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Solar modulation of the North Atlantic Oscillation: Assisted by the tides?

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Abstract

Several prominent lines in the spectrum of the North Atlantic Oscillation (NAO) are here considered as resulting from solar–tidal modulation. Lines near 8.9, 7.7, and 5.8 years are proposed to be a result of energy capture from internal oscillations into periods resulting from interference of solar and tidal cycles near 11 years (solar) and at 18.61 and 4.425 years (tidal). The dominant period in the range 10–5 years, near 7.74 years, is explained as a result of lock-in of mutually supportive interference cycles; that is, the difference tones between solar cycles near 10.3 years, and the two tidal periods. At the solar period of 10.33, the two difference tones (7.74 and 23.22) are separated by precisely a factor of 3.

1. Introduction

The interest in the North Atlantic Oscillation (NAO), when discussing drought patterns in the western regions of North America, derives from two sources. Firstly, according to McCabe et al. (2004), drought frequency in the western states of the US is highly correlated with multidecadal oscillations in sea surface temperatures in the northern North Atlantic. Secondly, multidecadal fluctuations presumably are linked to the shorter fractional periods of the NAO, by the fact that climate variability is tied to seasonally varying factors. That is, if forced by fractional periods, one would expect the smallest whole-number multiple of such periods to accumulate power (Berger et al., 2004). Power in the NAO, as reconstructed by Jones et al. (1997) (in Jones and Mann, 2004) back to 1824 (Fig. 1), is concentrated between the periods of 5 and 10 years. Thus, one important task is to try to understand the origin of the oscillations within this range.

The NAO is largely determined by the strength and position of the Icelandic low-pressure region during winter, which steers heat-bearing marine winds into NW Europe during the positive phase, and fails to do so during the negative phase (Wefer et al., 2002; Hurrell et al., 2003). The origins of the cycles within the 5–10-year band are obscure, but their positions suggest the possibility of external forcing. This is not to say that external forcing *causes* the oscillations. Instead, a steady and regular tapping of the oscillating system by outside forces causes energy to flow from ill-defined internally driven fluctuations to well-defined periodicities linked to celestial pace-making. The phenomenon, called ‘‘nonlinear resonance,’’ is well known in chaos theory as applied to climatic fluctuations. It provides a plausible framework for explaining ice-age climate cycles, where the Milankovitch mechanism provides the timing, and internal delayed feedback linked to ice buildup and decay creates long-term oscillations (Ghil, 1994; Berger, 1997; Berger et al., 2002).

In a similar manner, the history of the NAO suggests the presence of periods related to celestial mechanics. In fact, several major lines within the NAO spectrum can be rationalized by admitting combined solar and tidal forcing as important factors in the modulation of the oscillations. Of course, the possibility of solar forcing of North Atlantic climate fluctuations has long been considered, from early in the century (Sverdrup, 1918) to the present (Hoyt and Schatten, 1997; Lean, 2002; overview in Hurrell et al., 2003). The point I make here is that the sun’s influence emerges when combined with tidal forcing.

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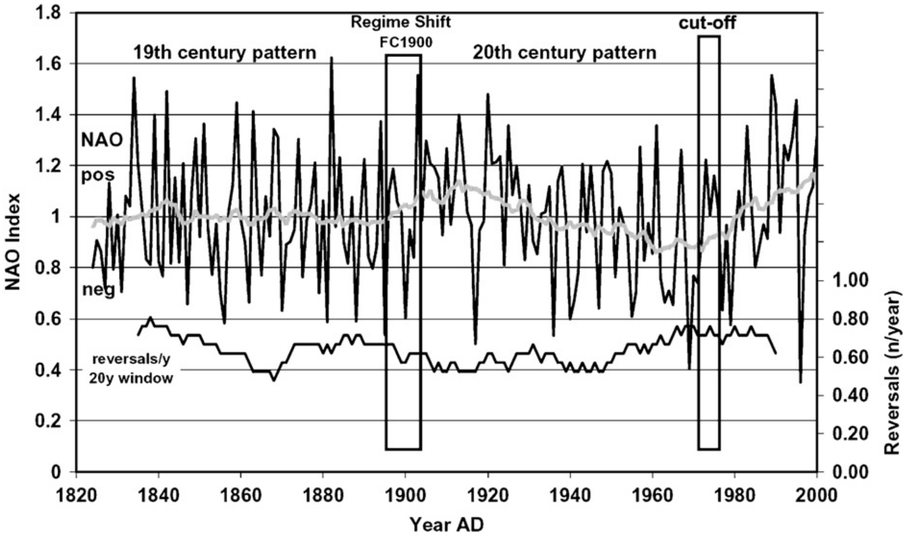

Fig. 1. Fluctuations of the NAO index between 1824 and 2000, as given in Jones and Mann (2004) and renormalized (avg. = 1; std. = 0.25). Two regimes are here recognized: a 19th century pattern with a high rate of reversals, and a 20th century pattern with a dominantly low rate of reversals (till 1950) in a 20-year gliding window. The time after 1975 may have anthropogenic effects in addition to those from natural background (see text).

2. Observations and questions arising

2.1. *Spectrum of the instrumental record of the NAO*

A great number of NAO reconstructions for several centuries into the past have recently emerged (Jones et al., 1997; Cook et al., 2002; Luterbacher et al., 2002; Meeker and Mayewski, 2002; Vinther et al., 2003; Jones and Mann, 2004) and their results are available for study. (For a compilation, see Jones and Mann, 2004.) Here I concentrate on the actual record of pressure differences between Iceland and the Azores (or Gibraltar), as collected and processed by Jones and collaborators and presented in Jones and Mann (2004). This record goes back to 1824, and is based on measurement rather than on the interpretation of proxies (as are all records longer than this). It has data for 176 years. It is entirely adequate for the study of periods less than 30 years (six cycles) and more than 2 years. There is an overall shift in the nature of the oscillations around the year AD 1900 (Fig. 1). Before that time, the number of reversals is greater than after it. Also, the 20-year mean is more variable after 1900 than before it.

An arbitrary cutoff was introduced at 1975, since the mid-1970s have been identified as a possible turning point in the ongoing climate change (Osborn et al., 1999; Hu and Wu, 2004). After this time, we may no longer deal with an entirely "natural" system, but with one that is substantially influenced by anthropogenic effects. I have excluded this portion from a pre-1900 versus post-1900 comparison (but not from the "all-data" set). Making the cutoff at 1975 has the additional advantage that the series to be compared (pre- and post-1900) are of equal length.

The periodogram of the all-data series (Fig. 2) resulted from a Fourier scan of an autocorrelation series. In the scan, the spacing between cycles fitted to the series is prescribed as $n_i/100$; that is, each successive fit has a cycle of length 1% shorter than the previous one. In a standard analysis, for comparison, the spacing is set as $1/n-1/(n+1)$, which yields unequal resolution for low and high frequencies, and invites producing the type of difficult-to-read plot that is usually seen in the literature on climate cycles, with the x-axis labeled in terms of cycles per year. The output in the scan here used is plotted in terms of logarithm of frequency. With a change of sign, this yields the period. Thus, the period "20" is at 1.3, "10" is at 1, and "4" is at 0.6, for example. The minus sign (frequency) reverses the order of plotting but does not affect the ease of reading. A factor of 2 is the distance of 0.3 along the x-axis.

The result of the analysis is that the oscillation series shows no response to solar cycles that goes beyond the noise level. Thus, one can state quite categorically that direct solar forcing is not obviously involved in producing the oscillations. Also, there is little or no response to the two main periods of the tides, which are linked to periodic line-up of Earth, Sun and Moon (18.61 years, nodal period, N in Fig. 2) and Earth's minimum distance to the Moon (4.425 years, perigee period, P in Fig. 2). However, two of the four observed periods (8.9 and 5.74) within the NAO-defining central band (labeled "activity center" in Fig. 2) are extremely close to periods that may be involved in tidal forcing. The period "8.9" is between one half the nodal cycle (9.3) and twice the perigee cycle (8.85), and close to both. The period "5.74" is only 1% off the difference tone between nodal and perigee cycles, which is at 5.8. If this correspondence is more than coincidence, we must then consider the possibility that none of the primary cycles, by themselves, find their way into the oscillations, but that when they combine forces they can do so.

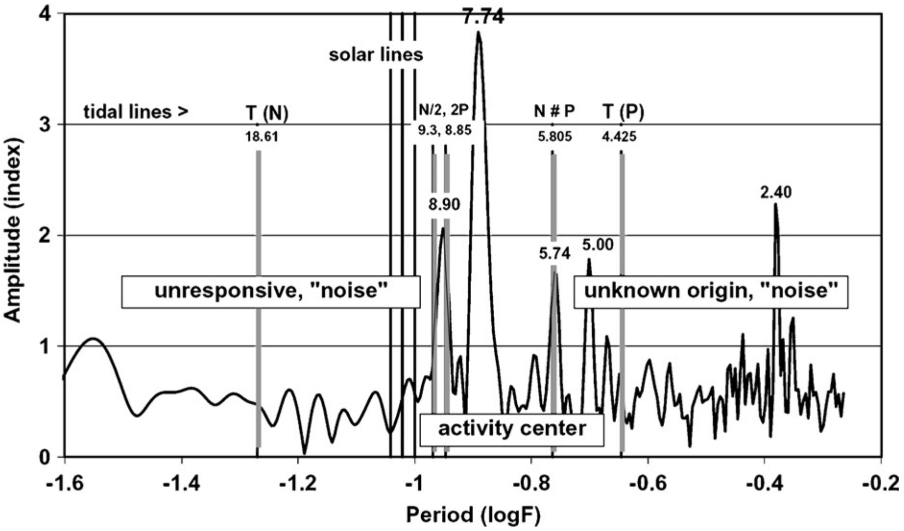

Fig. 2. Periodogram for the NAO index between 1824 and 2000. The most important lines are (in order) 7.74, 8.90, 5.00, 5.74. Expected for solar forcing are lines near 11, 10.5, and 10 (as shown). Tidal lines are near 18.61 (nodal cycle), 9.305 (one-half same), 8.85 (double perigee cycle), 5.8 (difference tone nodal and perigee), and 4.425 (perigee cycle). *X*-axis is the period, plotted as log of the frequency. A difference of 0.3 on the *x*-axis translates into a factor of 2 for period in years.

2.2. Concerning the 7.7-year cycle

The dominant cycle, with a period near 7.74 years, is neither readily interpreted as being of solar or of tidal origin. Thus, the discussion so far has not produced any explanation, however tentative. It should be pointed out, and this is of crucial importance to the entire argument, that this particular period is strong within the central NAO band over centuries. Its status as the lead period in the NAO frequency band is clearly indicated in the 600-year proxy record of Cook et al. (2002) who ascribe to it a 95% confidence level (ibid., their Fig. 7). It seems reasonable to assume that as long as we cannot explain this cycle near 7.7, we remain in the dark about the origins of the NAO, or at least of its cyclic components. No ready explanation is available for the definition of the 7.7-year cycle, judging from a lack of discussion of the issue. It would seem that outside forcing must be considered in the search for a viable hypothesis; rejection of this concept would imply (incorrectly) that the 7.7-year cycle does not exist or that is not important to our understanding of the NAO.

We have seen that an argument can be made, regarding the two major periods neighboring the main NAO cycle near 7.7, of the type that it is the combination of two potential forcing periods that can conceivably produce the observed periodicities in the oscillation record. Could the same argument be made for the ca.-7.7-year cycle?

The logic would be straightforward: If the solar cycles and the perigee tides are cooperating, we should get a difference tone with a period between 7 and 8 years. For an 11-year cycle, to be precise, the difference tone would be 7.40. While this is encouraging regarding the general vicinity of the calculated period in respect to the one observed, the difference of several percent is unsatisfactory. For a precise fit of the calculated and observed period, we would have to enter a solar cycle of 10.33. While this is about as close to the average length of the solar period as is the commonly used value of 11.0, and thus equally valid an assumption as is invoking a 11-year cycle, it would be entirely arbitrary to claim that 10.33 somehow represents the "true" forcing cycle of solar activity. In fact, this may be the case, as the theoretical analysis will suggest. But first we need to learn more about the nature of the 7.7-year cycle. The cycle comes and goes, and this is also true for many other sharply defined cycles in the range between 10 and 100 years, in North Atlantic climate fluctuations (e.g., Meeker and Mayewski, 2002).

In the case at hand, we can readily verify that the 7.7-year cycle is dominant after 1900, but not before (Fig. 3). The 5.8-year cycle, proposed to be tidal in nature, appears restricted to the time after 1900 in this record. Why should sharply defined cycles appear and disappear? It has to do with the nature of the forcing functions collaborating within the system. First of all, for the cycles to be both well defined and anything other than whole numbers (that is, not tied to seasons), they have to rely on outside forcing. Second, for the cycles to come and go, the forcing has to wax and wane. Clearly, the forcing will be strong when different sources support each other, and weak, when they do not. Also, to the degree that the sun participates, the intensity of solar activity will play an important role.

Armed with these simple concepts, we can attempt an explanation for why the 7.7-year cycle is so much stronger after 1900 than before. The tides, we know, remain much the same. Thus, the source of the difference with time must be with solar activity under the hypothesis of outside forcing. Indeed, from the record of solar activity (Hoyt and Schatten, 1997; Lean, 2002) we notice a higher output level of the sun in the 20th century, compared with earlier times. But also, and significantly, it is the periodicity

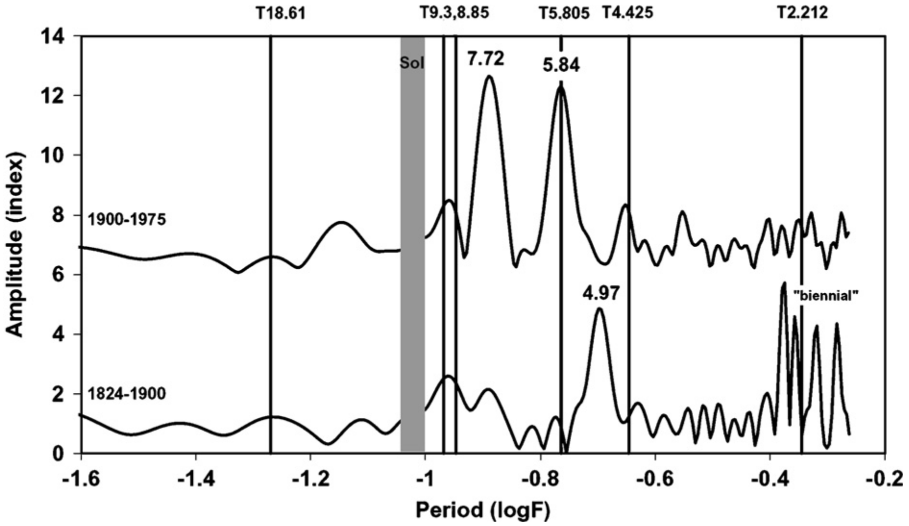

Fig. 3. Periodograms for the NAO index for the intervals 1824–1900 and 1900–1975. The 7.7- and the 5.8-year cycle are seen to be strong after 1900, while the 19th century has a strong 5-year cycle along with strong fluctuations with periodicities near 2–2.5 years. On top, *T* followed by a number denotes position of tidal periods within the diagram.

of the solar cycles that changes. Along with displaying higher amplitudes, the cycles show periods that, on average, are slightly shorter in the 20th century than in the 19th (Fig. 4).

These changes in solar activity with regard to both strength and length of cycles are in the right direction for enhancing interaction with the tidal periods. It is interesting that the (presumed) tidal period of 5.8 years also benefits from this increased solar input. As discussed below, both the nodal tidal cycle and the perigee tidal cycle are brought to bear on the system through their interaction with the solar cycle. Thus strengthened, they leave their mark on the oscillation by steering energy into the 5.8-year tidal difference tone, as well. One might expect that the phase relationships are important in the timing of onset and cessation of collaboration between the solar and tidal forcings. However, since any mechanisms have not been discussed in the literature (or are here proposed), it would be premature to identify favorable and unfavorable phase relationships.

The ca.-5-year cycle remains unexplained, it may be close to the preferred internal oscillation. The fact that it is very close to a whole-number period (less than 1% off 5.00) indicates that it is an oscillation that is strictly tied to seasons. Seasons are incompatible with tidal periods, excepting an effect from the closeness of the sun (perihel, in January).

With the sun entering a period of cycles between 10 and 11, from one with cycles near 11 and slightly greater, enhanced forcing by solar–tidal resonance patterns becomes more likely after 1900. The expected difference tones between 10 and 11 years on one hand and 4.425 years on the other have periods of 7.94 and 7.40, respectively. Thus, the sought-after period of 7.74 years becomes a feasible target.

3. Theory

As mentioned, dominance of the period of 7.74 requires interaction of a solar cycle of 10.33 with the perigee tidal period of 4.425, from the equation for difference tones

$$y = a \times b/(a - b), \qquad (1)$$

where a and b are the interfering periods, a being larger than b.

Solving for a, we get

$$a = y \times b/(y - b). \qquad (2)$$

Entering 7.74 and 4.425 into Eq. (2) yields the value of 10.33.

When plotting the periods for the solar cycles for the relevant time span (not shown), one notes that the solar period did indeed approach the special value of 10.33 over some length of time, in the 19th century. From 1920 to 1950 the actual cycle length was within 1% or so of this special value.

We next have to discuss what makes this value of 10.33 special. It is so special, in fact, that it deserves the label "privileged." The privilege derives from a lock-in of different beat cycles to each other. When interfering with the nodal tidal cycle, this solar cycle yields a difference tone that is precisely three times the difference tone with the perigee tidal cycle (Fig. 5). Thus, this longer cycle ($7.74 \times 3 = 23.22$) will support the shorter one with a significant boost on every third instance. But there is yet more: the smallest whole-number multiple of the solar partner (10.33) is 31, within less than 1%. The smallest whole-number multiple of 7.74 also is 31, within about 1%. Thus, these two numbers "lock in" in two ways: by generating a whole-number relationship to the solar–nodal interference and, in addition, by having a

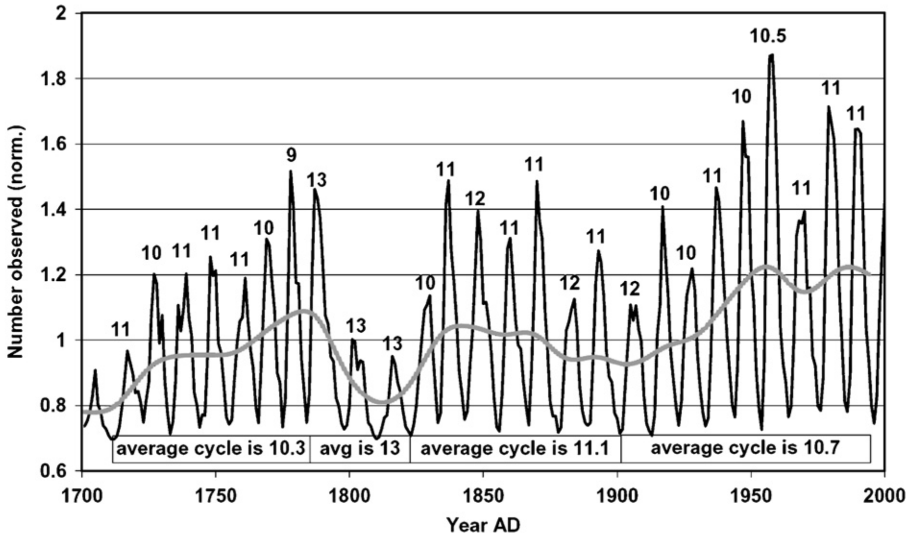

Fig. 4. History of solar cycles as seen in sunspots, according to Hoyt and Schatten (1997) and Lean (2002). The length of cycles (indicated at top of each cycle) changes through time. After 1900, cycles have more energy and are somewhat shorter than before (average cycle length: 10.7 years). Fat gray line; average activity level averaged over three cycles (smoothed).

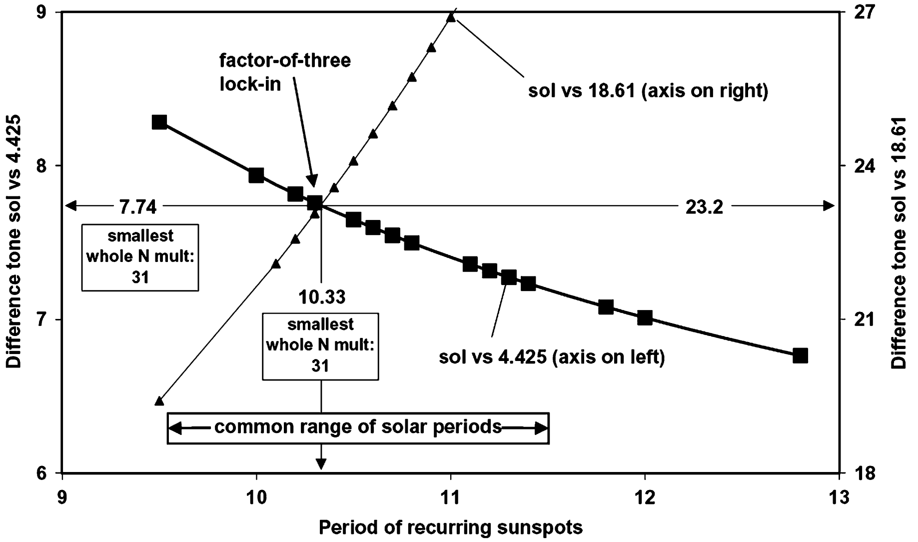

Fig. 5. Relationship between the period of recurring sunspots and the associated difference tones expected for interference with the perigee cycle (4.425 years, left axis) and with the nodal cycle (18.61 years, right axis). The *y*-axes differ by a factor of three, precisely. Lock-in occurs where the two relationships (line connecting squares, line connecting triangles) intersect. At that position the two solar–tidal difference tones differ by a factor of three (7.74 at left, 23.22 at right), and the solar cycle is 10.33 years. Thus, the two interference periods support each other. Also, note that the smallest whole-number multiple for 7.74 is 31 (30.96), and that the same is true for the sunspot period (30.99). Thus, these two periods also support each other. Thus, whenever the sunspot cycles approach the "magic" number of 10.33, the period of 7.74 is enhanced by compatible cycles (see text).

simple 4 to 3 ratio to each other. This is fundamentally the reason for the return of the 7.74 NAO cycle, through the centuries.

Through climate history, then, each time the solar activity allows for this, the mutual lock-in generates mutual support and enhances the amplitude of the oscillation, by focusing its energy into that privileged "lock-in" cycle of 7.74, which may be close to internal preferences. The lock-in is quite specific for the solar activity period of 10.33, but when periods fluctuate around this value, this will generate benefits of mutual support whenever the changing phase relationships are favorable.

The graphic representation of the factor-of-three lock-in (Fig. 5) uses the range of solar fluctuations over the last 300 years (the only ones that are well documented). Other lock-in situations are conceivable, as well (Table 1). These include the factors of 2 and 4, for which the solar cycles are 9.00 and 11.34, respectively. One would also expect interference lines with the tidal beat of 5.8,

Table 1
Solar-tidal interference lines

Whole-number lock-in occurs when

$x = (N+1)ab/(a+Nb)$,
where N is the factor (2, 3, or 4), while a and b are the tidal partner periods for interference with the solar period x and ($a > x > b$).

Solutions for whole-number lock-in are

		$N=2$	$N=3$	$N=4$
a	b	x	x	x
18.61	4.425	9.00	10.33	11.34

Realizations for lock-in and other solar cycles are as follows (lock-in periods in italics):

Solar		10	10.33	10.5	10.7	11	11.34
Nodal	18.61	21.61	*23.22*	24.09	25.17	26.90	*29.03*
Perigee	4.425	7.94	*7.74*	7.65	7.55	7.40	*7.26*
Factor			3				4

but this possibility is not pursued here. Analysis of long series such as provided by Cook et al. (2002), as well as others cited, will show whether the interaction of solar cycles with combination tidal cycles is indeed important.

4. Conclusions

The focus of this essay is on the nature of the 7.74-year NAO cycle, which appears in the instrumental record, especially in the 19th century, and which is highly visible over centuries in a proxy reconstruction of the NAO by Cook et al. (2002) and Cook (2002). The hypothesis here proposed is that we are dealing with a combination tone whose origin is in external forcing by solar cycles and tides. Only when the sun cycles are at the "correct" period can this NAO cycle appear. When it does happen, the mutually supportive interference patterns (solar–perigee, solar–nodal) greatly amplify the system output. A corollary of the hypothesis is that we should find a strong representation of a cycle near 31 years, for favorable time spans within those parts of the North Atlantic climate system whose oscillations are of appropriate bandwidth. The survival of the hypothesis hinges on finding that, where appropriate, the 7.74 cycle is accompanied by a cycle near 23.2, and one near 31. Possibly, also, a cycle near 5.8 should be present (and its whole-number equivalent, 29), because of entrainment of forcing periods into a structured system. If these conclusions hold, structuring of the NAO through history reflects both the strength and the periodicity of the sun, despite the apparent absence of solar cycles within the NAO index series.

The proposition that tides may be informing climate cycles at the decadal scale impacts the interpretation of tidal signals in varved sediments (Berger and von Rad, 2002; Berger et al., 2004). Such signals may not solely reflect shelf sediment processes linked to tidal action.

Acknowledgments

This paper is a follow-up to work done since 1999 with my geologist colleagues J. Paetzold and G. Wefer (U. Bremen), work that gave me the opportunity to study growth series in a massive and ancient coral from Bermuda, from the tidal zone. It seemed reasonable to expect tidal information in a coral record collected in the tidal zone (Berger et al., 2002). But it came as a surprise to see related spectral lines in data based on meteorological measurements. I am indebted to the late C. David Keeling, who first directed my attention to the possibility that tidal periods might appear in the climate narrative. I am grateful for discussions with those skeptical colleagues who, while reluctant to contemplate tidal forcing as part of climate history, have suggested clarifying the hypothesis, rather than rejecting it as lunatic. I thank two anonymous reviewers for useful suggestions for improvement of the manuscript.

References

Berger, W.H., 1997. Experimenting with ice-age cycles in a spreadsheet. Journal of Geoscience Education 45, 428–439.

Berger, W.H., von Rad, U., 2002. Decadal to millennial cyclicity in varves and turbidites from the Arabian Sea: hypothesis of tidal origin. Global and Planetary Change 34, 313–325.

Berger, W.H., Pätzold, J., Wefer, G., 2002. A case for climate cycles: orbit, sun and moon. In: Wefer, G., et al. (Eds.), Climate Development and History of the North Atlantic Realm. Springer, Berlin & Heidelberg, pp. 101–123.

Berger, W.H., Schimmelmann, A., Lange, C.B., 2004. Tidal cycles in the sediments of Santa Barbara Basin. Geology 32, 329–332.

Cook, E.R., 2002. Multi-proxy reconstruction of the North Atlantic Oscillation (NAO) Index: a critical review and a new well-verified winter NAO Index reconstruction back to AD 1400. American Geophysical Union Geophysical Monograph 134, 63–79.

Cook, E.R., D'Arrigo, R.D., Mann, M.E., 2002. A well-verified, multi-proxy reconstruction of the winter North Atlantic Oscillation Index since A.D. 1400. Journal of Climate 15, 1754–1764.

Ghil, M., 1994. Cryothermodynamics: the chaotic dynamics of paleoclimate. Physica D 77, 130–159.

Hoyt, D.V., Schatten, K.H., 1997. The Role of the Sun in Climate Change. Oxford Univ. Press, New York, Oxford, 279pp.

Hu, Z.-Z., Wu, Zh., 2004. The intensification and drift of the annual North Atlantic Oscillation in a global warming scenario simulation. Tellus 56A, 112–124.

Hurrell, J.W., Kushnir, Y., Ottersen, G., Visbeck, M. (Eds.), 2003. The North Atlantic Oscillation—climatic significance and environmental impact. American Geophysical Union Geophysical Monograph, 134, 279.

Jones, P.D., Mann, M.E., 2004. Climate over past millennia. Reviews of Geophysics 42 (2) doi:10.1029/2003RG000143.

Jones, P.D., Jónsson, T., Wheeler, D., 1997. Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. International Journal of Climatology 17, 1433–1450.

Lean, J., 2002. Solar forcing of climate change in recent millennia. In: Wefer, G., et al. (Eds.), Climate Development and History of the North Atlantic Realm. Springer, Berlin & Heidelberg, pp. 75–88.

Luterbacher, J., Xoplaki, E., Dietrich, D., Jones, P.D., Davies, T.D., Portis, D., Gonzalez-Rouco, J.F., von Storch, H., Gyalistras, D., Casty, C., Wanner, H., 2002. Extending North Atlantic Oscillation reconstructions back to 1500. Atmospheric Sciences Letters 2, 114–124.

McCabe, G.J., Palecki, M.A., Betancourt, J.L., 2004. Pacific and Atlantic influences on multidecadal drought frequency in the United States. Proceedings of the National Academy of Science 101 (12), 4136–4141.

Meeker, L.D., Mayewski, P.A., 2002. A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia. The Holocene 12, 257–266.

Osborn, T.J., Briffa, K.R., Tett, S.F.B., Jones, P.D., Trigo, .M., 1999. Evaluation of the North Atlantic Oscillation as simulated by a coupled climate model. Climate Dynamics 15, 685–702.

Sverdrup, H.U., 1918. Die Beziehung der elfjährigen Klimaschwankungen zur Sonnentätigkeit. Annalen der Hydrographie und Maritimen Meteorologie, 191–193.

Vinther, B.M., Johnsen, S.J., Andersen, K.K., Clausen, H.B., Hansen, A.W., 2003. NAO signal recorded in the stable isotopes of Greenland ice cores. Geophysical Research Letters 30, 1387.

Wefer, G., Berger, W.H., Behre, K.-E., Jansen, E. (Eds.), 2002. Climate Development and History of the North Atlantic Realm. Springer, Berlin Heidelberg, p. 486.