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On glacier retreat and drought cycles in the Rocky Mountains of Montana and Canada

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Abstract

The enigma of why mountain glacier started to retreat in the 1850s in the Rocky Mountains and elsewhere remains unresolved. The most important factor affecting climate change presumably was a change in the mode of operation of the sun one or two decades earlier, (from irregular periodicity and low output to regular periods and greater brightness). But the direct cause appears to have been the onset of drought in the 1830s. Interestingly, there is no obvious solar information in the drought narrative in Montana and southwestern Canada. The presence of tidal lines in the spectrum of the Pacific Decadal Oscillation, together with the presence of lines that could be interpreted as beat periods between solar and tidal forcing in the drought series, suggests that the energy of solar variation is preempted for interference with tidal forcing, within the system of oscillations informing precipitation patterns in the region. The suggestion is supported by the presence of a strikingly dominant 12.5-year period in the drought series, which is interpreted as a difference tone between the main sunspot cycle (at 10.8) and a tidal period at 5.8. Also, this period is close to 2/3 of the nodal tide (at 18.61).

1. Introduction

When visiting the Glacier National Park in Montana, one notes that most of the ice bodies in the cirques rimming the mountain peaks are surrounded by bare rock and fresh moraines, suggesting rapid retreat of the ice. In fact, glacier retreat in the region is well known and well studied, not just for Montana, but for a large region of the Rockies bearing ice fields and pocket glaciers, including southwestern Canada (Hall and Fagre, 2003; Ommanney, 2007). Retreat started in or about the 1850s, and has continued since, slowing and accelerating in response to changes in winter precipitation and summer warming. Retreat accelerated within the 1920s (Ommanney, 2007). The overall range of retreat is remarkable. In Banff National Park, for example, ghost glaciers (represented only by moraines) and small remnant glaciers flanked by rubble are the rule rather than the exception (Fig. 1). It seems reasonable to ascribe much of the retreat to global warming since the middle of the 20th century, as the melting of mountain glaciers is one of the most conspicuous consequences of modern greenhouse warming (IPCC, 2008). However, this obvious link leaves open the question why the retreat started in the first

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place, in the 1850s. Presumably, at that time, effects from the excess greenhouse mechanism were still too small to have triggered the process.

Figure 1. A common sight in the Canadian Rockies: small remnant ice bodies well above the moraine rubble that fills the site of substantial glaciers recently vanished. Stanley Glacier, Kootenay National Park, Aug. 2005.

The question about the initiation of glacier retreat in the Rocky Mountains and elsewhere in the high mountains of the northern hemisphere is intimately connected to the question of why the Little Ice Age ended in the 19th century. Many who studied the problem have thought that changes in the brightness of the sun are responsible, following a suggestion of Eddy (1976). The concept is attractive, because the retreat of mountain glaciers seems to be a global rather than a regional problem; glaciers in the Alps and in the Rockies retreat in unison (Oerlemans, 1994, 2005). However, the connection between solar activity and climate change has been an elusive and difficult subject (reviewed in Hoyt and Schatten, 1997, and by Pap et al., 2002; recent modeling results are presented in Ammann et al., 2007). While it is likely that a changing sun is indeed an important agent in the Holocene climate narrative (Chambers et al., 1999), the manner in which the link is created has remained obscure. Some have proposed that, in addition to changes in brightness, modifications of the composition of the atmosphere are involved (e.g., Foukal et al., 2006; Svensmark et al., 2007).

Arguments linking solar activity to climate change on centennial time scales commonly call on the history of radiocarbon and of beryllium-10. Both isotopes are produced in the atmosphere by processes involving cosmic ray flux modulated by solar activity. Also, both isotopes become part of their own geochemical cycles, which are modified by climate change. Thus, it is not always clear, when comparing radiocarbon or beryllium stratigraphy with the climate narrative, which is cause and which is effect. A relatively safe assumption, based on direct observation, is that there is indeed a link between the number of sunspots and the brightness of the sun (Lean, 1997, 2002). In any case, sunspot cycles do show sufficient relationship to recent climate history to support the idea that they are relevant to the question under discussion (Scafetta and West, 2006).

Independently of the history of solar activity, significant insights have been gained in recent years from the discovery of intriguing teleconnections, such as the fact that drought cycles in North America are somehow linked to changes in the surface temperature of large regions of the ocean (Cayan et al., 1998; Biondi et al., 2001; Hidalgo-Leon, 2004; Cook et al., 2007). More specifically, we learned that the winter snow in the Rocky Mountains depends on the state of the Pacific Decadal Oscillation (McCabe et al., 2004; Pederson et al., 2004). If drought cycles are important in informing the growth and decay of mountain glaciers, we must inquire about the origin of large-scale climatic variability in the sea, to find clues for the initiation of glacier retreat. Such ocean-climate oscillations, by definition, have the nature of cycles, although the periods involved are not fixed through time (Biondi et al., 2001; Wilson et al., 2007), but vary according to rules that have not been explained in satisfactory fashion.

In this essay, I review the evidence that the onset of major drought around 1840 (Watson and Luckman, 2004) helped initiate the retreat of mountain glaciers in the Rocky Mountains in the northern U.S. and southern Canada, using published data from tree-ring studies (Cook and Krusic, 2004; Cook et al., 2004). Furthermore, I suggest (as have others) that there is a shift of periodicity from short climate cycles to long ones in the 1850s (in the present case involving precipitation). It is puzzling that the spectra before and after this shift show no solar influence whatever; in fact, the absence of solar cycles is sufficiently striking to invite comment. Finally, I consider the connection to the Pacific Decadal Oscillation, and point out that its cycles are dominated by tidal information. An obligatory interaction between solar cycles and tidal cycles could conceivably explain the absence of solar cyclicity in the spectrum of drought, as well as the prominence of a precipitation cycle centered near 12.5 years. If the suggestion has merit, it supports the pioneer work of Currie (1981, 1991; 1993), who has long argued that both sun and moon are important in influencing the climate narrative in North America.

2. Drought: the Narrative and the Cycles

Evidently, a glacier maintains its bulk if and only if the snow feeding it in its upper portions equals the ablation of ice in its lower reaches. The downward gravity-driven motion of the ice, across the ablation zone, keeps the overall topography in balance. In principle, therefore, we can expect that a glacier will retreat for either of two reasons: a decrease of incoming snow feed, or an increase of summer melt, or both. The second factor has attracted more interest than the first, on the whole, so that glacier retreat is commonly linked to warming. This makes good sense, since there is much evidence for warming in the second half of the 19th century, in the entire northern hemisphere (Jones and Moberg, 2003). On the other hand, the wet side in ice-bearing mountains, where most of the snow is dumped by moisture-bearing winds, is generally seen to have the bigger and lower-reaching glaciers in the ranges of Norway, and the history of changing winter precipitation lines up with the growth and retreat of these glaciers (Nesje, 2005). Thus, even with warming, some glaciers can grow, and even with cooling, some can retreat, depending on precipitation patterns (Shea et al., 2004).

When comparing precipitation (or the inverse: drought) with the behavior of glaciers, we would not expect an immediate response of large ice mass to fluctuations from year to year. Instead, glaciers presumably act as cumulative devices, with delayed and integrative response. For this reason, it seems logical to adopt a strategy of keeping track of the sum of drought indices over a properly defined time span ("look-back" accumulation) for defining the relevant quasi-instantaneous environment of glacier growth and decay. The time span of looking back should be appropriate for the response time of the ice in the particular ice mass considered, and will vary greatly. For present purposes, which involve raising general questions rather than offering answers concerning specific glaciers, I have taken a look-back interval of twenty years as a useful time interval; that is, indices at any one point in time are summed for the previous two decades.

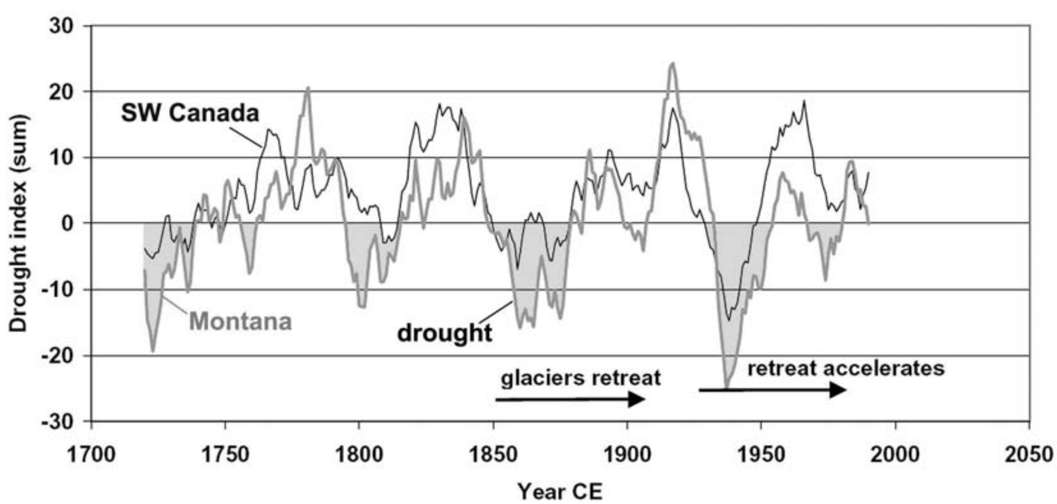

Figure 2. Drought look-back series for southwestern Canada (solid line) and Montana (gray line). Each point accumulates the drought indices for the previous twenty years. The data (based on tree-ring information) are from the NOAA drought project (Cook et al., 2004; Cook and Krusic, 2004). Shaded: times of severe drought in Montana.

A comparison of the long-term drought patterns in the Rocky Mountains north and south of the U.S.-Canada border shows great similarity, with inferred precipitation fluctuations in the north being slightly subdued relative to those in the south (Fig. 2). These patterns, incidentally, also reach well into Utah (not shown), but not into Arizona, where the history of drought follows a different path. Thus, when studying these particular drought patterns of Montana and southwestern Canada, there is no direct implication for "western drought" or any similar abstract entity involving large areas in North America.

It appears that glaciers initiated retreat (in the 1850s) when they were starved of precipitation (Fig. 2; the drought indices for Montana are more reliable than those for SW Canada, according to Cook et al., 2007). Also, the acceleration of their retreat in the late 1920s and 1930s (as given in Ommanney, 2007) fits well with the onset of long-term drought in the region. However, there is a lack of recovery and re-advance early in the 20th century, which is quite puzzling. Also, the lack of recovery within the second half of the 20th century is not readily explained, since temperatures in North America only increase strongly from around 1980 (Jones and Moberg, 2003). Perhaps the somewhat lower precipitation values reflected in the cumulative drought index for Montana (Fig. 2) are relevant, at least up to the point when warming was strong enough to take over. Even then, within the last two decades, drought must be considered an important factor.

Identifying long-term drought as the trigger for glacier retreat in the region leaves open the question why glaciers retreated elsewhere on the planet (reviewed in Oerlemans, 1994, 2005) and why there was a long-term drought spell in Montana in the first place. One might invoke stochastic processes (admitting that interacting oscillations in the climate system are sufficiently chaotic to defy any attempt at introducing deterministic apects), or one might look to changes in the chief forcing agent of climate change, the sun. As it happens, the sun does change its mode of operation in fundamental ways at roughly the right time, a point taken up again in the Discussion section.

To attempt to understand something about the fluctuations in the patterns of precipitation through time, one might profitably turn to the nature of periodicities within such fluctuations. If there is outside forcing of oscillating climate systems from the sun or from a combination of sun and moon (for literature review see Hoyt and Schatten, 1997), we should see sharply defined peaks within the spectrum of climate proxy series, peaks that relate to solar activity and tides, or both. Of course, when considering tidal lines in such spectra, one must be aware that the recording devices themselves (sedimentary basins, coral growth) may be directly influenced by tides (Berger et al., 2002, 2004). Thus, the evidence for tidal forcing in such records does not necessarily support an argument for a tidal effect on climate. However, when finding a tidal signature in tree-ring series (Currie, 1981, 1991) a link to precipitation is difficult to explain away.

The analysis of the combined drought series of Montana and southwestern Canada (using a Fourier scan of the autocorrelation series; Berger et al., 2004) yields a spectrum that has some interesting properties (Fig. 3). Two of these stand out: a strikingly sharp and high peak near a period of 12.5 years, and a total lack of power in the vicinity of solar periodicity (marked sol in Fig. 3). Another line that is lacking is one near 22 years, widely present in drought series in the "western United States" according to Mitchell et al. (1979). It is indeed well represented in the drought series south of Utah (not shown) but not in the set here analyzed. The highest and sharpest peak in the range of periods shorter than decadal ($\log F > -1$) is a peak near 5.8. (This period is also prominent in the spectrum of the ENSO oscillation; that is, the air pressure difference between Darwin and Tahiti.) In passing, we note three things. First, a fractional period is an extraneous element within climate fluctuations that are presumably strongly tied to seasons. We should expect a strong representation of the smallest whole-number multiple of this period (at 29.0). Second, the beat period [axb/(a-b)] of 5.8 with the main solar cycle (at 10.8) is 12.5. Third, the value of 5.8 is within less than 1 permil of the beat period of the two main multi-annual tidal lines (at 18.61 and 4.425). The possibility arises, then, that the reason for the missing solar lines is the capture of their energies into a beat period, by interaction with tidal forcing. We shall return to these topics in the Discussion section.

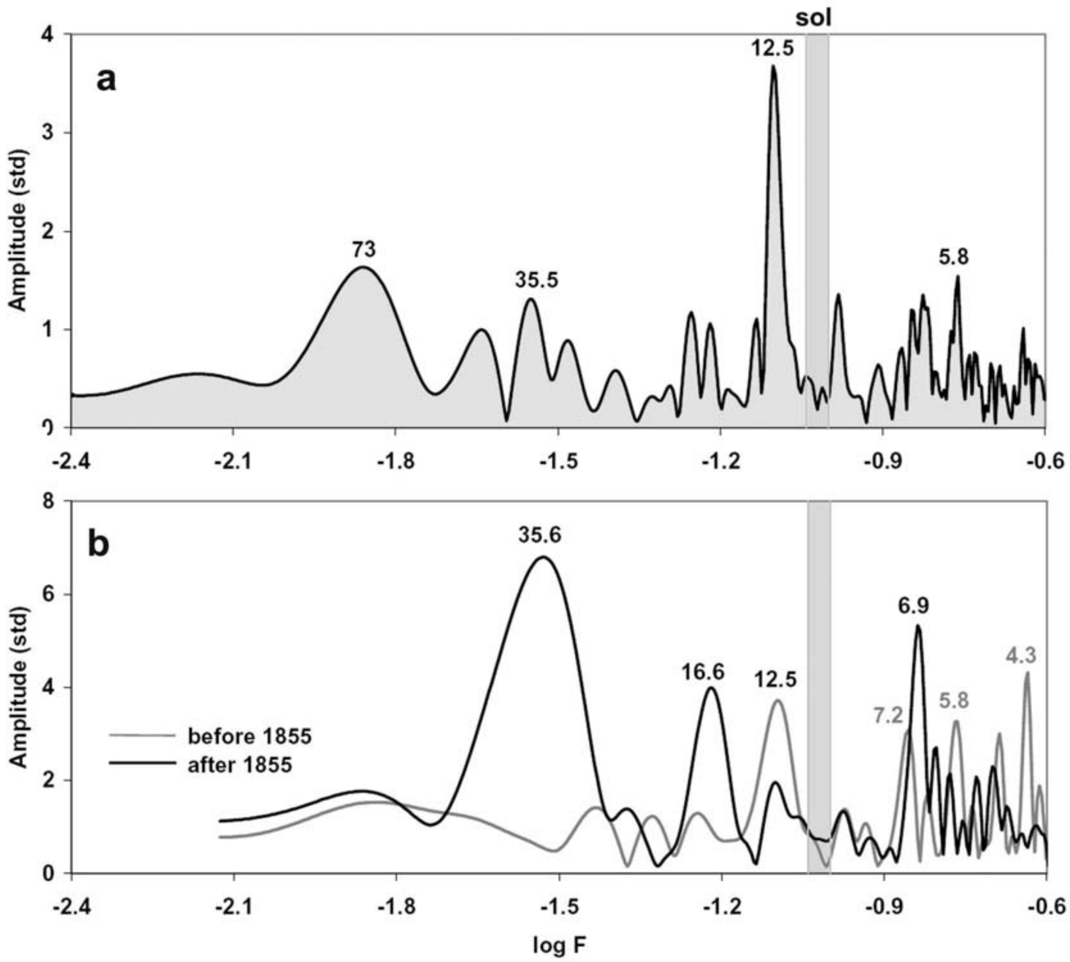

Figure 3. Periodogram for the drought index series (PDSI) of Montana and southwestern Canada (combined). **a**, 1700-1990; **b**, 1720-1855 and 1855-1990. Data from NOAA drought project (Cook and Krusic, 2004; Cook et al., 2004).

To explore the changes that occurred in connection with the retreat of the glaciers in the 1850s, we examine the spectra for the periods before and after that time (Fig. 3b). Evidently, there was a distinct shift from relatively short-period fluctuations to a longer cycle centered between 35 and 36 years (a climate cycle thought prominent by E. Brűckner, late in the 19th century: Stehr and von Storch, 2000). The lengthening of precipitation cycles (at 16.6 and 35.6) allowed the pile-up of deficit during the drought phase of the cycles, in the look-back mode that applies to glaciers (Fig. 2). Power at solar cycles remains missing in both series, and the 12.5 line is present in both. A line near 6.9 appears after the shift (reminiscent of the North Atlantic Oscillation), and lines near 5.8 and 4.3 (presumably of tidal affinity) tend to disappear. The only agreement in the two series is the presence of power near 12.5 and the absence of solar-cycle information (as already implied by the spectrum in Fig. 3a). While the shift from short to long cycles seems important when attempting to explain the retreat of glaciers in Montana, it is not clear what might have caused the shift, unless it be the interaction of different types of oscillations, coinciding and re-enforcing each other (e.g., Minobe, 1999).

3. Periodicities in the Pacific Decadal Oscillation

The Pacific Decadal Oscillation – a mathematical entity based on temperature anomaly patterns and reflecting, in part, the fluctuations in the strength of the Aleutian Low and conditions in the western Pacific– is captured in the PDO index. It is based on anomalies of sea surface temperature distributions in the North Pacific and thus reflects both temperature and pressure anomalies in the Pacific, with implications for wind fields and the transport of heat and moisture. The PDO strongly influences the precipitation narrative in the region considered (Gershunov and Barnett, 1998; Biondi et al., 2001; D'Arrigo et al., 2001; McCabe et al., 2004) and to a lesser degree also elsewhere (Latif and Barnett, 1994; Cayan et al., 1998; McCabe and Dettinger, 2002; McCabe et al., 2004; Frauenfeld et al., 2005; Cook et al., 2007; for background, see the review by Mantua and Hare, 2002). A positive index (warm western Pacific) is associated with a higher probability for precipitation on the adjacent continent. The PDO may owe some of its power to stimulation by ENSO-related processes (Deser et al., 2004). Also, ENSO-based variations, by themselves, may influence rainfall patterns in much of the West (Ropelewski and Halpert, 1987). In what follows, we stay with the observation that the PDO is important in the region under discussion.

One way to assess the influence of the PDO on precipitation in the region of interest is to compare its spectrum with that of the drought narrative – a high correlation is only possible if the periodicities show a good match. The PDO series is available from Nathan Mantua, University of Washington, Seattle; it spans the 20th century. As is known from previous studies (cited in Mantua and Hare, 2002), there is a prominent periodicity in the "duo-decadal" range, between 15 and 20 years (Fig. 4). More precisely, the period in question is centered on the value of 18.6, which is within less than one permil of the tidal period long ago identified by Currie (1981) as being present in the temperature and rainfall variations in North America (nodal line-up at 18.61).

Comparing the spectrum of the PDO with that of the drought series (Fig. 3) one notes the possibility that the prominent drought period near 36 years could serve for lining up the two series in ways favorable to produce correlations, provided the phase is correct. The one common period is the one near 5.8, close to the tidal difference tone (18.61#4.425=5.805) and whose smallest whole-number multiple is 29.0 (signifying that for every fifth cycle, there is a coincidence with seasonal information). Besides the line at 5.8, there is one other thing that the PDO and drought series have in common; that is, the lack of energy at the period of solar variation (between 10 and 11 years). On the whole, the PDO spectrum is rather simple, with only three peaks being prominent. Longer records, naturally, yield longer periods of variation and more variety in the shorter periods, as well. For example, Wilson et al. (2007) report oscillatory modes at 18.7, 50.4, 38.0, 91.8, 24.4, 15.3 and 14.1 (in this order) for tree-ring data in the Gulf of Alaska. Interestingly, the dominant mode is again the familiar tidal line near 18.6. The line at 50 is a fourfold multiple of the 12.5 line so prominent in the drought spectrum.

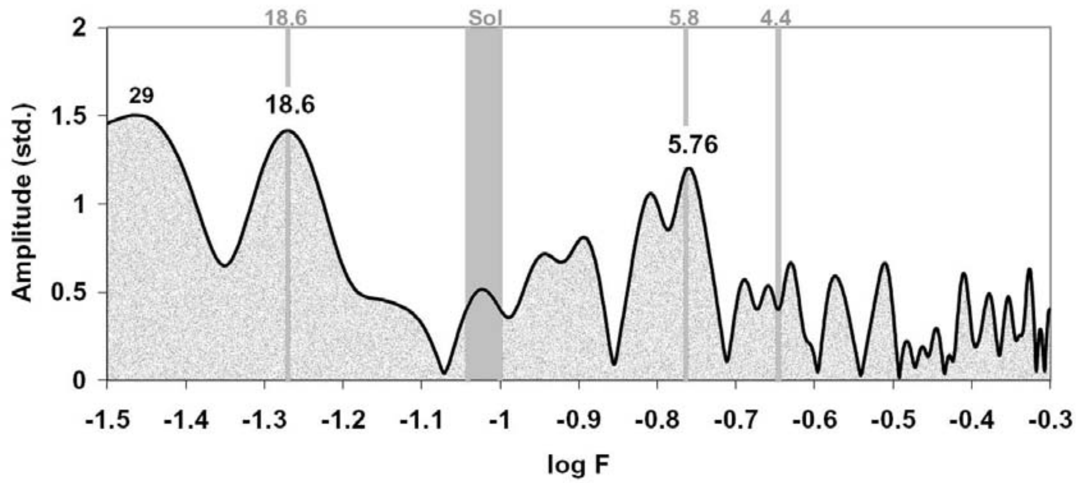

Figure 4. Periodogram of the index of the Pacific Decadal Oscillation (for definition, see Mantua and Hare, 2002). The index describes conditions in the Pacific, involving the strength of the Aleutian Low and the temperature of surface waters in the California Current and the eastern tropical Pacific. The vertical gray lines mark the position of tidal periods, which are given. “Sol” refers to the position of solar cycles (10-11). Data are from Nathan Mantua, Seattle.

It appears, from this type of examination of the evidence, that the drought series spectrum indeed has some properties that could derive from the PDO, and that such similarities as are evident may be related to tidal forcing, in preference to solar forcing.

4. Discussion and Conclusions

The results of scrutinizing the periodicity in drought series and in the PDO are interesting but inconclusive, in regard to finding a driver for drought. Also, the lack of a link into solar forcing of either series is somewhat surprising. Concerning the initiation of the retreat of glaciers in the middle of the 19th century – the main problem at issue in the present essay – one would surely suspect that the sun had a role in it. When studying the history of sunspot activity (e.g., Lean, 2002; see Fig. 5a), one notes that there is an important shift in the sun’s mode of operation around 1835 (marked S). The previous 80 years had irregular cycle length, and many solar cycles with very low sunspot numbers. The years that follow had regular, high-energy cycles. Clearly, there is here a potential source for a large shift in climatic conditions, both from the increase in the activity of the sun, and the increase in well-defined periodicity (Fig. 5b).

Well-defined periodicity in solar activity, presumably, creates opportunities for regular interaction with tidal forcing, favoring large amplitudes in the fluctuations arising from interference. While tidal lines are in evidence both in the drought series and in the PDO, tides cannot be made responsible for a change in conditions: they are invariably the same over geologic time spans. Thus, the origin of natural climate shifts, if forced from the outside, must be with solar forcing. The lack of solar power in the spectra of climate variation here analyzed is an anomaly that needs to be explained.

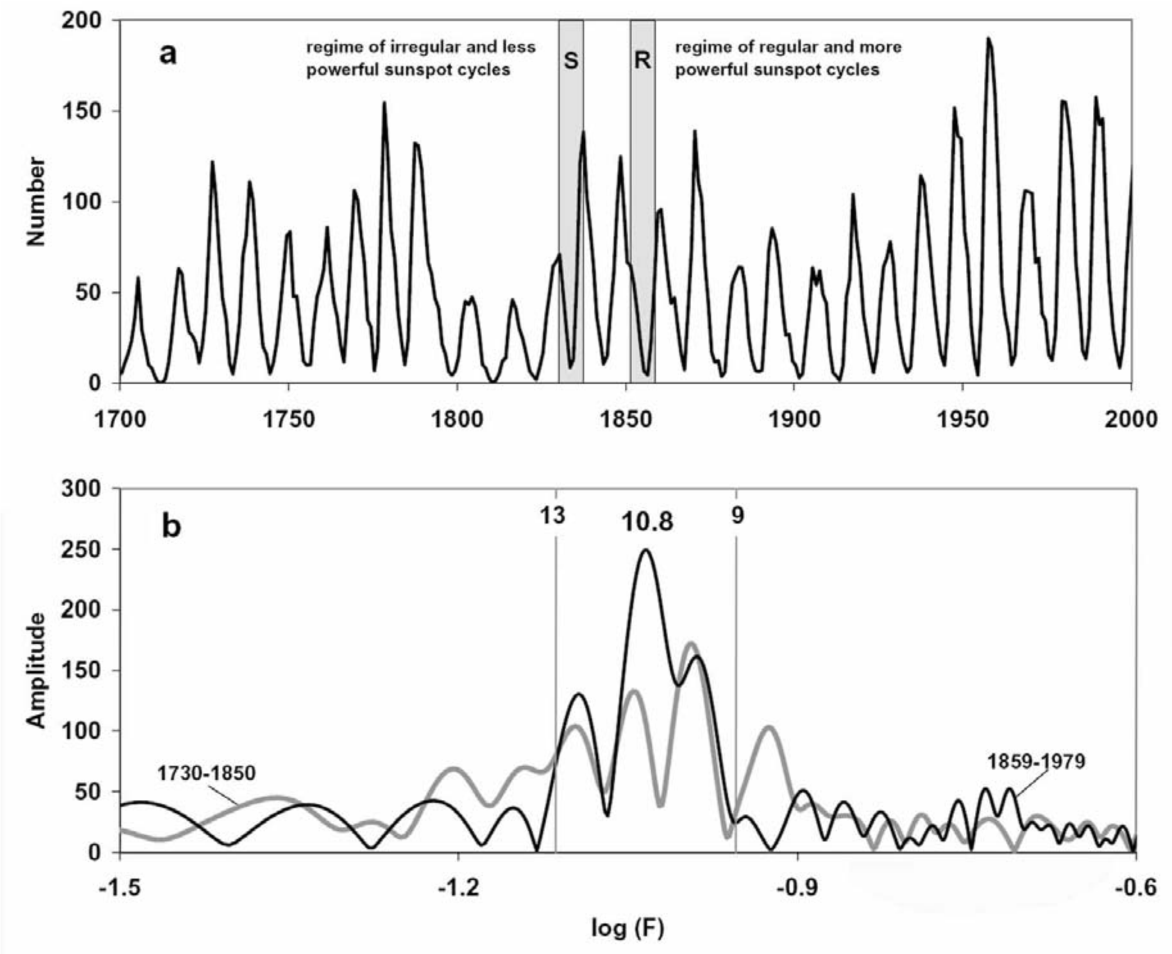

Figure 5. Sunspot activity since 1700 and its change in the middle of the 19th century, as seen in the change of periodogram properties. a, series since 1700 CE; b, spectra for the two time spans marked. S, shift in the nature of solar cycles. R, retreat of glaciers and regime shift in climate (i.e., change in the nature of oscillations).

I suggest that the energy belonging to the solar range (10-11 years) has been captured into beat cycles generated by the interaction of solar cycles with tidal-range fluctuations. (The possibility of such beating is mentioned as a mechanism for generating 25-year cycles by Hoyt and Schatten, 1997, p. 167, but not endorsed.) By simple math, the nonlinear interaction of solar and tidal cycles will produce cycles near 7.5, 12.5, and 25 (with tidal periods of 4.425, 5.805, and 18.61, respectively). The two latter beat cycles

(12.5 and 25) re-enforce each other, and lines at or close to these values are indeed ubiquitous in drought cycles and climate oscillations. The main conclusion from this analysis is that the sun may indeed be prominently present, but in cryptic form, hiding its influence by interaction with tides. This conclusion is in accord with evidence from periodicities within the North Atlantic Oscillation (Berger, 2008). In addition, it is noteworthy that the nodal tidal cycle by itself (18.61) has a simple relationship to the 12.5 cycle: a ratio of close to 2/3. Thus, a direct lock-in is conceivable, which would favor recurrent appearance over long time spans (as seen e.g. in the sediments of the Santa Barbara Basin; Biondi et al., 1997).

That tidal range may be important in helping to generate SST anomalies in large shelf areas (such as the Bering Sea) seems obvious. That such anomalies would in turn influence the level of pressure in the region of the Aleutian Low appears likely, although it remains to be established whether this is the case, and if so, whether it is important. In any case, the presence of tidal information in the climate of the interior of North America (Currie, 1981, 1991) holds no mystery if it is assumed that sea surface temperature distributions in the ocean owe some of their variability to the tides.

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