past or current climate have been correlated with presumed variations of solar irradiance or solar activity proxy records, and a de facto cause and effect relation has been established. For those convinced of the Sun's dominance, this is generally sufficient. For critics, the correlations often do not extend sufficiently long to establish statistical significance; nothing suffices short of complete understanding of how the energy associated with solar variability produces the responses at each step of the process. Rarely is the latter achieved for any forcing of the climate system, even when physical relations are apparent (witness the search for the smoking gun of anthropogenic greenhouse warming). Empirical correlations do not necessarily imply causation, especially when the climate data quality and dating is imperfect and solar forcing is poorly known. However, the sheer number of empirical Sun-climate relations defies ready dismissal.

One difficulty is that different sides typically adopt absolutist views of the problem: either the Sun is responsible in a dominant way or it is of no consequence whatsoever. The reality is that Earth's atmosphere, land surface, and oceans are not passive recipients of any forcing, be it solar variability, volcanic eruptions, or altered greenhouse gas concentrations. Rather, the entire interconnected system participates in the final climate outcome via multiple, nonlinear feedbacks that can amplify or diminish climate forcing as well as change the nature and consistency of the response. To appreciate the solar effect, we need to disentangle the contributions made by system feedbacks, natural variability and other forcings. Here, I review the solar variations and climate system response for a range of time scales. Without more progress, such separation will likely occur only by observing the response to increased greenhouse gases.

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Eons and the Faint Sun Paradox

The concept is well established that the Sun was 25 to 30% less luminous 4.5 Ga, which should have produced a completely ice-covered Earth for some 2 Gy (*1*). Yet free flowing water and the beginnings of life were apparent 3.5 to perhaps more than 4 Ga (the "faint Sun paradox"). Large amounts of greenhouse gases are presumed to have been present in the atmosphere to offset the solar deficit, although it is not understood precisely which gases. If it were reducing gases, such as CH_4 or NH_3, organic mixing ratios would be three orders of magnitude more easily generated by lightning discharges, than if it were CO_2 (*2*). But the Sun's ultraviolet (UV) radiation would destroy the reducing gases in short order (*3*). Regardless of the ultimate answer, it is apparent that what would have been expected from solar forcing alone was not what the climate system registered, due presumably to even greater forcings or feedbacks such as altered greenhouse gas concentrations. A comparison of what should have happened if solar forcing were to predominate versus what did happen is given in Table 1.

Conversely, by some 700 Ma the solar reduction of 6% would not have been expected to produce an ice-covered Earth [which in one model seemed to require some 10 to 15% reduction (*4*, *5*)], and yet evidence of ice on equatorial land masses exists for that and other such time periods (*6*). Now explanations are required for the magnitude of the low-latitude cooling, and they range from possible high obliquity (*7*) to reduced greenhouse gases (*8*, *9*) in conjunction with serendipitously arranged continents (*10*). Again, the magnitude of solar irradiance was not unimportant and may even have triggered the system responses that eventually led to the observed state, but ultimately it was also not the dominating factor. What else may have happened is shown in Table 1 as well.

Table 1. Faint Sun paradox. Time scale, age of Earth; mechanism, solar evolution, irradiance increases by 25 to 30% over 4.5 Gy. Forcing, 100 W m^{-2}.

What should have happened	What did happen
Water frozen solid for ~ 2 Gy	Water and life existed ~4 Ga
Earth warmed out of ice age conditions by 700 My	Low-latitude glaciation 750, 600, and 300 Ma
Warm up of Earth over time	Earth appears to have cooled over past 60 My
What else happened?	
Perhaps high levels of greenhouse gases (CO_2, CH_4, NH_3) decreased with time, maybe to very low levels (~600 Ma)	
Reduced gases (CH_4, NH_3) allow for more ready explanation of the origin of life	
Solar UV would have photodissociated reduced gases on short time scales	
Continental positions changed with time	
Perhaps obliquity changed with time	

Millennia and Orbital Variations

Though not normally thought of as "solar variability," orbital variations force climate by altering the solar input (albeit with variable percentage as a function of latitude) and uniform spectral irradiance change. Because of the prevalence in numerous climate

Table 2. Orbital variations. Time scale, 2 My; mechanism, solar irradiance at high latitudes during NH summer changes with time due to precession, obliquity and eccentricity variations; forcing, ~30 W m^{-2} at 65°N in summer.

What should have happened	What did happen
Ice ages with less NH summer irradiance	GCMs did not get cold enough
Interglacials with more NH summer irradiance	Interglacials did not always match
SH responds to NH lead	SH led in some responses
Domination of precession and obliquity cycles at 40 ky, ~23 ky	100-ky cycle dominated
What else happened?	
Possible ice sheet instabilities	
Possible deep water changes	
Greenhouse gas (CO_2, CH_4) changes	
Dating uncertainties	

records of cycles near 23, 40, and 100 ky corresponding to precession, obliquity, and eccentricity cycles, respectively, in the Earth's orbit about the Sun, orbital variations have been called the 'pacemaker of the ice ages' (*11*). They are a prime example of the presumed solar dominance of climate on Earth during the past several My. Following the standard assumption that irradiance variations at high northern latitudes during summer cause ice sheets to wax and wane, presented in Table 2 is an assessment of what should have happened with respect to orbital variations, versus what did happen. As in the previous two examples, the climate system has displayed a surprising amount of independence of the forcing.

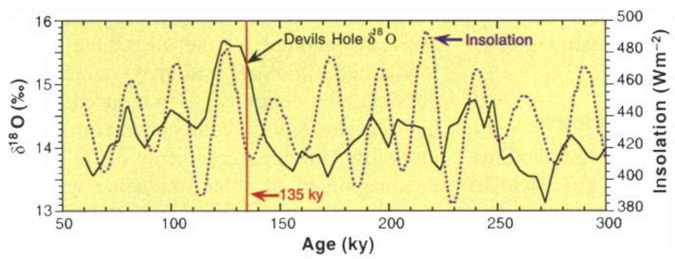

Fig. 1. Well-dated isotopic record from the Devils Hole cave showing the warming of the penultimate deglaciation essentially finished before the summer insolation at 65°N began to increase. This is in agreement with some other data sources, including the latest temperature reconstructions from the Vostok ice core. [Reprinted from (*18*) with permission.]

Considerable evidence of the 40- and 23-ky cycles in the paleorecord extends back in time for hundreds of millions of years (*12*). These solar variations do appear to influence the climate in a (temporally) linear fashion. However, the big climate changes, associated with the ~100-ky cycle (or before 1 My, 450-ky cycle), appear mismatched with the small solar irradiance variations due to eccentricity (<0.7 W m^{-2} over the past 5 My). Proposed mechanisms rely on the feedbacks of the climate systems to amplify the solar forcing, although some reports have gone so far as to suggest that the 100-ky cycle may be completely due to ice sheet instabilities and lithosphere deformation, as deglaciation proceeds through nonlinear interactions between the ice sheets, oceans, and lithosphere with little direct solar influence (*13*, *14*) (Table 2).

The inappropriateness of solar forcing for the 100-ky cycle has been suggested by observations implying the previous deglaciation was essentially complete by 135 ky (*15–17*) [e.g., Fig. 1 (*18*)], when solar irradiance was still low. The match between the paleorecord and the insolation is also poor for some other time periods, including the well-known discrepancy between 350 to 450 ka when a full glacial cycle has no corresponding insolation extremes. Computer climate model simulations of the beginning of the last ice age have generally shown the solar insolation change was not sufficient (*19*, *20*) unless additional, somewhat extreme feedbacks are hypothesized, which then lead to ice in inappropriate places (*21*, *22*).

Were the Sun completely unimportant, the disappearance of the last ice sheets timed to match increasing solar irradiance during Northern Hemisphere (NH) summer ~14 ka (Fig. 2) would be a coincidence. An intermediate suggestion would be that at this point in time the solar forcing could have acted to trigger the appropriate ice sheet instability, thus appearing to exert a prevailing influence on the climate. Alternatively, the solar irradiance and/or ice sheet changes could induce ocean circulation or trace gas changes (CO_2, methane), which would then provide much of the climate forcing and might help explain the lead of the Southern Hemisphere (SH) in some aspects of the glacial cycle. As emphasized by the opposing relations in Figs. 1 and 2, in a system with many competing nonlinear feedbacks a consistent response may be a naïve concept.

Centuries and Total Irradiance Change

Solar irradiance has now been monitored for the past 2 decades, and shows peak-to-peak changes on the order of 0.1%. Maximum irradiance occurs during sunspot maxima (*23*); though the sunspot itself reduces radiation, excess illumination is associated with the faculae, bright regions that surround the sunspots. This has led to attempts to reconstruct irradiance variations during the past millennia on the basis of variable sunspots, either directly observed or inferred from the variations in ^{14}C and ^{10}Be found in the paleorecord. With reduced sunspot activity, Earth's magnetic field is less disturbed and better shields the atmosphere from the high-energy particles that produce these isotopes. To produce solar irradiance changes >0.1% requires an additional mechanism when sunspots disappear for long periods of time (such as the Maunder Minimum, between 1645 and 1715), perhaps involving the background activity network on the Sun. Changes for this time period have been estimated in the range of 0.2 to 0.35% (*24*, *25*), similar to those estimated from the difference between cycling and noncycling Sun-like stars (*26*, *27*).

A total irradiance change of such magnitude used to force General Circulation Models (GCMs) produces a global average climate change of some 0.5°C (*28–30*). With respect to the global mean temperature, a reasonable match with some temperature reconstructions is achieved by models, particularly in the preindustrial epoch between 1600 and 1800 (Fig. 3). From this perspective, solar variations dominated climate in preindustrial times. That both the estimated solar irradiance and surface temperatures exhibit overall increases in the 20th century has led some empirical analyses (*31*) and model results (*32*) to claim that this dominance has

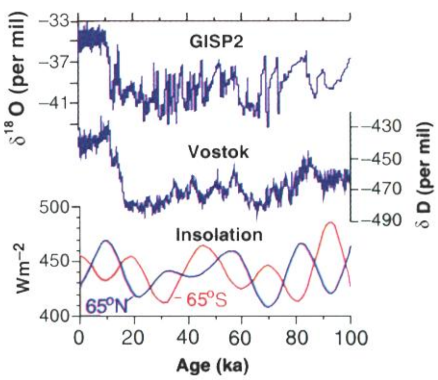

Fig. 2. GISP 2 and Vostok isotopic records, showing the latest deglaciation in phase with summer insolation at 65°N. [Reprinted from (*13*) with permission.]

extended through the first half of the 20th century (*33*).

However, a closer look at the observations indicates the climate system has been much more variable than implied by the global mean temperature. There is little consistency in the growth of mountain glaciers during the 'Little Ice Age' (i.e., 1500–1850 AD), with ice advances at different times that do not necessarily coincide with the reconstructed solar irradiance reductions (*34*, *35*). Nor does the Medieval Warm Period of higher reconstructed irradiance (1000–1400 AD), show consistency in warming from one region to another (*36*, *37*). At the very least, this implies that natural variations or other forcings of the system can override the climate's response to solar forcing of this (estimated) magnitude for particular regions. In addition, solar forcing of several decades' duration will have less effect on oceans, with their higher heat capacity, than on land, which sets up temperature gradients that lead to wind changes and changes in the advection of heat. Hence, some regions warm even when the globe cools (*29*). The failure to find cooling everywhere in conjunction with proposed solar reductions, therefore, does not mean that solar-induced climate changes have not occurred but rather that the system response is neither simple nor direct.

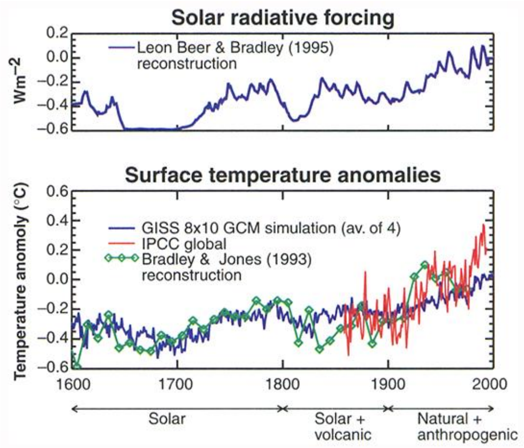

Fig. 3. Estimated solar radiative forcing (top) and global surface temperature anomalies, from both GISS model simulations (*29*) and observations. One canonical view is that solar forcing provides a good match for the observations before 1800, volcanic forcing becomes important during the 19th century, and anthropogenic forcing begins dominating during the 20th century. [Figure courtesy of J. Lean.]

Table 3. Total solar irradiance variations. Time scale, decades to centuries; mechanism, total solar irradiance changes, possibly in cycles, due to variations in active regions on the Sun alter Earth's radiative balance; forcing, 1 W m^{-2}.

What should have happened	What did happen
Reduced irradiance with reduced (sunspot) activity	Inconsistent climate correlations with sunspots
Global warming (cooling) with increased (decreased) solar activity	Neither warming nor cooling is ubiquitous or synchronous
No externally driven activity cycles in the Sun	Unclear whether apparent cycles in paleodata related to periods of big planets
What else happened?	
Solar irradiance estimated changes may be wrong	
Advective temperature changes may overwhelm radiative forcing	
Climate observations may be inadequate	
Natural variations (cycles) may dominate	

These concepts are highlighted in Table 3, as is a reference to apparent cycles in paleodata, which have also been related to cycles in the Sun. Such climate cycles are continually being reported, with the two most often-noted variations being the Suess (~210-year) and Gleissberg (88-year) cycles, seen for example in varved sediments (*38*) and in the isotope record (*39*). The 210-year cycle has recently been associated with droughts in the Maya lowlands (*40*) and East Africa (*41*), possibly influencing the demise of these civilizations. To what do these cycles refer? Are they natural variations within the Sun or natural cycles within the atmosphere-ocean system, either in the Pacific or the Atlantic (*42*, *43*)? (Although why such internal cycles should affect the isotope record corrected for accumulation changes is not obvious.) The Suess cycle has been related to the various astronomical phenomena, such as the angular momentum of the Sun about the center of mass, due to the periods of the four big planets or other orbital effects (*44*, *45*), a possibility most solar physicists reject. An approximately 1500-year cycle seen in the North Atlantic has been correlated with inferred changes in production rates of ^{14}C and ^{10}Be and, thus, may also be solar driven. This may be possibly amplified by North Atlantic deep water changes (*46*), another example of how feedbacks might significantly alter the nature of the climate response.

Decades and Spectral Irradiance Change

Many atmospheric phenomena exhibit decadal variability on both regional and global scales. Such phenomena have often been related empirically to solar cycle variations, on the order of 11 or sometimes 22 years (*43*, *47*, *48*). In some cases, the relation appears energetically realistic, in ocean temperatures (*49*), for example. However, in many instances, problems arise in establishing the physical link between the small magnitude of the forcing and the alleged response.

One possible explanation involves solar UV irradiance variations (*50*) affecting ozone, which then changes the temperature and wind patterns in the stratosphere, modulating planetary wave energy propagating from the troposphere. This, in turn, alters tropospheric planetary wave energy, wind and temperature advection, and a host of other climate phenomena. Observations (*51*) and GCM studies with sufficient coverage of the Middle Atmosphere (*52*, *53*) have converged on a number of these features, and its reality is becoming more firmly if not completely verified. This mechanism has also been modeled for multidecadal time scales, such as the Maunder Minimum, and found to result in higher pressure near the pole [the negative phase of the Arctic Oscillation (AO)] (*54*, *55*).

However, on both the decadal and century time scales, the planetary wave response cannot explain important components of the observations (Table 4). Shown in Fig. 4 (*56*, *57*) are the solar maximum minus solar minimum temperatures and heights during NH summer at various locations. This effect has not been duplicated in GCMs; in summer, planetary wave energy is smaller and the prevalence of east winds in the stratosphere further minimizes planetary wave influence. On the longer time scale, the Little Ice Age growth of glaciers in Western Europe is similarly unexplained by this mechanism alone. These glaciers respond to winter mass balance (snow accumulation) and summer temperatures (*58*). The AO [or the North Atlantic Oscillation (NAO)] has little direct expression during summer, and the negative phase produces negative mass balances for these glaciers during winter (*58*). In the GISS GCM, the negative phase also depends on substantial tropical cooling, which is not evident in the latest temperature reconstructions (*59*–*62*).

What else may have happened is indicated in Table 4. Eleven- or 22-year cycles have been related to internal mechanisms in the climate system, specifically anomalies in the ocean (*42*, *43*). Conceivably, these may be related to solar-induced variations, affecting either the surface wind field or deep-water production for the Little Ice Age. Other atmospheric mechanisms may be responding to solar forcing, such as the low-latitude Hadley Cell (*63*), although the energy mismatch be-

Table 4. Solar cycle spectral variations. Time scale, 11 years, possibly decades; mechanism, small solar UV variations affect ozone, stratospheric temperatures and winds, and propagation of tropospheric planetary waves (may affect natural atmospheric modes); forcing, 0.3 W m^{-2}.

What should have happened	What did happen
Effects propagate down from stratosphere	Downward propagation seen in observations but not in most GCMs
Effects much stronger in winter	Solar cycle effects also strong in summer
Multidecadal AO–NAO phase change depends on significant tropical response	Tropical response uncertain on expected time scales
What else happened?	
Solar forcing may be by some other mechanism	
Other atmospheric processes may be involved (e.g., Hadley Cell)	
Climate forcing may be by some other mechanism (e.g., ocean circulation anomalies) with or without solar involvement	

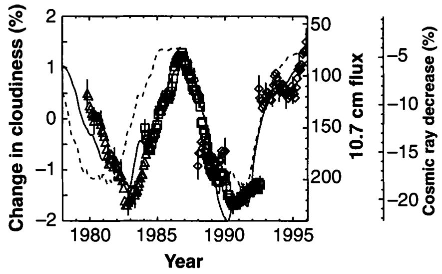

Fig. 5. Changes in cloud cover compared with the variation in cosmic ray fluxes (solid curve) and 10.7 cm solar flux (broken curve). Data is from Nimbus 7 and Defense Meteorogical Satellite Program (DMSP) (SH over oceans) and International Satellite Cloud Climatology Project (ISCCP) over oceans with the tropics excluded. All data smoothed with a 12-month running mean. [Reprinted from (*64*) with permission.]

tween the small solar input and the latent heat release driving tropical cells would require some especially sensitive catalytic component. Or the forcing due to solar cycle variations may be by some other means.

Variability and Geomagnetic Activity

Another characteristic of solar variability is fluctuations of plasma in the Sun-Earth space environment. Emitted solar protons, energetic electrons in the magnetosphere, and the interplanetary magnetic field all vary as a result of the basic solar magnetic dynamo that drives the 11-year cycle. Galactic cosmic ray (GCR) intrusions into the lower atmosphere respond to variations in Earth's magnetic field induced by its coupling with the interplanetary magnetic field and perturbations by eruptive solar events that propagate via the solar wind.

One aspect that has intrigued researchers is the possibility of charged particles acting as cloud condensation nuclei. If clouds are affected, the reasoning goes, significant impacts would undoubtedly follow because the clouds would alter the radiation balance of the atmosphere, altering climate (*64*). A presumed relation between clouds in specific regions and measures of solar activity is shown in Fig. 5 (*64*). High geomagnetic activity is thought to influence galactic cosmic rays, hence cloud condensation nuclei, and produce an increase in clouds when solar activity is low (allowing more cosmic rays to enter Earth's atmosphere).

The expectation and result associated with this mechanism is discussed in Table 5. The response should maximize at high latitudes where the input of GCRs (which enter Earth's atmosphere primarily along its polar magnetic field lines) due to solar variability is greatest, but in the observations analyzed it actually was largest at low latitudes (*65*). The GCR or the cloud response is not consistent with time; extending the record forward to the latter part of the 1990s produces no systematic change from the mid 1990s (*66*).

As noted in Table 5, the low-latitude phenomena may be responding to other things such as El Nino–Southern Oscillation (ENSO) changes (*67*). Our understanding of the influence of particle phenomena on the neutral atmosphere is not great, and subtle influences could be operative without our ability to observe them. Alternatively, the cloud cover variations may be driven by a different solar-induced mechanism such as changing UV radiation affecting the atmospheric circulation (*68*).

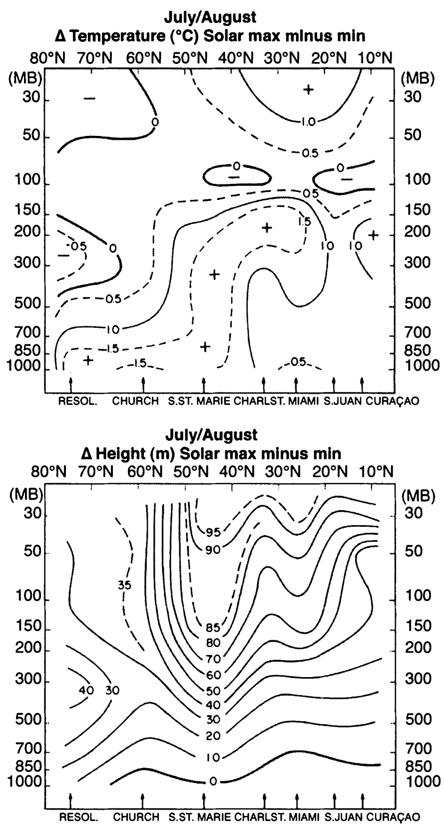

Fig. 4. Temperature and height differences between four solar maximum and solar minimum conditions during July and August at various stations between 65°W and 95°W. GCM simulations cannot reproduce the magnitude of this effect. More than 40% of the interannual temperature variance during this season is associated with the 11-year cycle (*57*). [Reprinted from (*56*) with permission.]

Conclusions

The common denominator among an array of potential solar forcing mechanisms operating on a wide range of time scales is that they all are interacting with system feedbacks or variability that may be stronger than the forcing

Table 5. Geomagnetic activity. Time scale, 11 years, possibly decades or more; mechanism, variations in relativistic electrons, solar wind, and galactic cosmic rays affect climate via changes in cloud formation; forcing magnitude uncertain.

What should have happened	What did happen
Cloud condensation nuclei increase with greater ionization	Real world effects uncertain
Increased low level clouds affect climate	Relation of clouds to solar cycle inconsistent with time
Response maximizes at high latitudes	Low level cloud effects greater at low latitudes
What else happened?	
Apparent low cloud effect may be due to other phenomena (e.g., ENSOs, natural variability, short data record)	
Apparent cloud effect may be due to other solar mechanisms (UV-induced circulation changes)	

itself. Ironically, this is true even for earlier time periods when the solar forcing was much larger. This state of affairs helps explain why potential Sun-climate relations are controversial and difficult to prove. It also implies that even if the solar forcing could be predicted, the response would still be uncertain due to our present incomplete understanding of climate system feedbacks and internal oscillations. There is no doubt that there are some clear signatures of solar forcing in the system, including some of the orbital variations and planetary wave–mean flow interactions and possibly total irradiance variations. Whether the Sun acts as the controller of climate changes on various time scales, simply instigates the subsequent feedbacks that then dominate the observed record, or is only a convenient explanation for unobserved forcings or system oscillations, will probably be a matter of debate and continued investigation for many years. The answer may also bear on whether the continued growth of atmospheric trace gases will dominate the system response or whether it too will be swamped by the feedbacks, making predictions of any response equally difficult.

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54. D. T. Shindell, G. A. Schmidt, M. E. Mann, D. Rind, and A. Waple [*Science* **294**, 2149 (2001)] find the negative phase for the AO during the Maunder Minimum.
55. J. Luterbacher, C. Schmutz, D. Gyalistras, E. Xoplaki, and H. Wanner [*Geophys. Res. Lett.* **26**, 2745 (1999)] reconstructed NAO values show a generally negative phase (higher pressure over Iceland) for the entire time period from 1700-1850. This would then not appear to be directly from solar forcing, which is thought to have been relatively high during the 18th century (Fig. 3).
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61. L. G. Thompson *et al.* [*Science* **269**, 46 (1995)] show tropical ice core data that indicates a temperature difference of greater than 1°C (Ô^{18}O>1 per mil) between the late 1600s and late 1800s. In contrast, the reconstruction in (*59*) shows no temperature change between those time periods. That is one reason why (*59*) shows essentially no correlation between temperature and solar irradiance for the 19th century.
62. Additional questions concerning the tropical temperature reconstruction arise from modeling studies. The simulation discussed in (*54*), which produced extratropical temperature responses (and AO phase changes) in general agreement with (*59*) has tropical temperature changes twice as large as those in (*59*); without that magnitude of tropical response, the planetary wave refraction and tendency for negative phase of the AO would have been greatly reduced in the model.
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